Integrated Neurotechnologies Laboratory

EPFL

Advanced analog integrated circuit design (EE-523), Lecture 2

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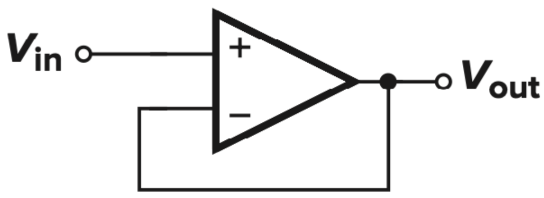
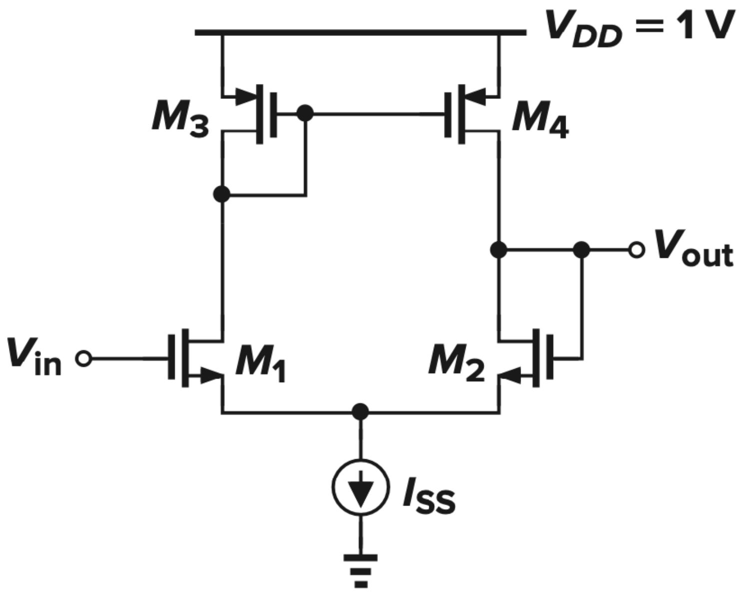
Example: Input CM Range and Output Impedance

- Find the input common-mode voltage range and closed-loop output impedance of the unity-gain buffer shown below. Assume V_{th} = 0.3V and V_{od} = 0.1V.





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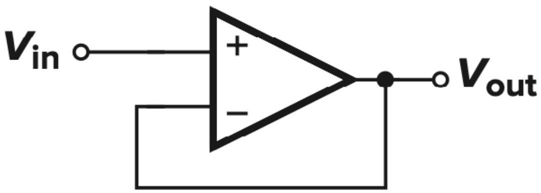
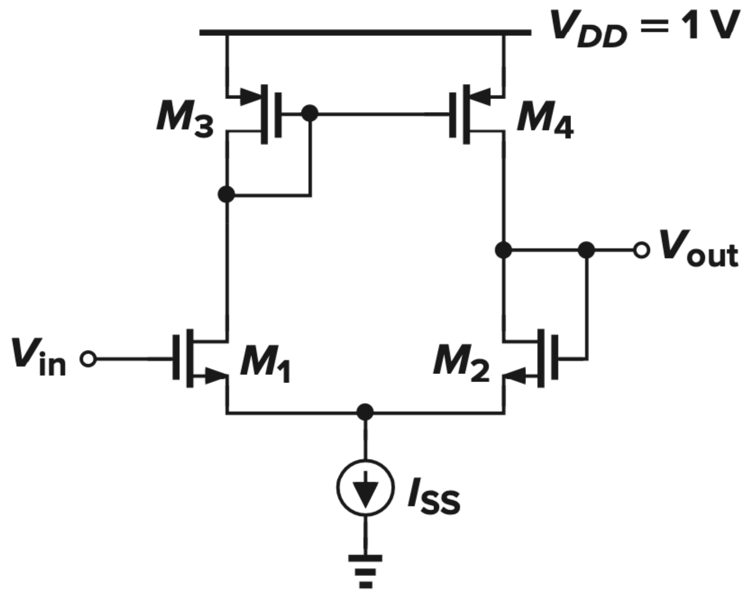


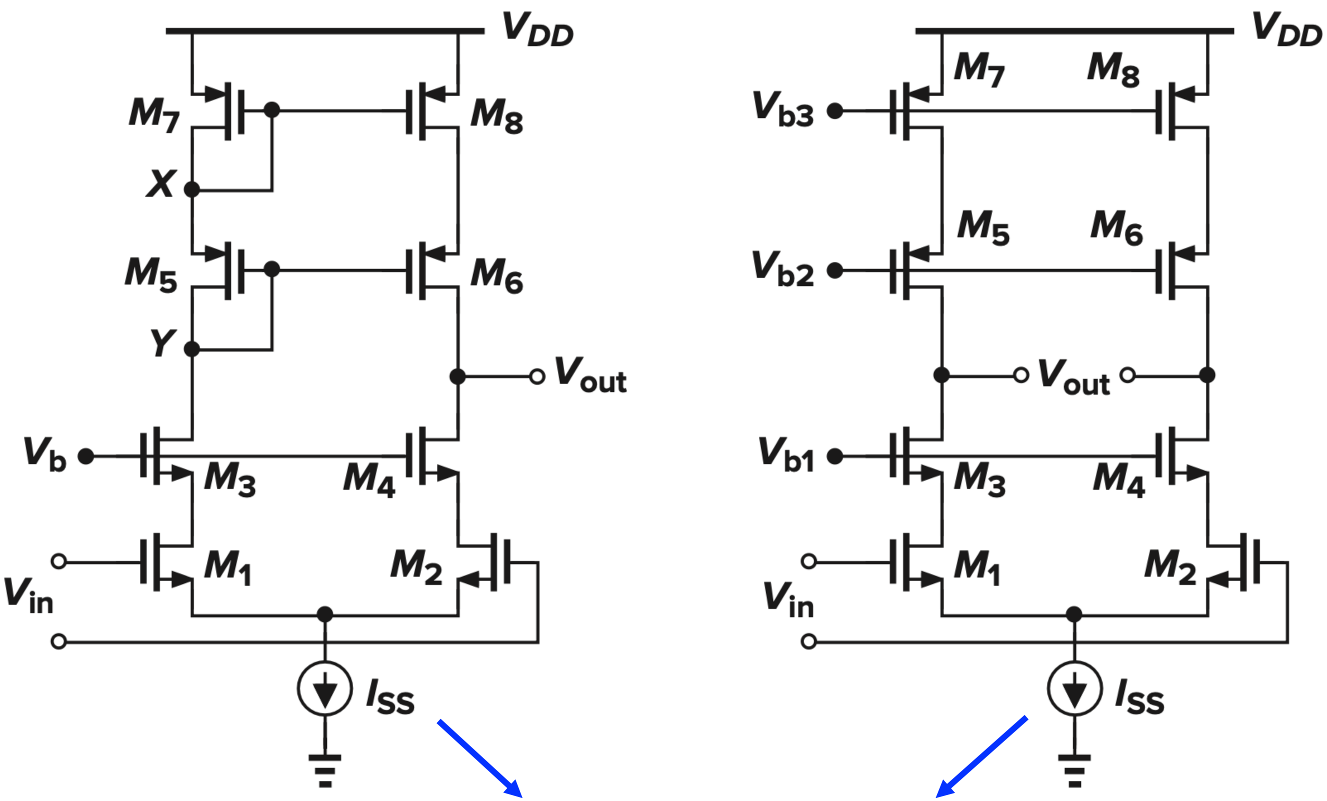


$$V_{ISS} + V_{GS1} \longrightarrow V_{DD} - |V_{GS3}| + V_{TH1}$$

$$(r_{OP} \| r_{ON})/[g_{mN}(r_{OP} \| r_{ON})] = 1/g_{mN}$$

One-Stage Op amps with Higher Gain: Cascode

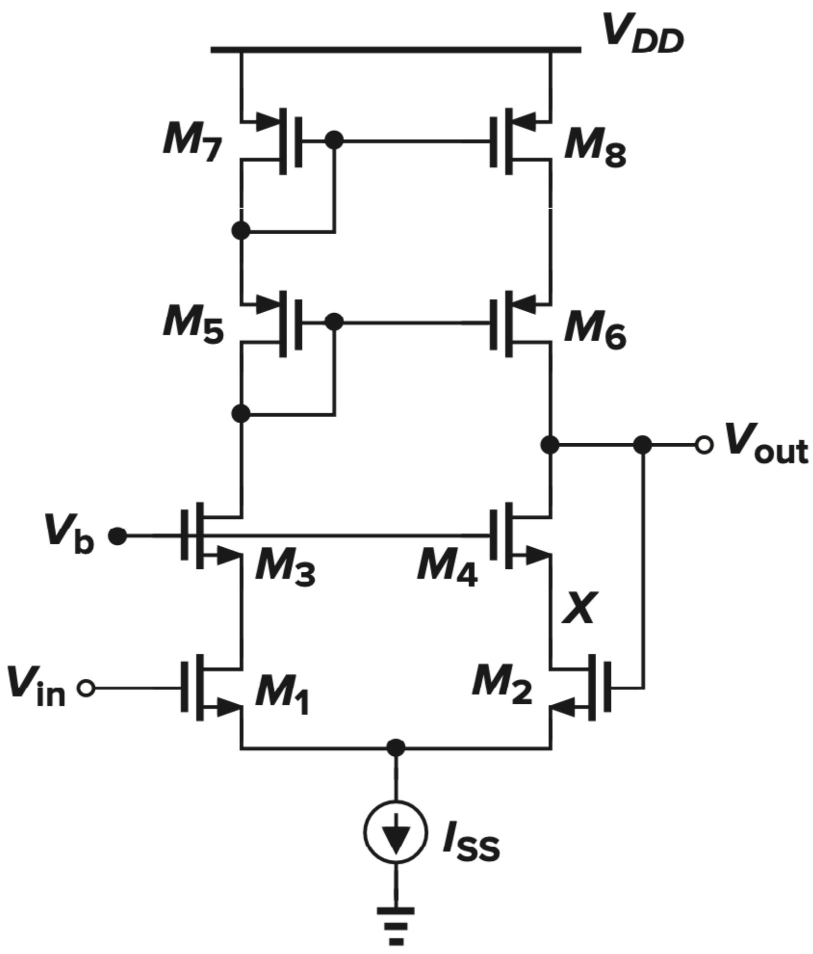
- Telescopic cascode with **single-ended** and **differential** outputs
- High gain at the cost of output swing and additional poles



$$g_{mN}[(g_{mN}r_{ON}^2)\|(g_{mP}r_{OP}^2)]$$

Cascode Op Amp

- Difficult to use as a unity-gain buffer: limited output range
- **Op Amp design procedure** will be practiced during the TP sessions



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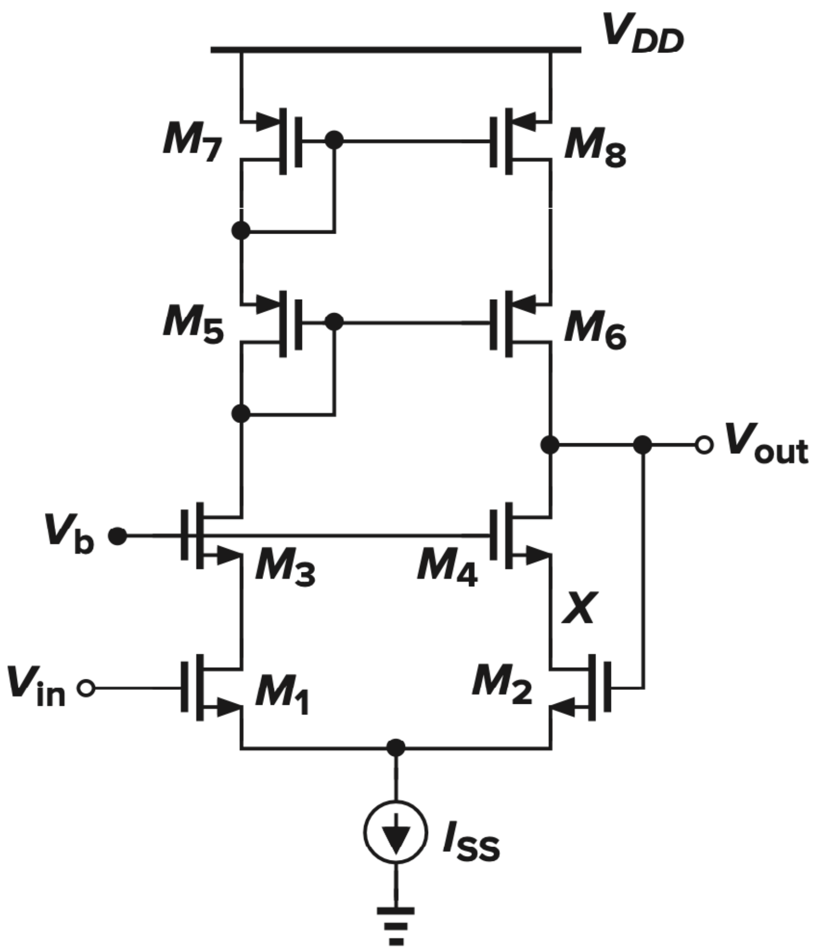
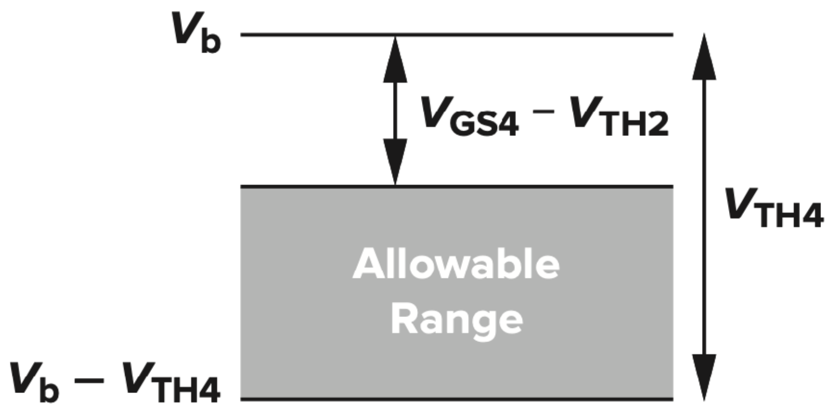
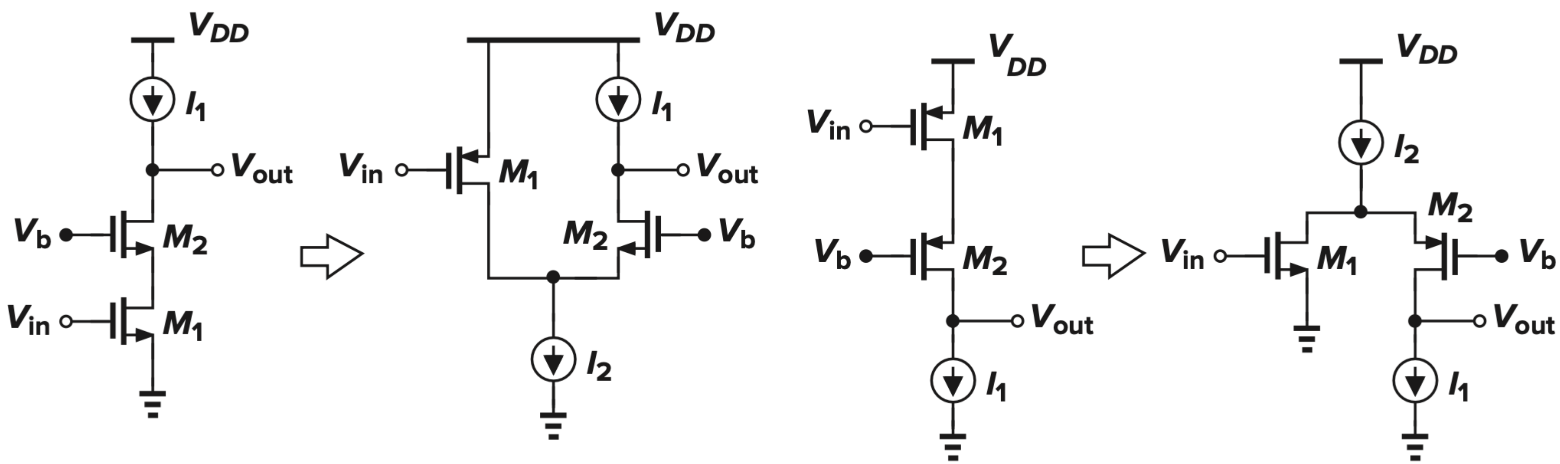




Folded-Cascode Op Amp

- Folded structure: To address the limited output swing and difficulty in choosing equal input and output CM levels for the telescopic cascode



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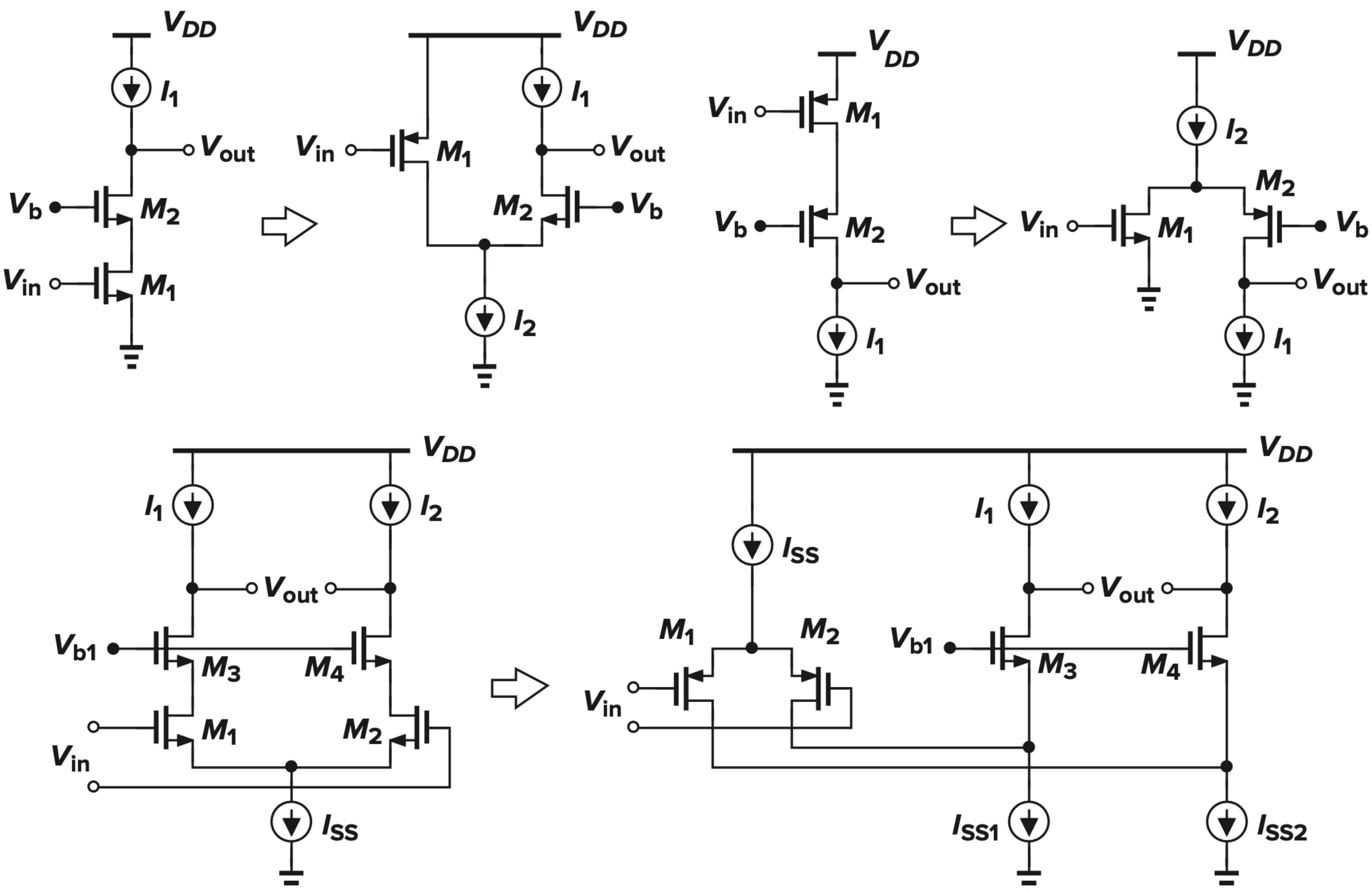
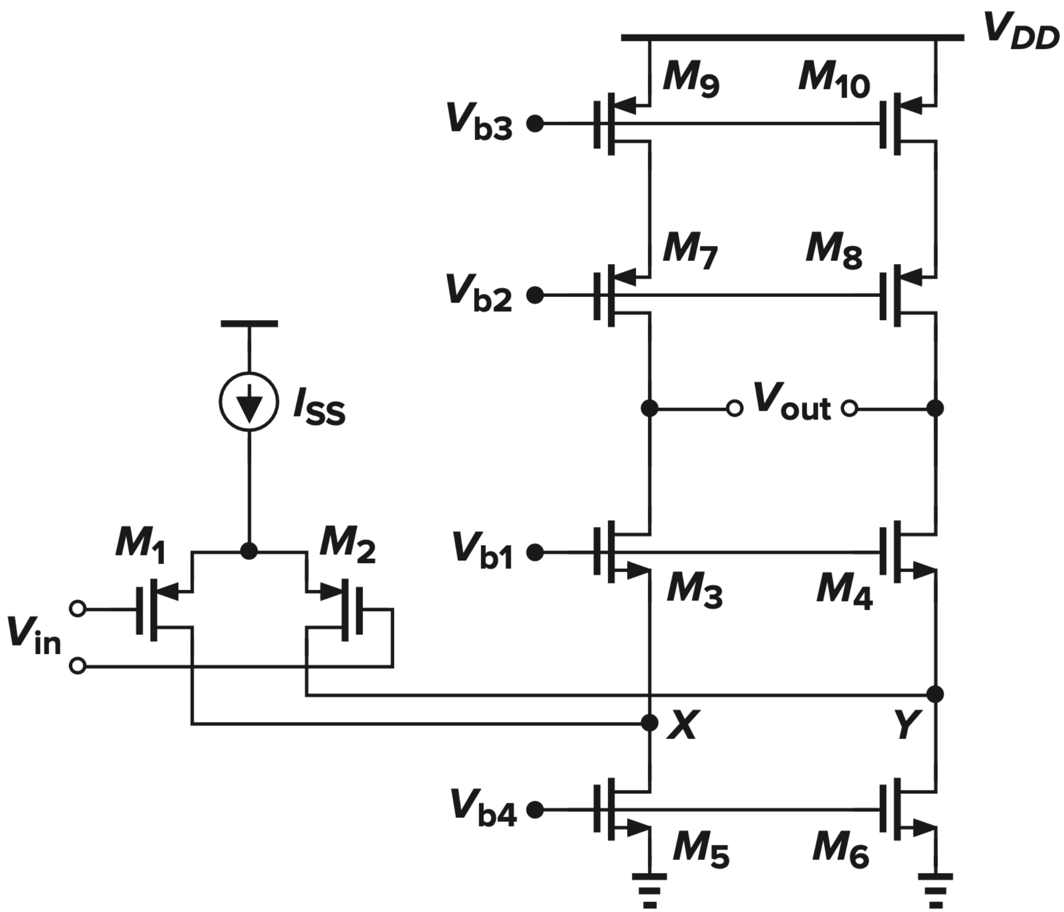


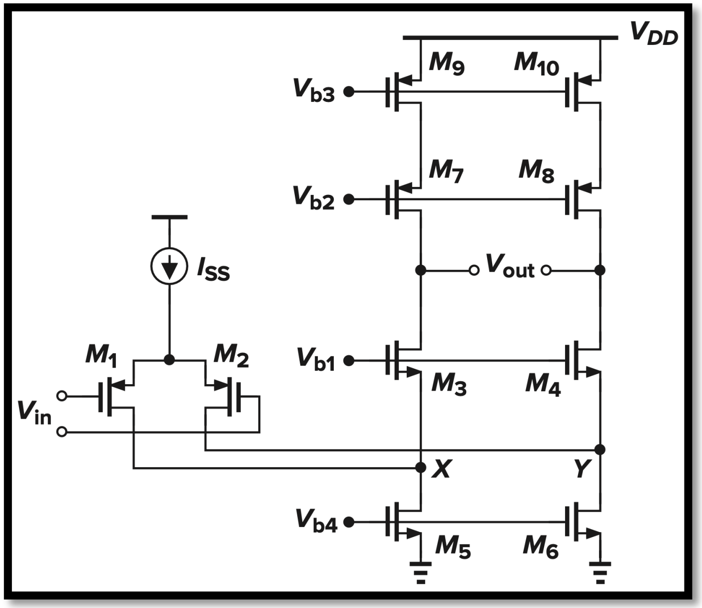
Folded-Cascode: Maximum output swing



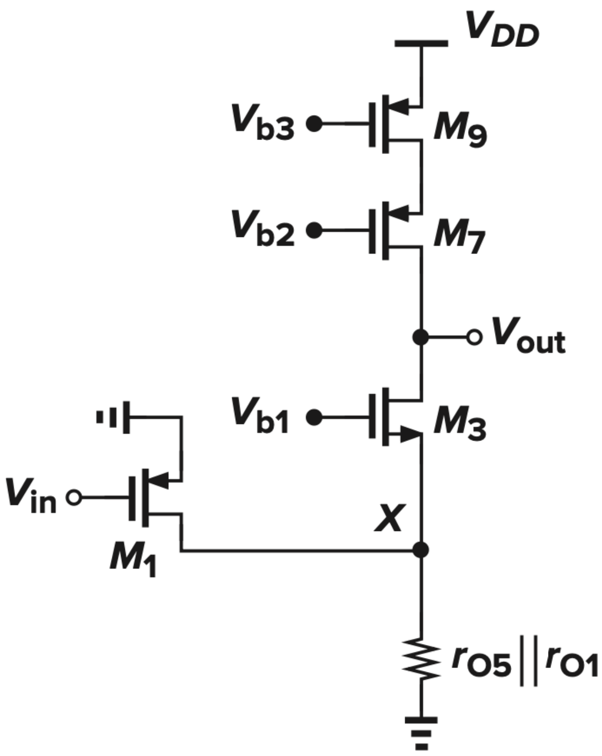
- Single-ended output swing:

$$V_{DD} - (V_{OD3} + V_{OD5} + |V_{OD7}| + |V_{OD9}|)$$

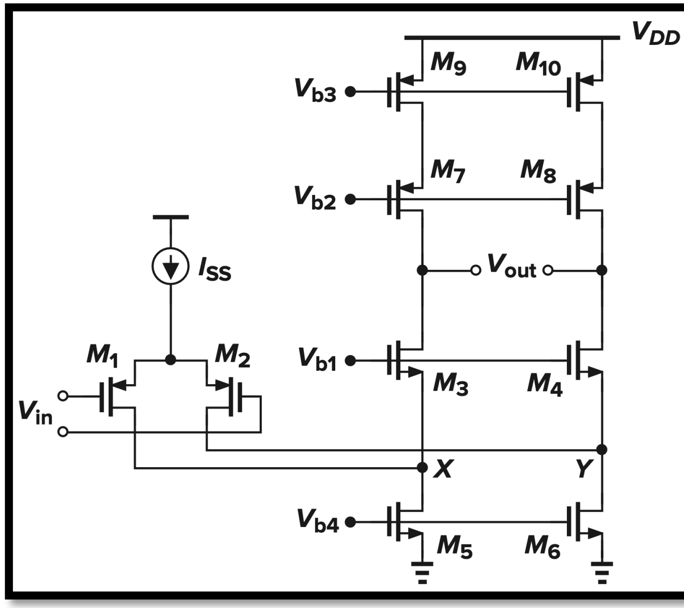
Folded-Cascode: Voltage gain



Half-circuit



Folded-Cascode: Voltage gain



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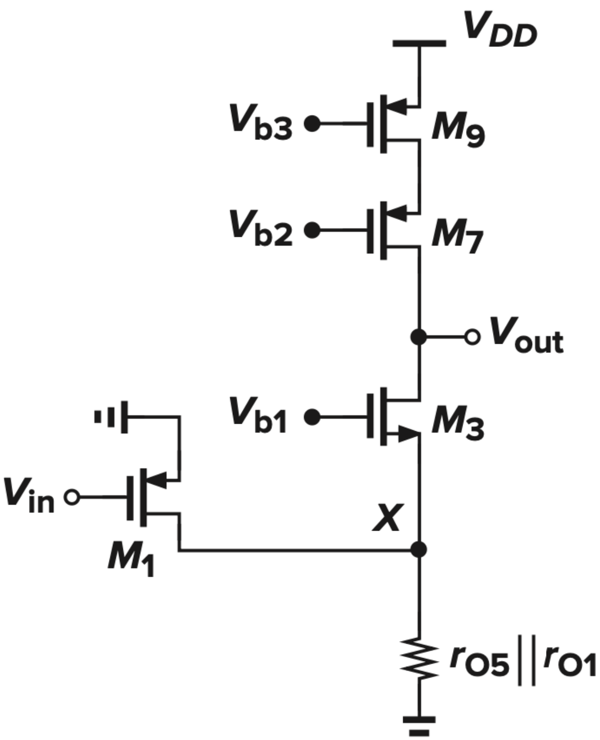
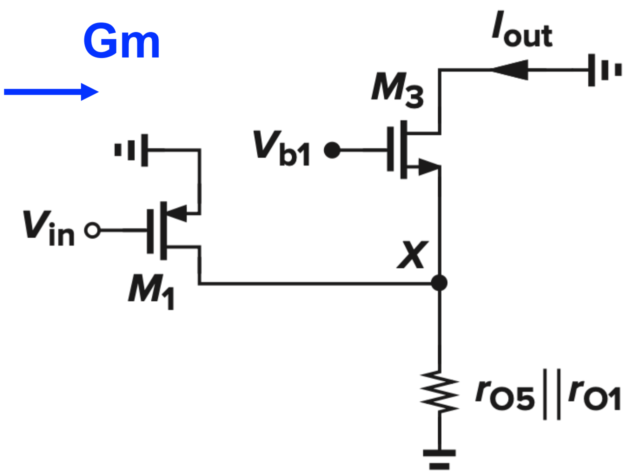
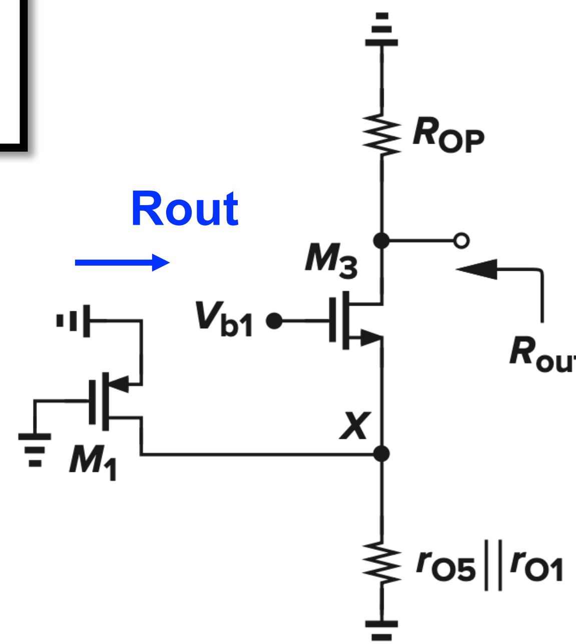


Gm

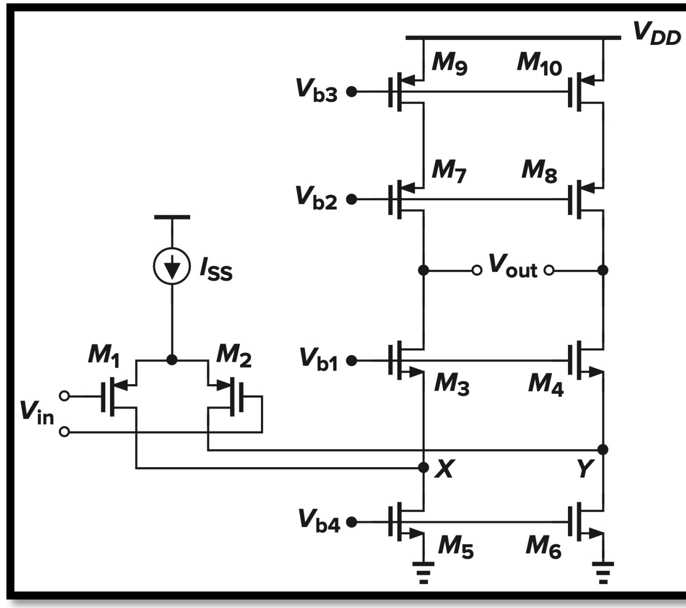


Rout

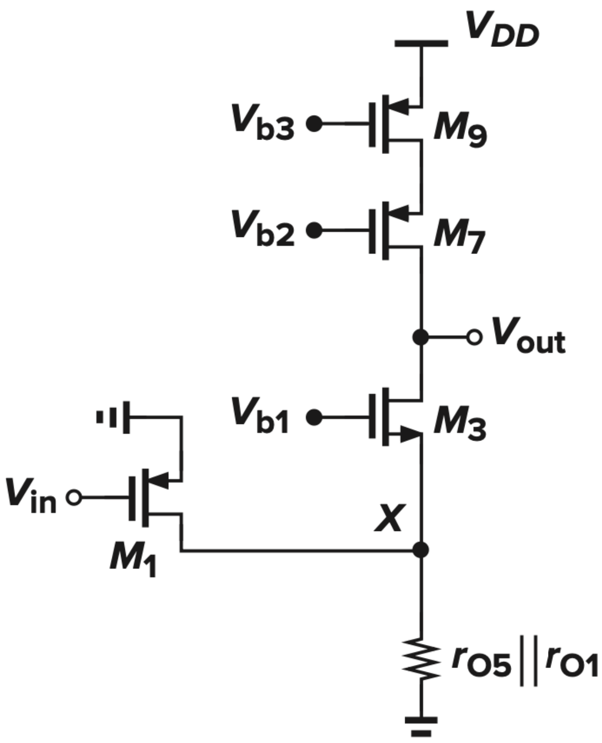


$$|A_v| = G_m R_{out}$$

Folded-Cascode: Voltage gain



Half-circuit



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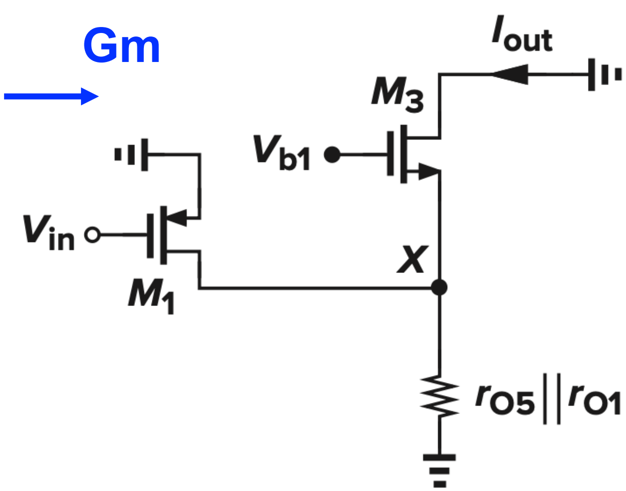

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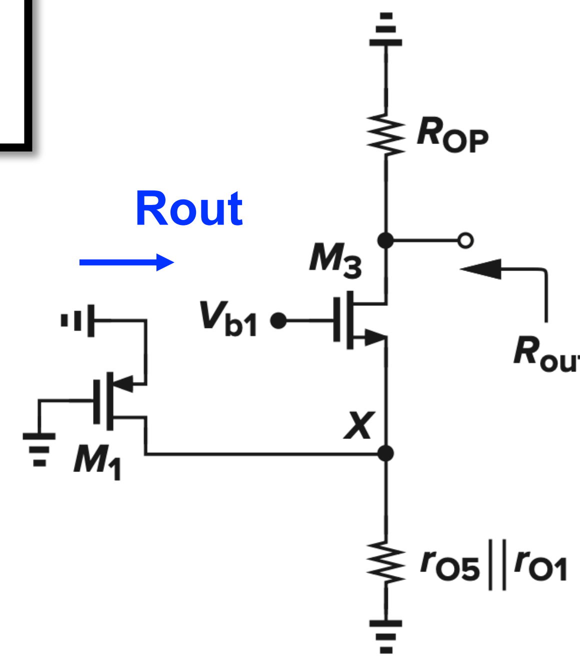
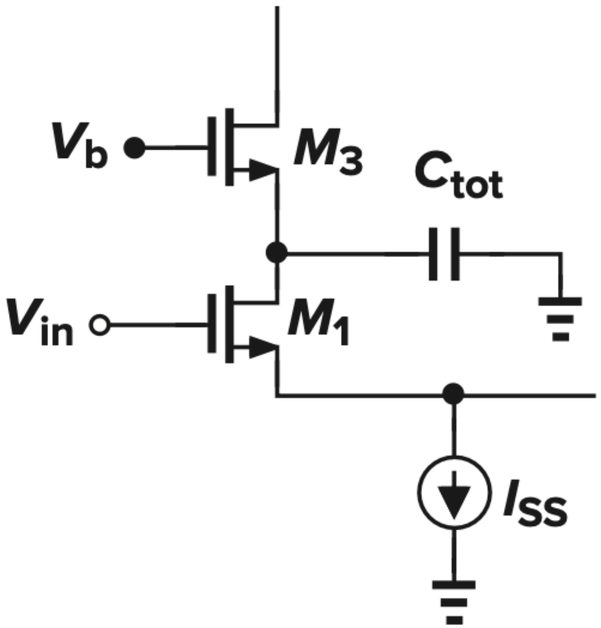


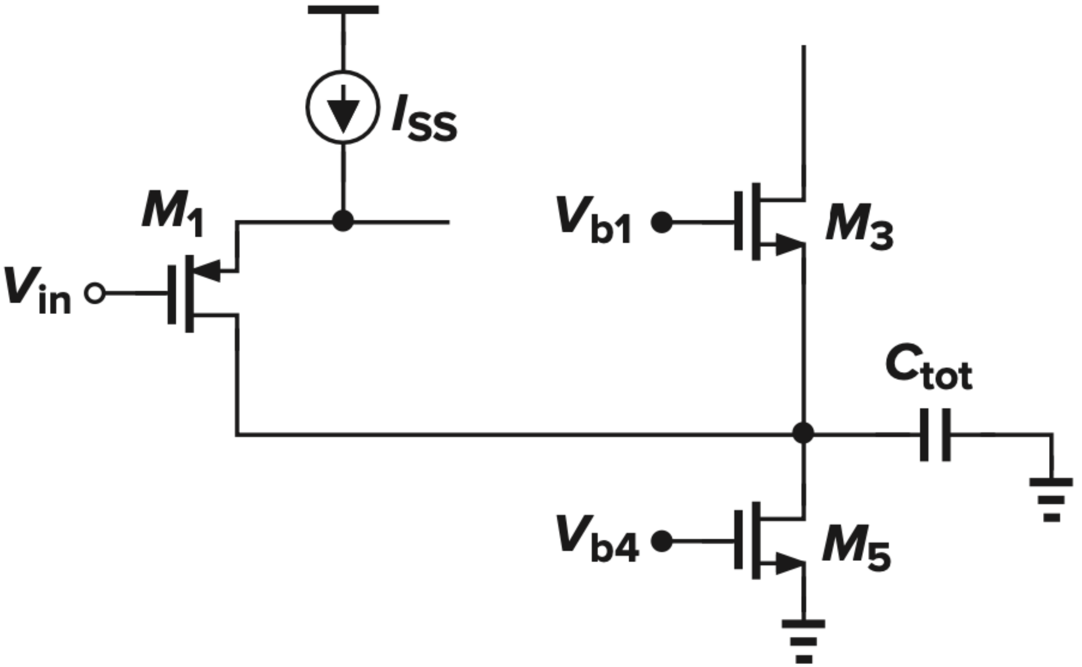
$$|A_v| \approx g_{m1}\{[(g_{m3} + g_{mb3})r_{O3}(r_{O1}\|r_{O5})]\|[(g_{m7} + g_{mb7})r_{O7}r_{O9}]\}$$

Folded-Cascode: Nondominant pole location

Telescopic Cadcode

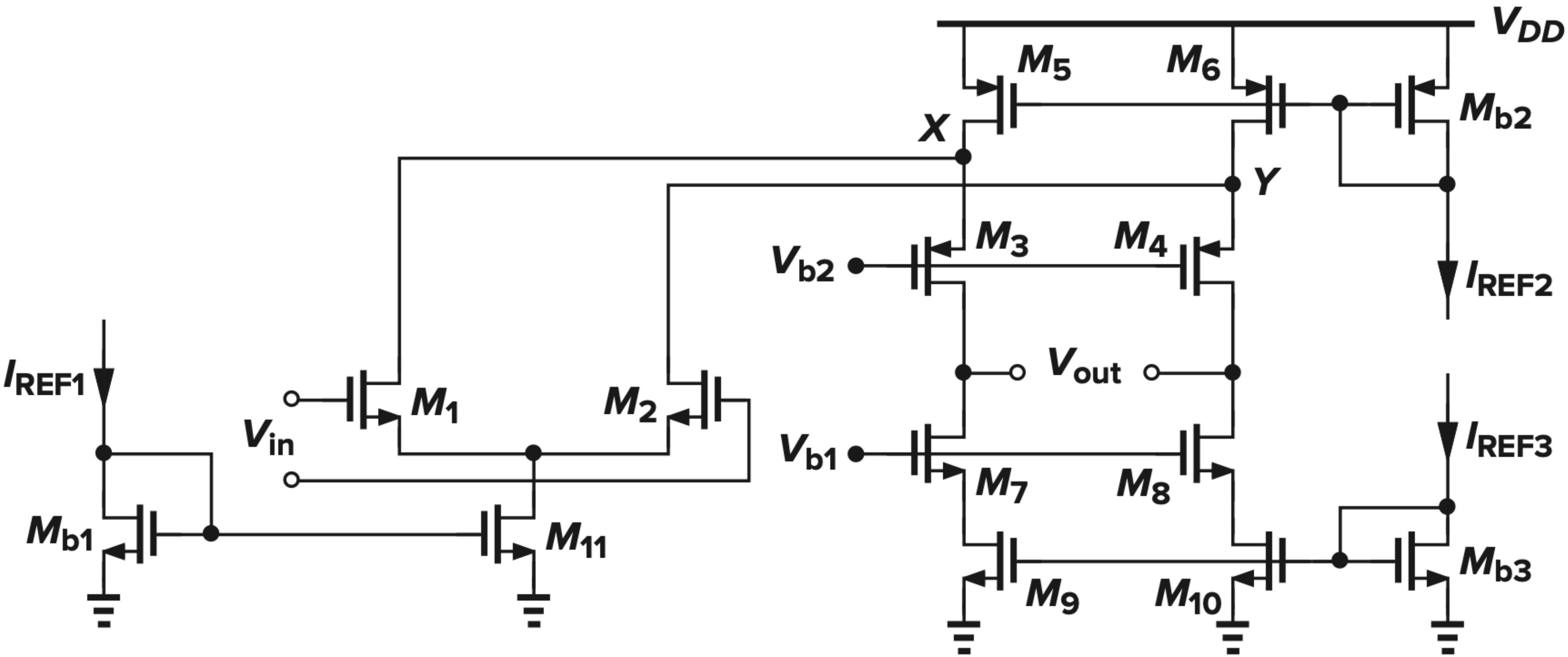


Folded Cadcode



Folded-Cascode with NMOS input pair

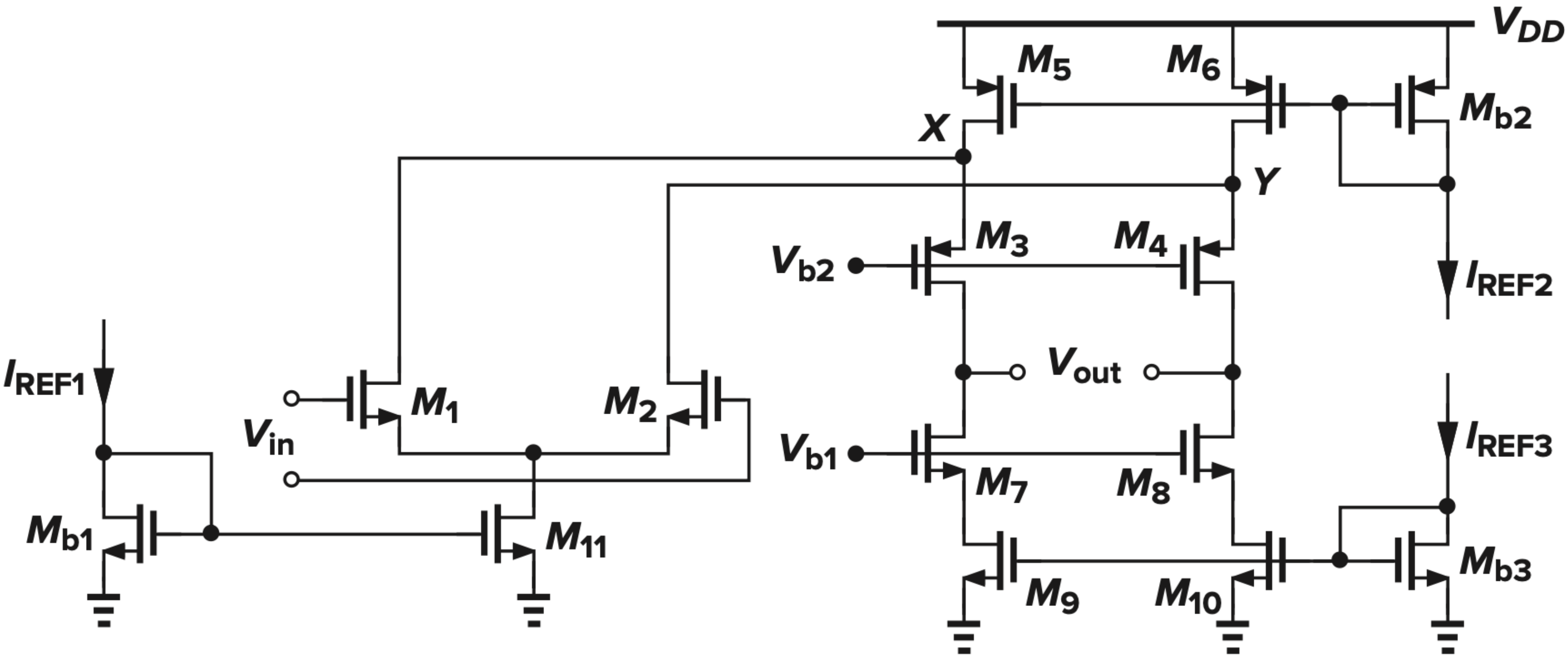
- Folded cascode with **NMOS input devices**: Higher gain



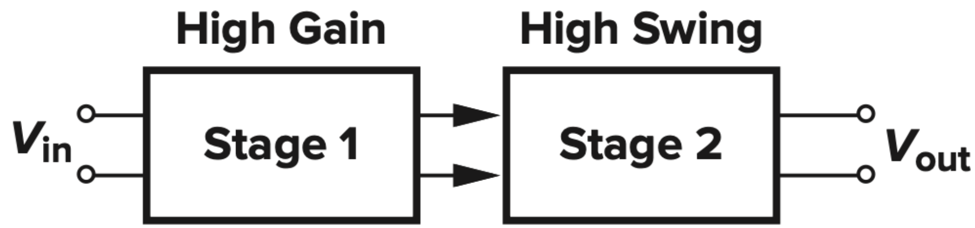
Folded-Cascode Advantages

- Folded-cascode op amps are used more widely than telescopic because:

(1) Input & output CM levels can be chosen equal without limiting output swing
(2) They can accommodate a wider input CM range



- In contrast to cascode op amps, a two-stage configuration isolates the gain and swing requirements.

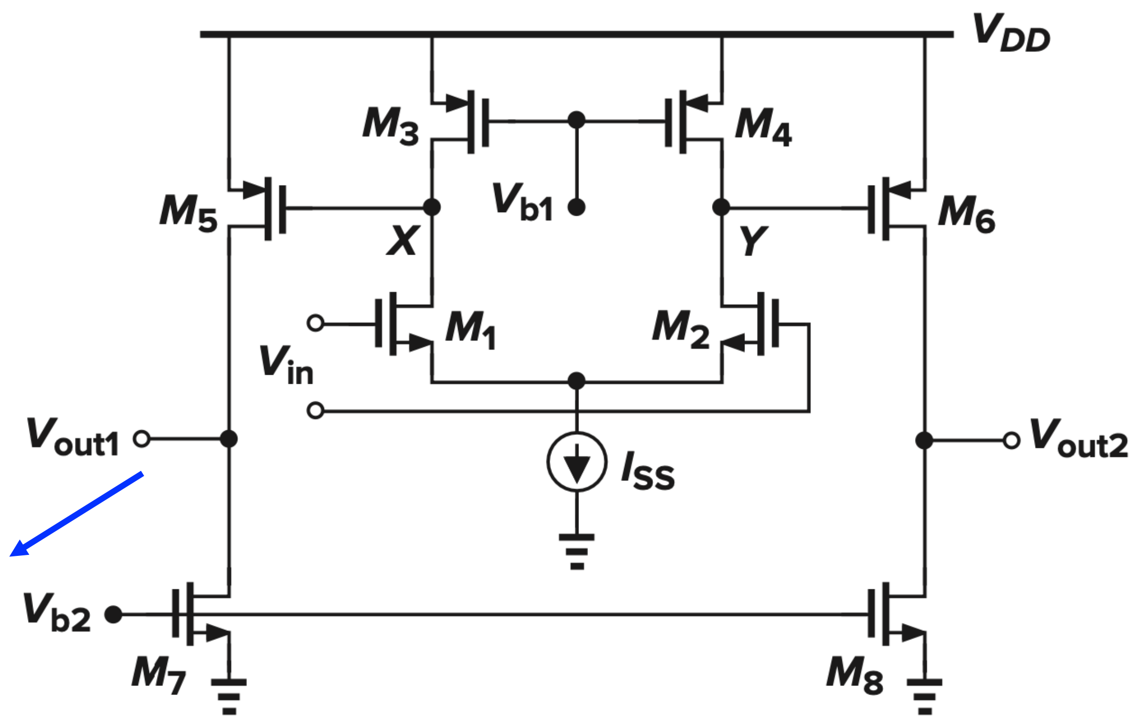


$$g_{m1,2}(r_{O1,2} \| r_{O3,4})$$

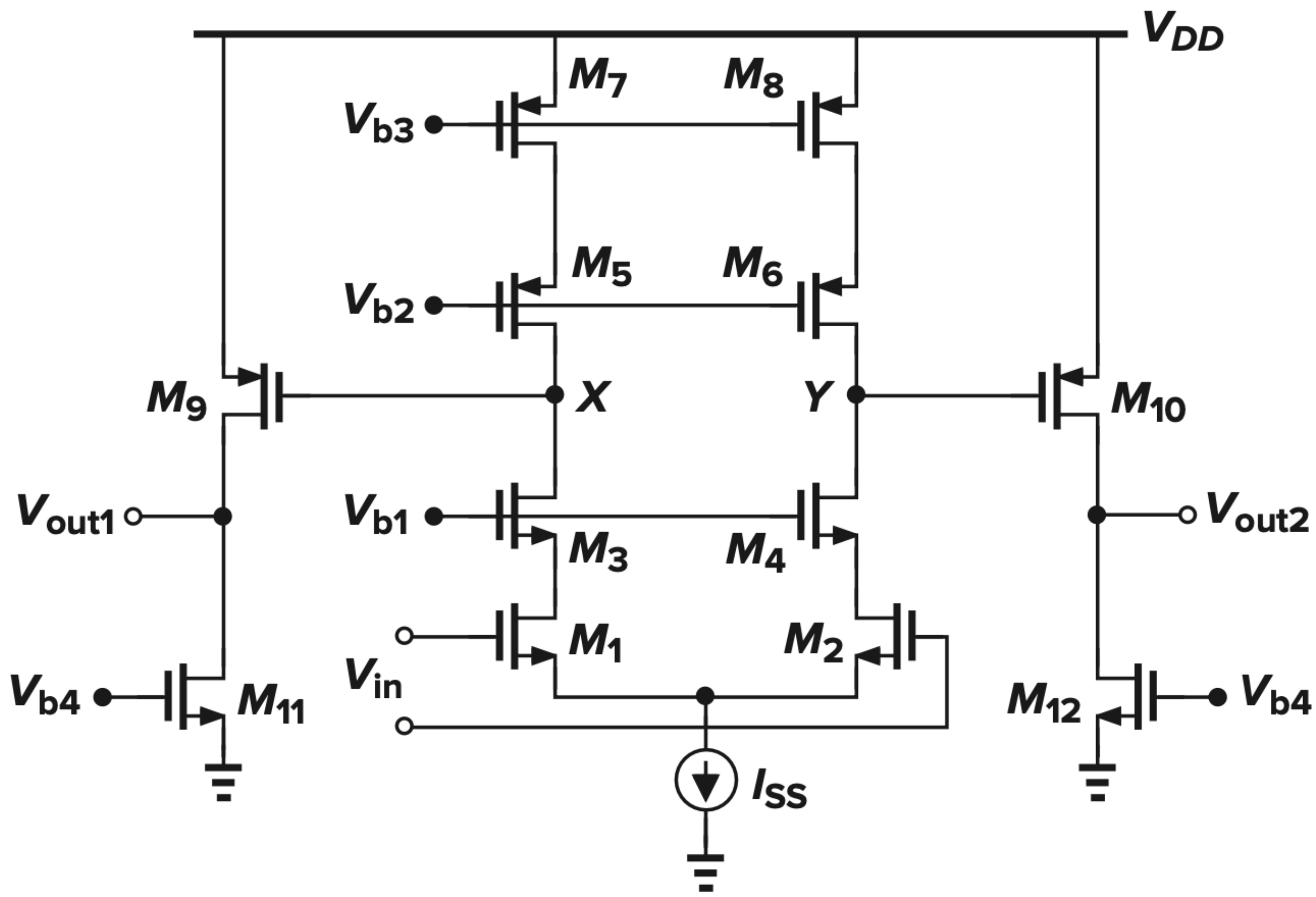
$$\times$$

$$g_{m5,6}(r_{O5,6} \| r_{O7,8})$$

$$V_{DD} - |V_{OD5,6}| - V_{OD7,8}$$



Two-Stage Op Amps

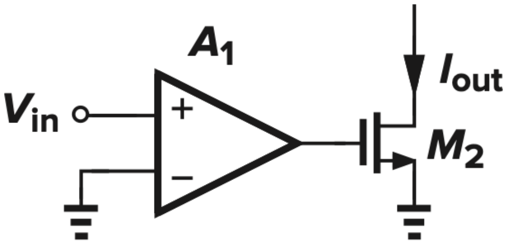


$$A_v \approx \{g_{m1,2}[(g_{m3,4}+g_{mb3,4})r_{O3,4}r_{O1,2}] \| [(g_{m5,6}+g_{mb5,6})r_{O5,6}r_{O7,8}]\}$$

$$\times\ [g_{m9,10}(r_{O9,10} \| r_{O11,12})]$$

Gain Boosting

- Motivation: The limited gain of the one-stage op amps and the difficulties in using two-stage op amps at high speeds necessitate new topologies
- The idea behind gain boosting is to increase the output impedance **without adding more cascode devices**



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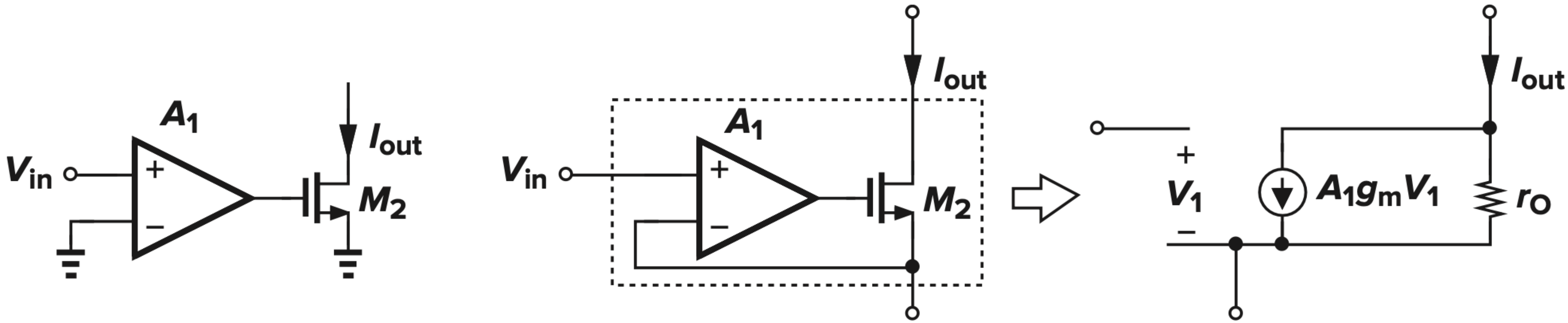
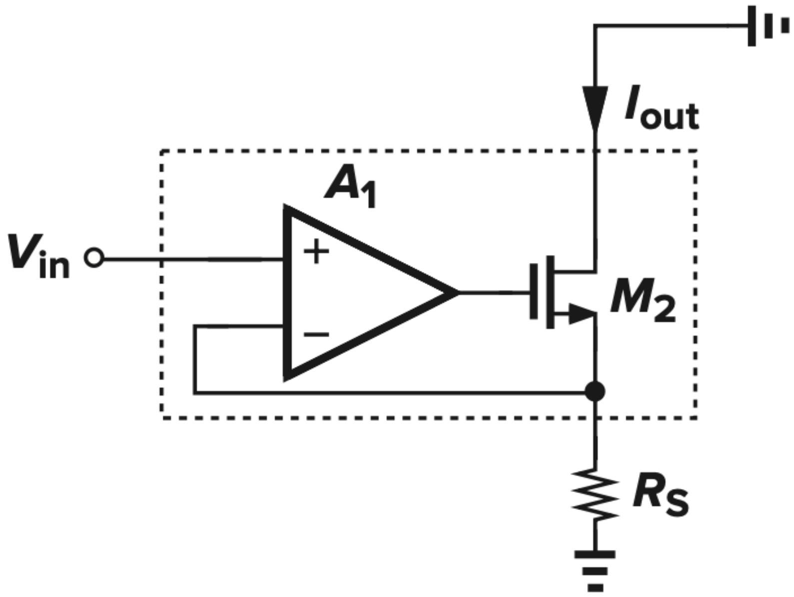


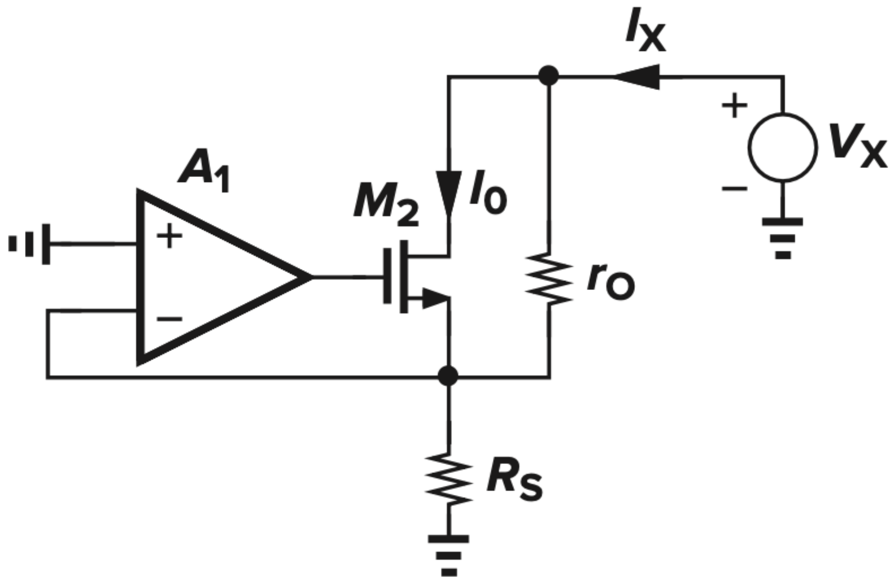
Gain Boosting: Gm



$$I_{out} = g_m[(V_{in} - R_S I_{out})A_1 - R_S I_{out}]$$

$$\frac{I_{out}}{V_{in}} = \frac{A_1 g_m}{1 + (A_1 + 1) g_m R_S}$$

Gain Boosting: Rout



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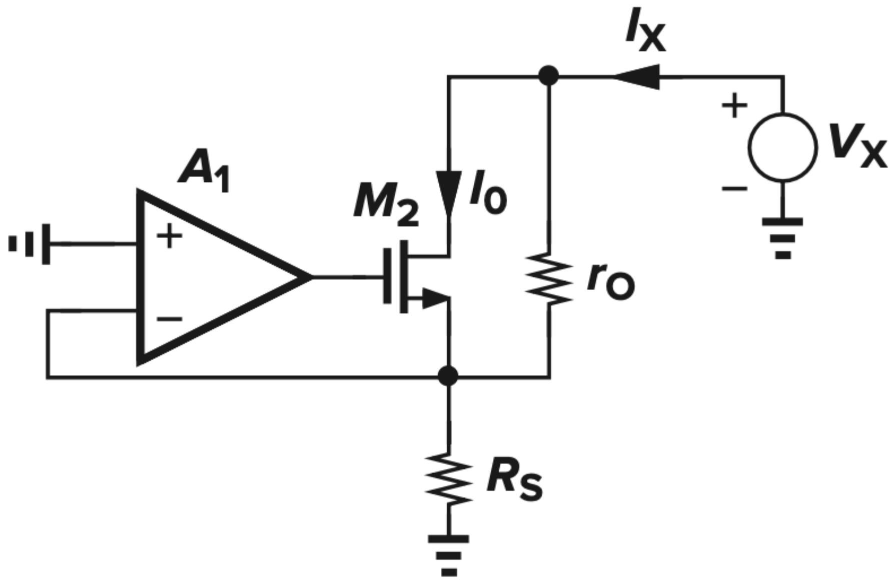
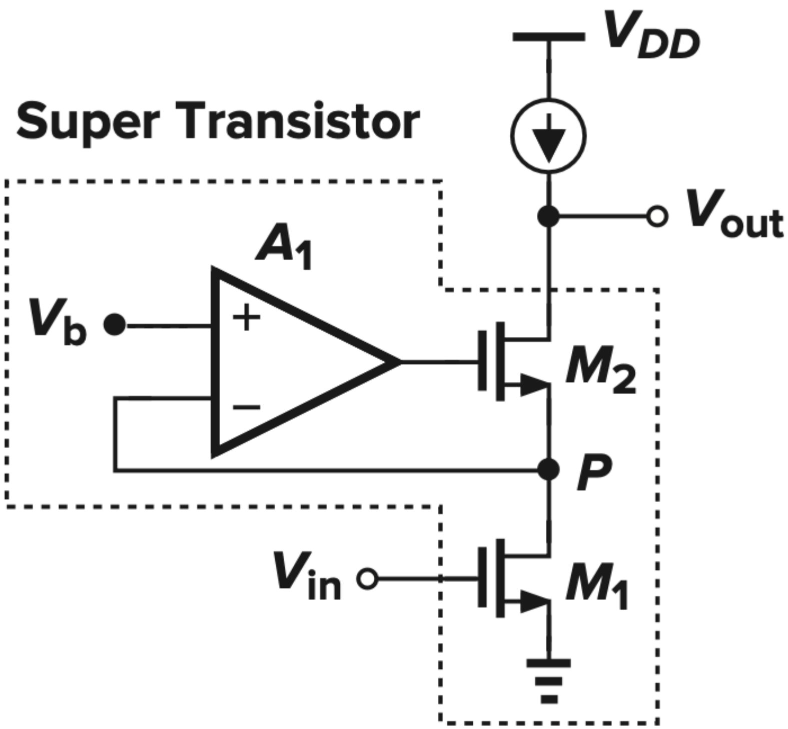


$$I_X = (-A_1 R_S - R_S) g_m I_X + \frac{V_X - R_S I_X}{r_O}$$

$$R_{out} = r_O + (A_1 + 1) g_m r_O R_S + R_S$$

Gain Boosting: Voltage Gain



Output impedance:

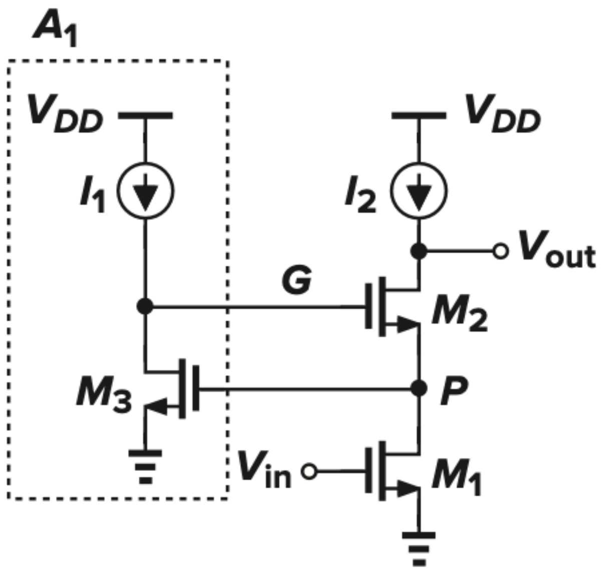
$$r_{O2} + (A_1 + 1)g_{m2}r_{O2}r_{O1} + r_{O1}$$

$$G_m \approx g_{m1}$$

$$|A_v| \approx g_{m1}[r_{O2} + (A_1 + 1)g_{m2}r_{O2}r_{O1} + r_{O1}]$$

$$\approx g_{m1}g_{m2}r_{O1}r_{O2}(A_1 + 1)$$

Gain Boosting: Circuit Implementation



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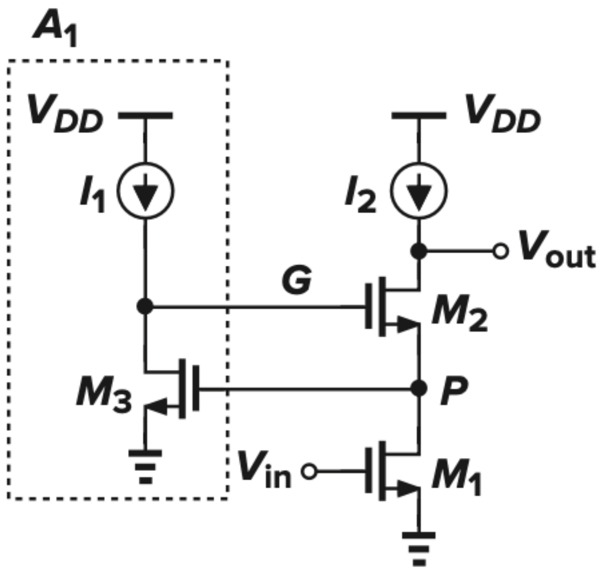
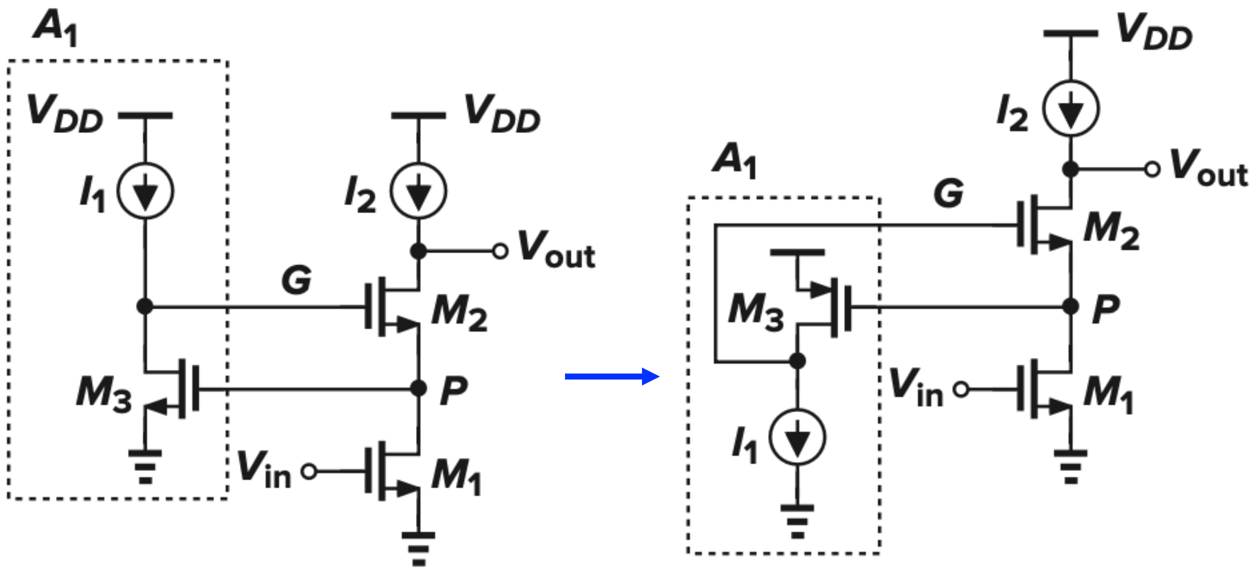


$$|A_1| = g_{m3} r_{O3}$$

$$|V_{out}/V_{in}| \approx g_{m1} r_{O1} g_{m2} r_{O2} (g_{m3} r_{O3} + 1)$$

Gain Boosting: Circuit Implementation



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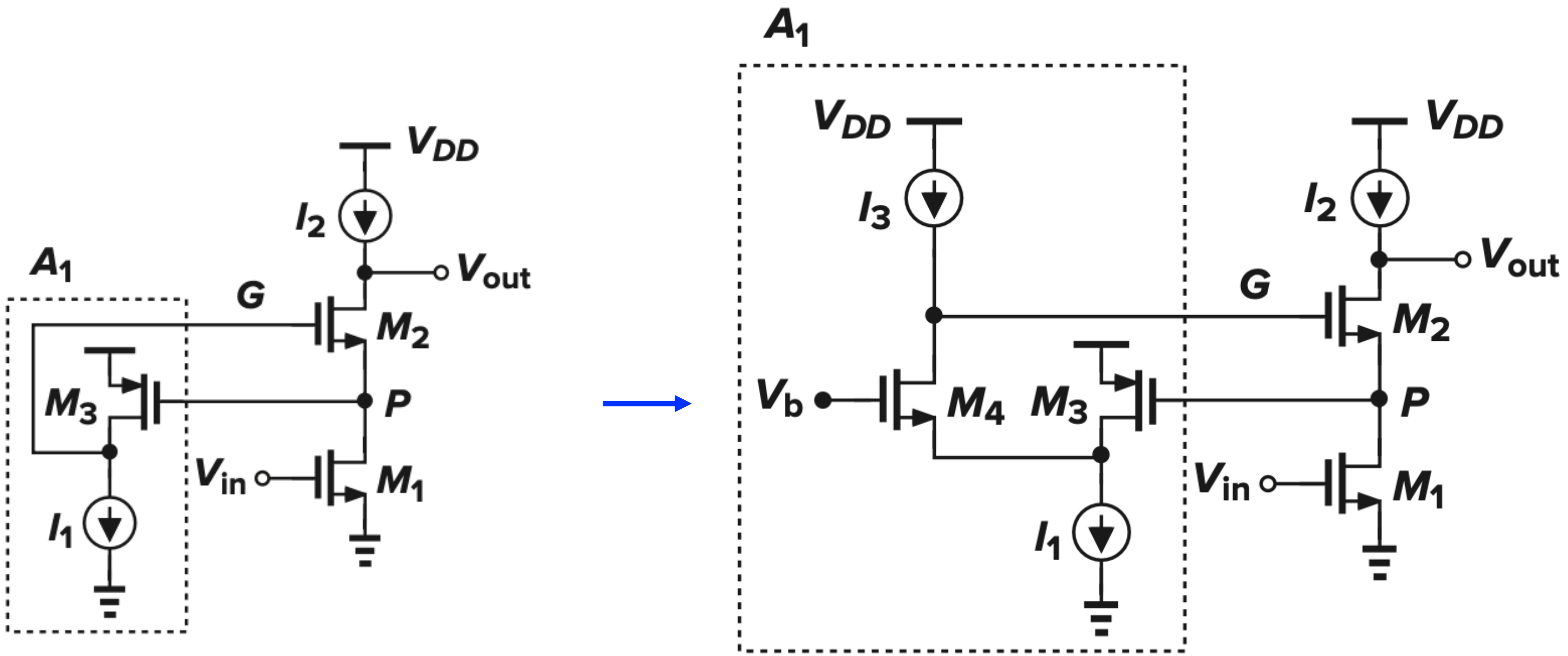
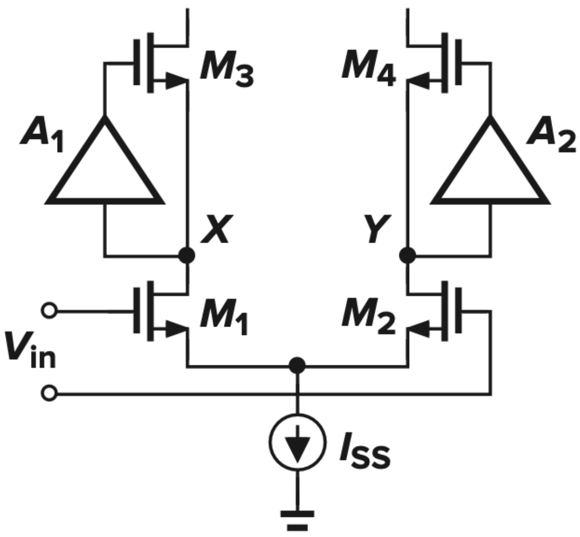
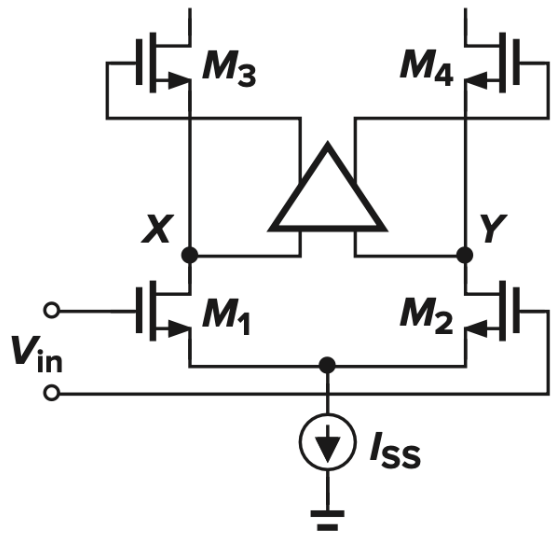
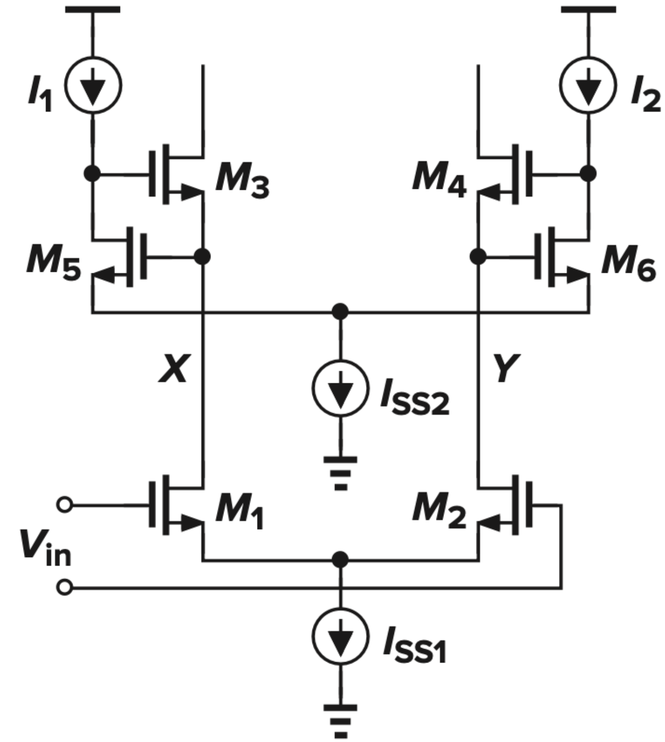


Gain Boosting: Differential







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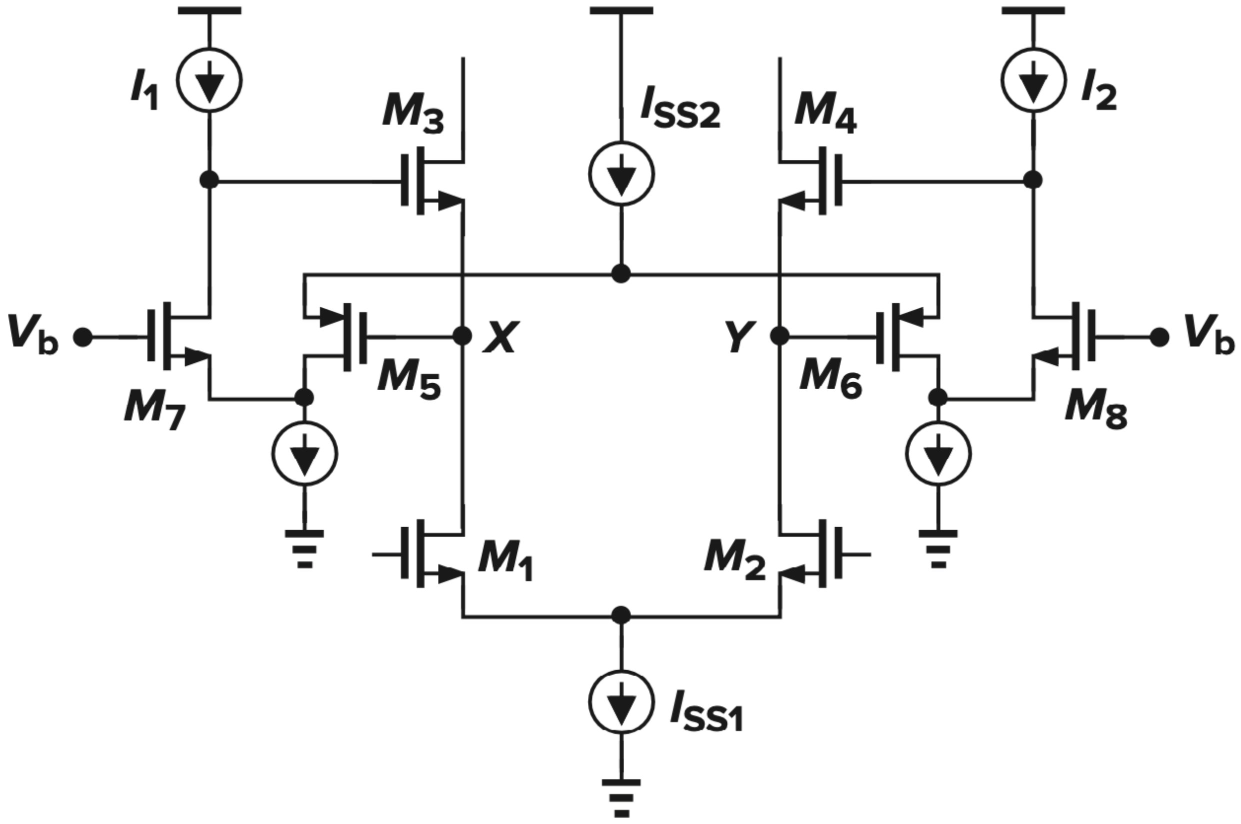
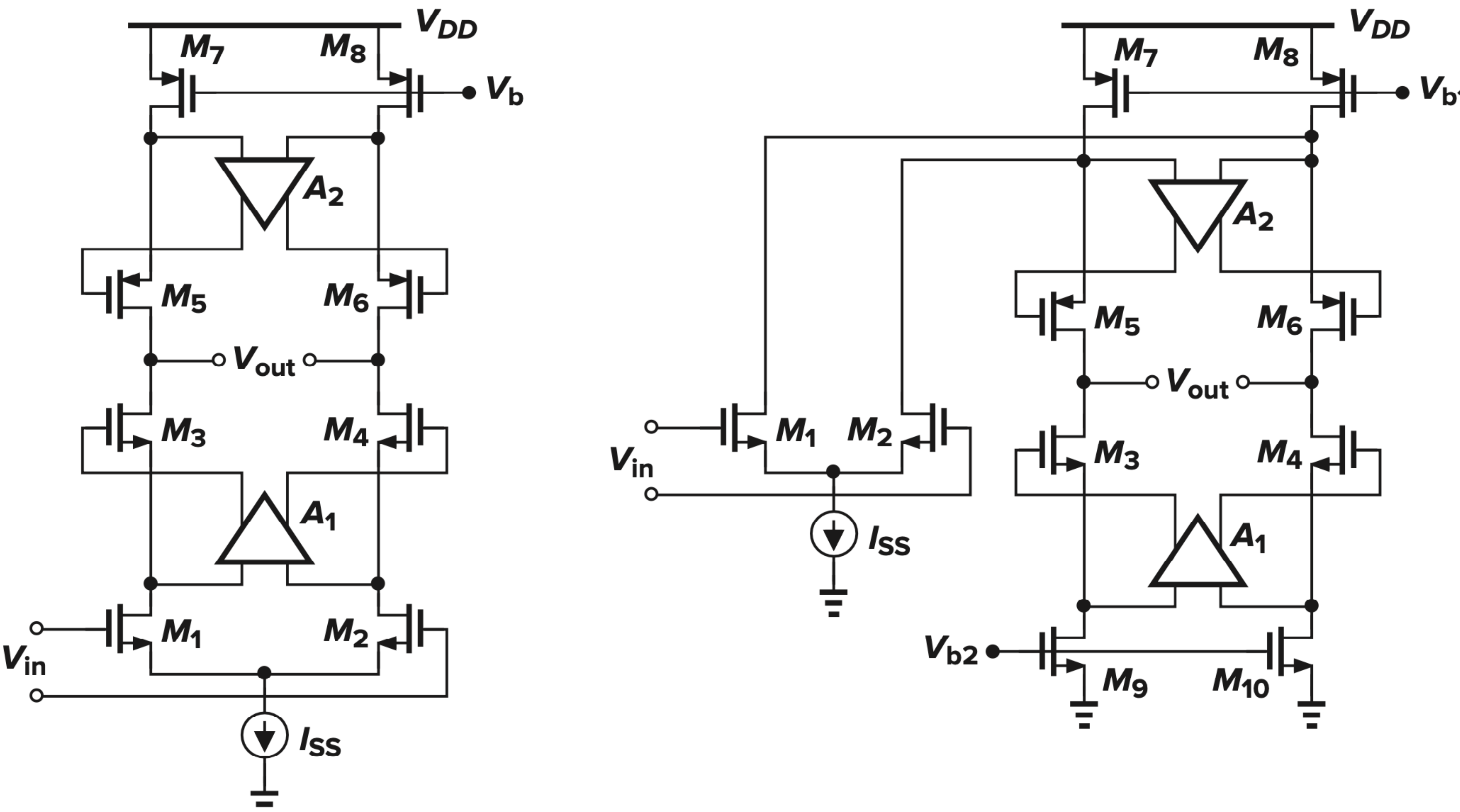
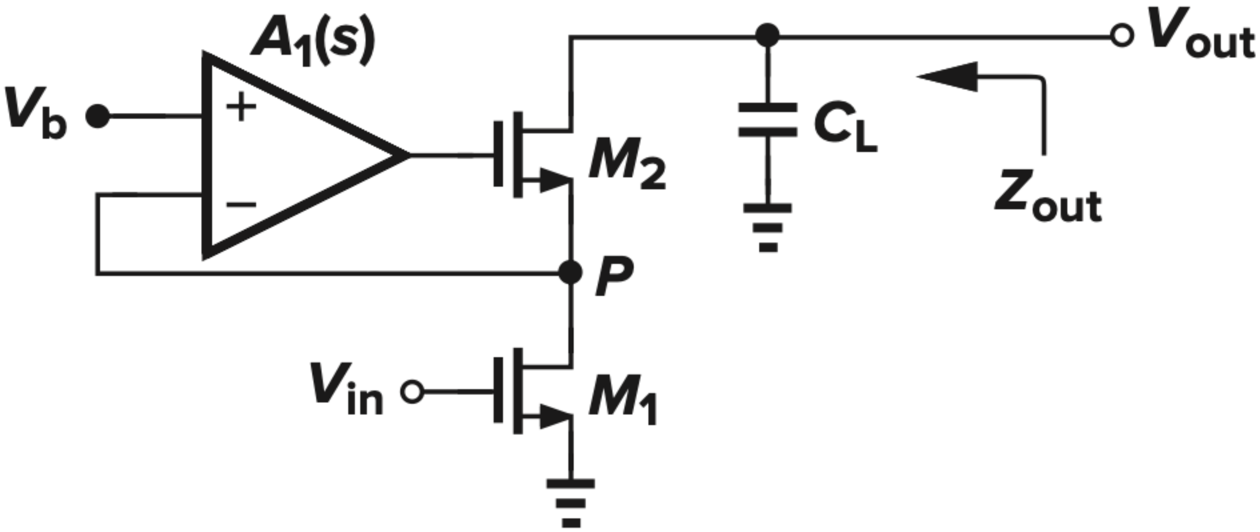


Gain Boosting in both Signal Path and Load Devices



Gain Boosting: Frequency Response



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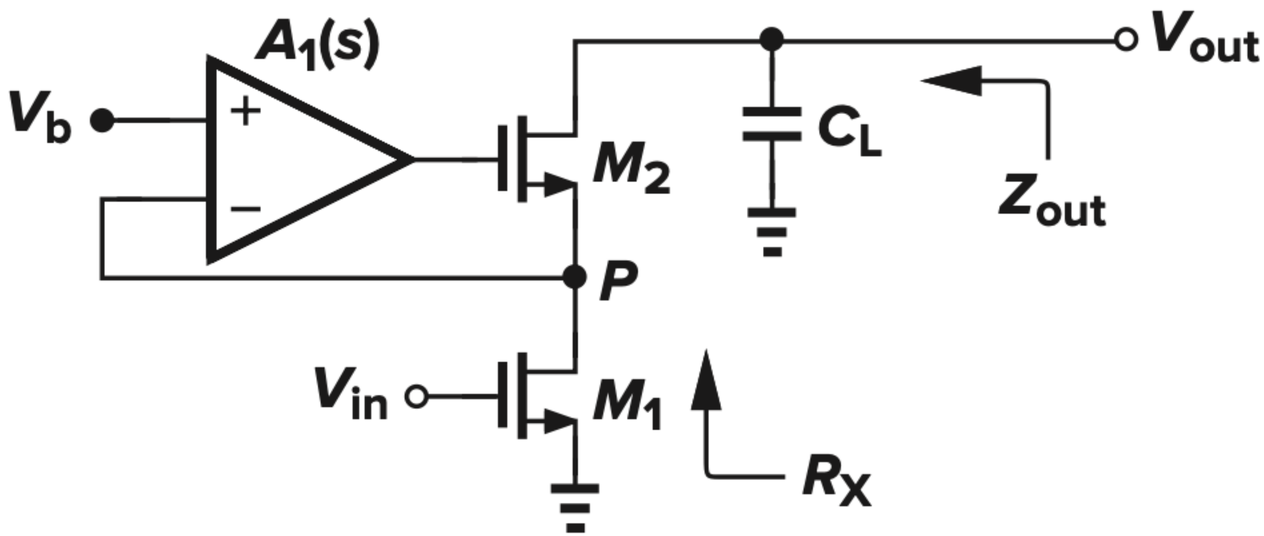


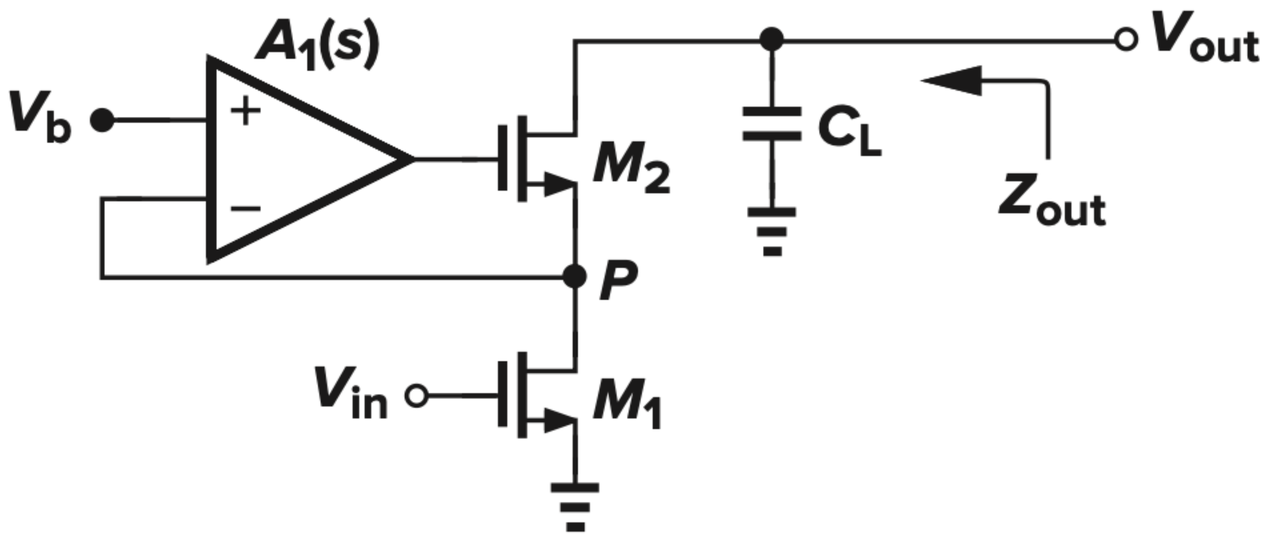
$$r_{O2}/[1 + (A_1 + 1)g_{m2}r_{O2}]$$

$$G_m(s) = g_{m1}\frac{r_{O1}}{r_{O1} + \dfrac{r_{O2}}{1 + (A_1 + 1)g_{m2}r_{O2}}}$$

$$= \frac{g_{m1}r_{O1}[1 + (A_1 + 1)g_{m2}r_{O2}]}{r_{O1} + (A_1 + 1)g_{m2}r_{O2}r_{O1} + r_{O2}}$$

$$Z_{out} = [r_{O1} + (A_1 + 1)g_{m2}r_{O2}r_{O1} + r_{O2}]||\frac{1}{C_L s}$$

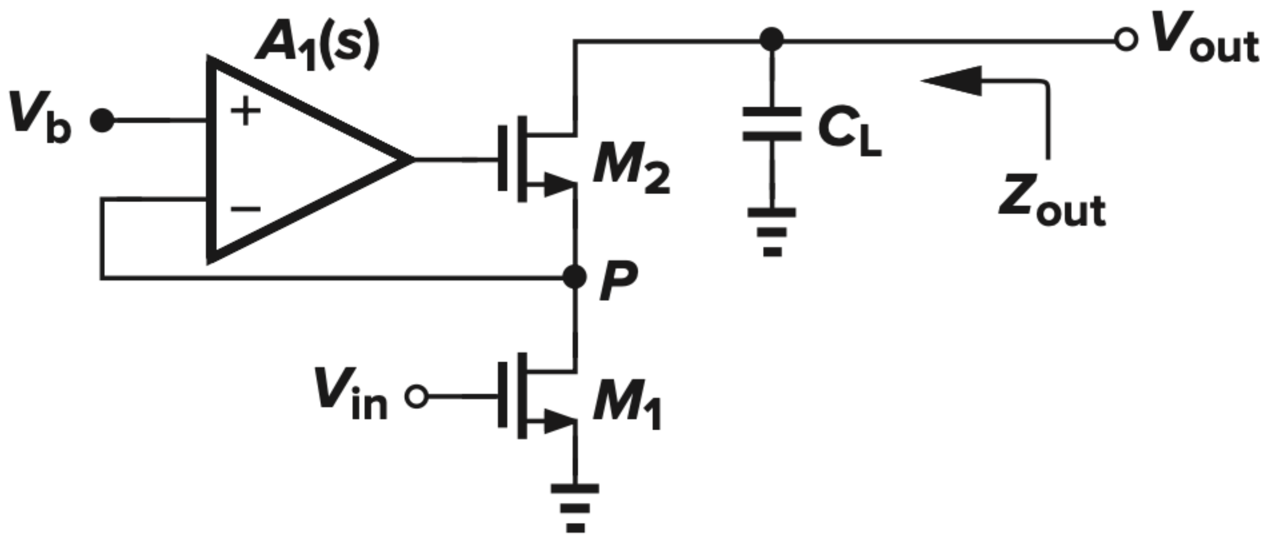
Gain Boosting: Frequency Response



$$\frac{V_{out}}{V_{in}}(s) = -G_m(s)Z_{out}(s)$$

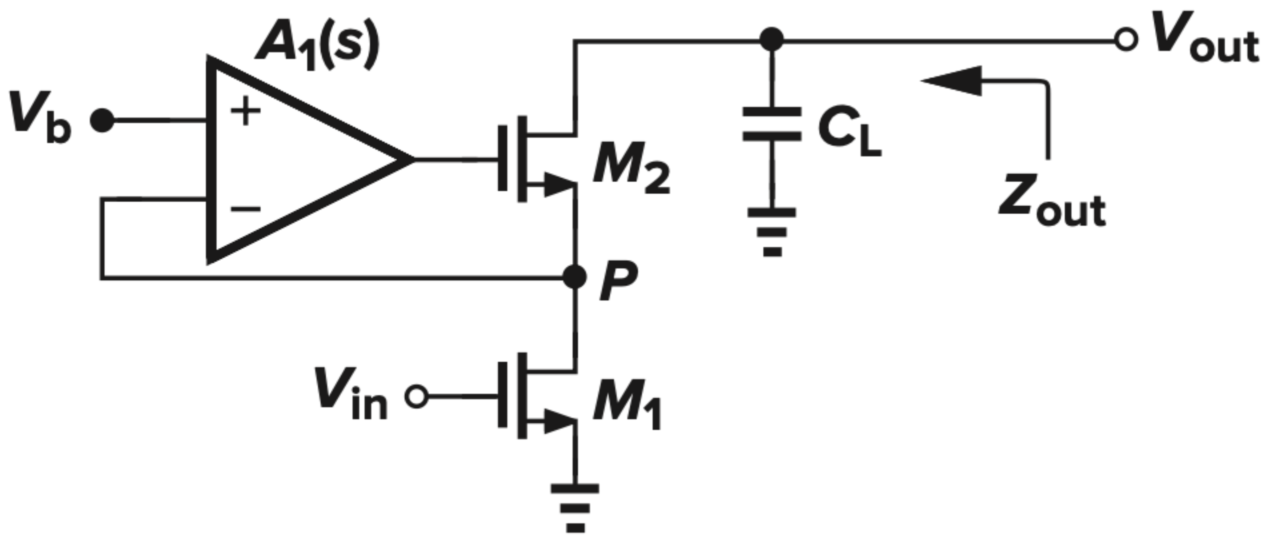
$$= \frac{-g_{m1}r_{O1}[1 + (A_1 + 1)g_{m2}r_{O2}]}{(r_{O1} + r_{O2})C_L s + (A_1 + 1)g_{m2}r_{O2}r_{O1}C_L s + 1}$$

Gain Boosting: Frequency Response



$$\frac{V_{out}}{V_{in}}(s) = \frac{-g_{m1}r_{O1}[(1+g_{m2}r_{O2})\frac{s}{\omega_0} + (A_0+1)g_{m2}r_{O2}+1]}{\frac{(r_{O1}+r_{O2})C_L}{\omega_0}[1+g_{m2}(r_{O2}||r_{O1})]s^2 + [(r_{O1}+r_{O2})C_L + (A_0+1)g_{m2}r_{O2}r_{O1}C_L + \frac{1}{\omega_0}]s+1}$$

Gain Boosting: Frequency Response



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$$|\omega_{p1}| = \frac{1}{[r_{O1}+(A_0+1)g_{m2}r_{O2}r_{O1}+r_{O2}]C_L + \frac{1}{\omega_0}} \approx \frac{1}{A_0 g_{m2}r_{O2}r_{O1}C_L}$$

$$|\omega_{p2}| = \frac{[r_{O1}+(A_0+1)g_{m2}r_{O2}r_{O1}+r_{O2}]C_L + \frac{1}{\omega_0}}{\frac{(r_{O1}+r_{O2})C_L}{\omega_0}[1+g_{m2}(r_{O1}||r_{O2})]} \approx (A_0+1)\omega_0 + \frac{1}{g_{m2}r_{O2}r_{O1}C_L}$$

Gain Boosting: Frequency Response