وَمَا أُوتِيتُمْ مِنَ الْعِلْمِ إِلَّا قَلِيلًا

Analog IC Design

Lecture 07
Cascode Amplifiers

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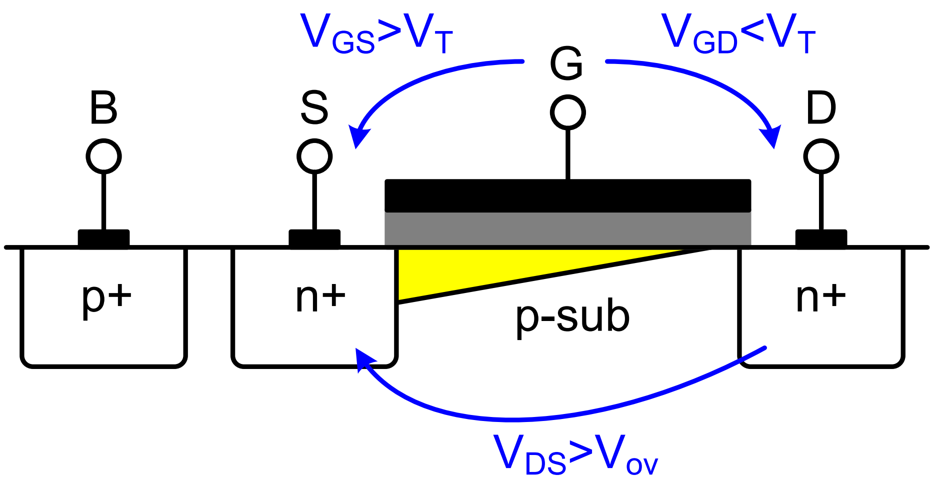
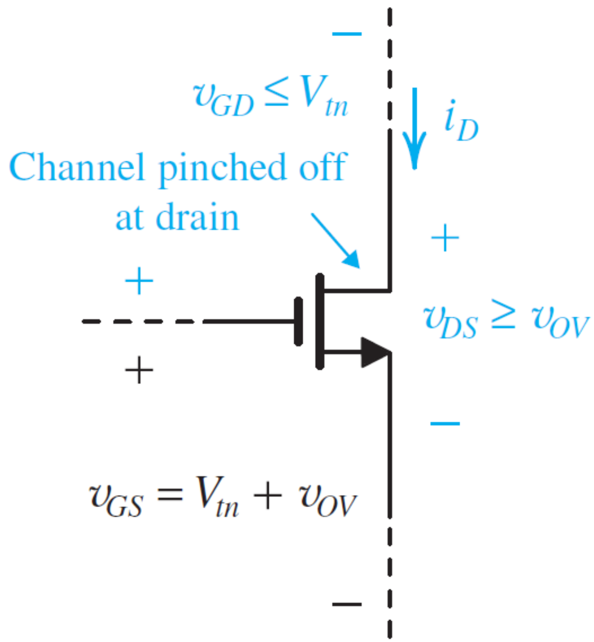
MOSFET in Saturation

- The channel is pinched off if the difference between the gate and drain voltages is not sufficient to create an inversion layer

$$I_D = \frac{\mu_n C_{ox}}{2} \frac{W}{L} \cdot V_{ov}^2 (1 + \lambda V_{DS})$$





Regions of Operation Summary

OFF (Subthreshold)

$V_{GS} < V_T$

ON

$V_{GS} > V_T$

Triode

$V_{DS} < V_{ov}$

Or

$V_{GD} > V_T$

$$I_D = \mu C_{ox}\frac{W}{L}\left(V_{ov}V_{DS} - \frac{V_{DS}^2}{2}\right)$$

Pinch-Off (Saturation)

$V_{DS} \geq V_{ov}$

Or

$V_{GD} \leq V_T$

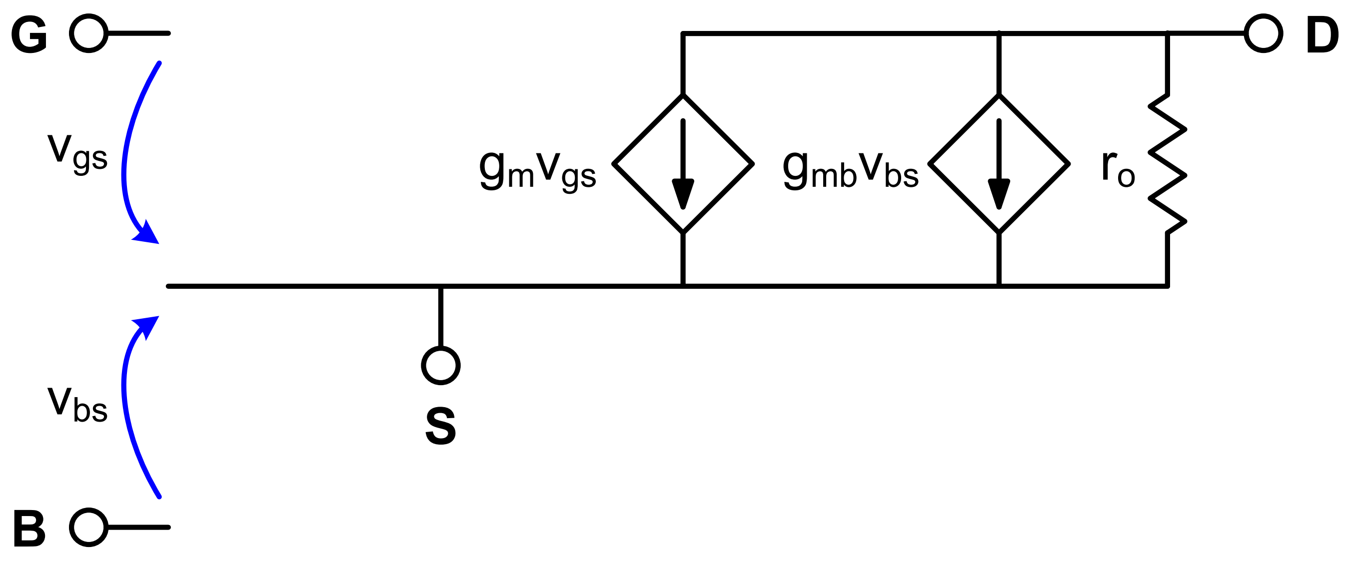
$$I_D = \frac{\mu C_{ox}}{2}\frac{W}{L}V_{ov}^2(1 + \lambda V_{DS})$$

Low-Frequency Small-Signal Model

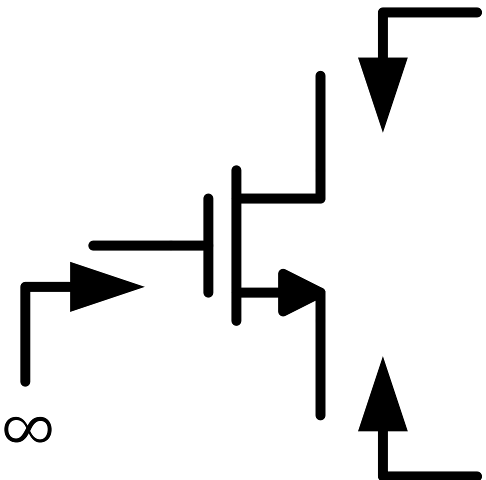
$$g_m = \frac{\partial I_D}{\partial V_{GS}} = \mu C_{ox} \frac{W}{L} V_{ov} = \sqrt{\mu C_{ox} \frac{W}{L} \cdot 2I_D} = \frac{2I_D}{V_{ov}}$$

$$g_{mb} = \eta g_m, \qquad \eta \approx 0.1 - 0.25$$

$$r_o = \frac{1}{\frac{\partial I_D}{\partial V_{DS}}} = \frac{1}{\lambda I_D}, \qquad \lambda \propto \frac{1}{L}$$



Rin/out Shortcuts Summary



$$r_o[1 + (g_m + g_{mb})R_S]$$

H.I.N.

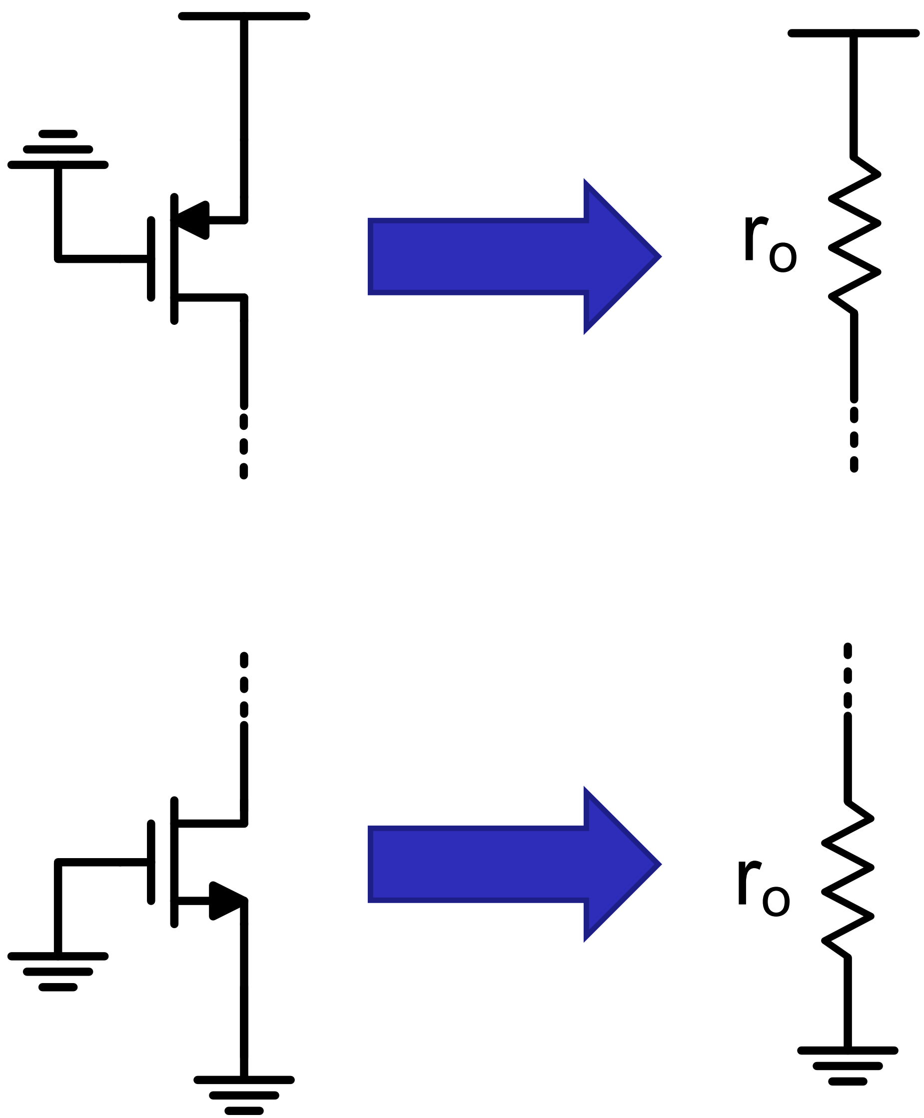
∞

At low frequencies **ONLY**

$$\frac{1}{g_m + g_{mb}}\left(1 + \frac{R_D}{r_o}\right)$$

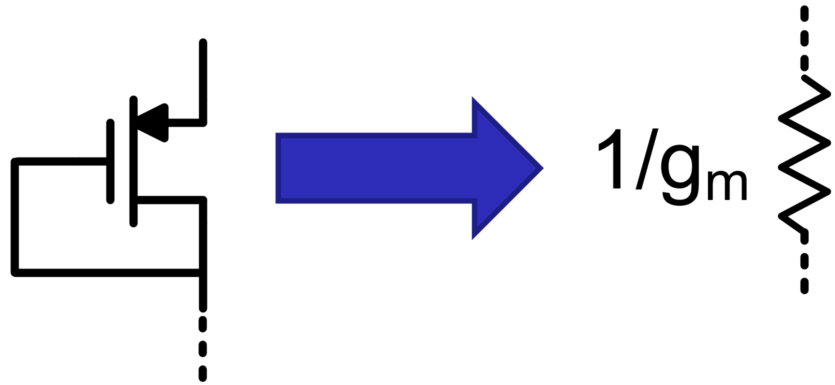
L.I.N.

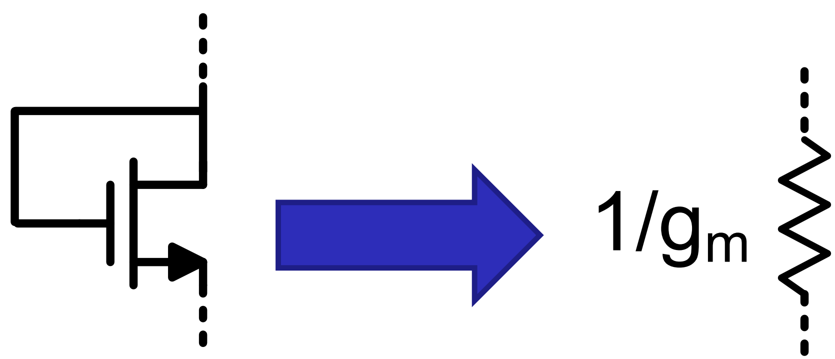
Active Load (Source OFF)



Diode Connected (Source Absorption)

- Always in saturation
- Bulk effect: $g_m \rightarrow g_m + g_{mb}$





Why GmRout?

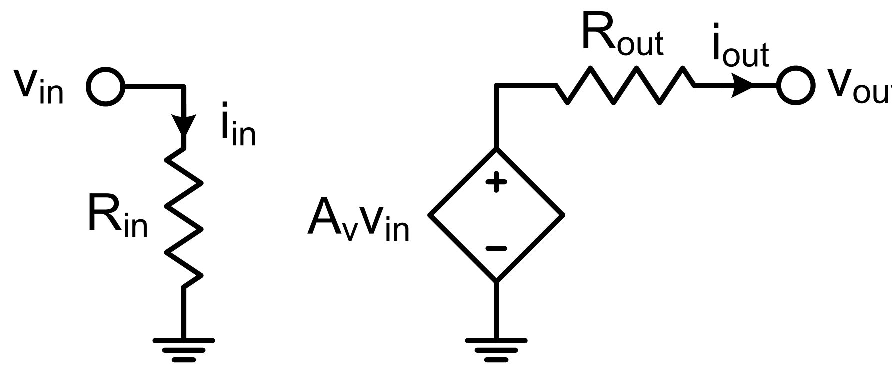
$$R_{out} = \frac{v_x}{i_x} @ v_{in} = 0$$

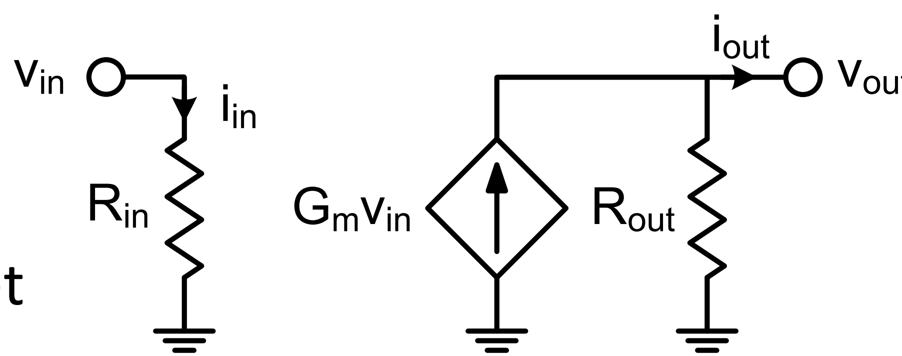
$$G_m = \frac{i_{out,sc}}{v_{in}}$$

$$A_v = G_m R_{out}$$

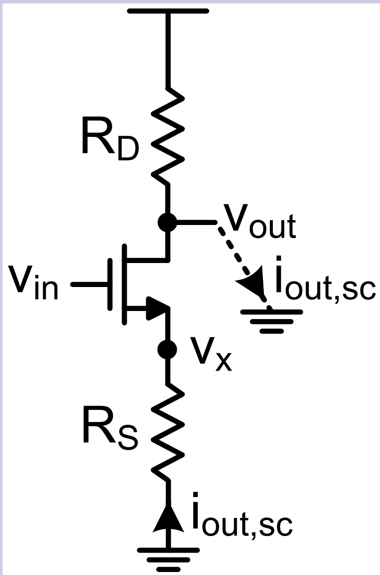
$$A_i = G_m R_{in}$$

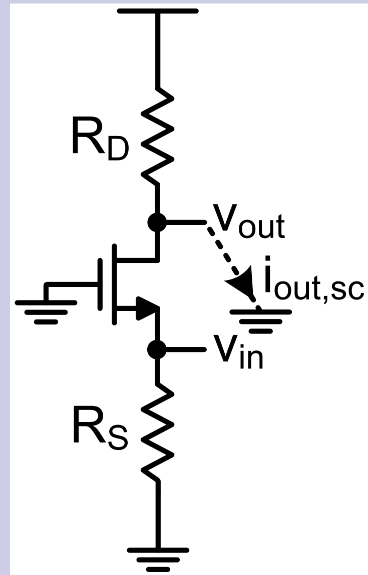
- Divide and conquer
  - Rout simplified: vin=0
  - Gm simplified: vout=0
  - We already need Rin/out
  - We can quickly and easily get Rin/out from the shortcuts

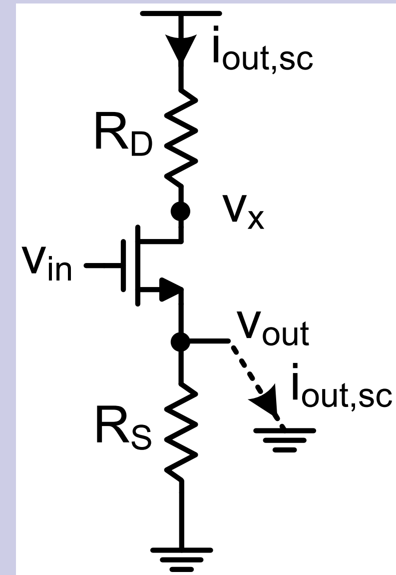




Summary of Basic Topologies



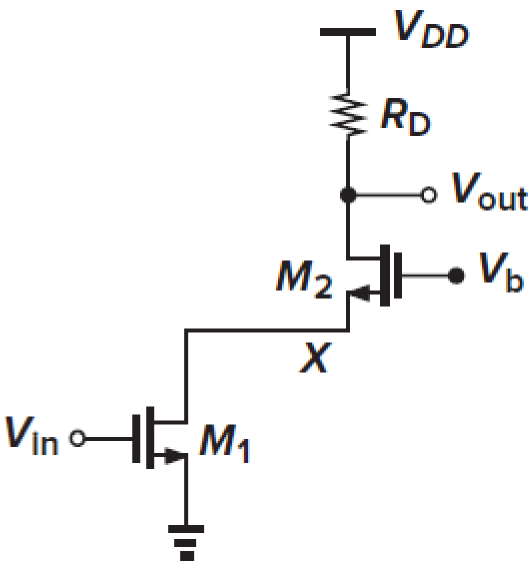




	CS	CG	CD (SF)
	Voltage & current amplifier	Current buffer	Voltage buffer
Rin	∞	$R_S // \frac{1}{g_m + g_{mb}}\left(1 + \frac{R_D}{r_o}\right)$	∞
Rout	$R_D // r_o[1 + (g_m + g_{mb})R_S]$	$R_D // r_o$	$R_S // \frac{1}{g_m + g_{mb}}\left(1 + \frac{R_D}{r_o}\right)$
Gm	$\frac{-g_m}{1 + (g_m + g_{mb})R_S}$	$g_m + g_{mb}$	$\frac{g_m}{1 + R_D/r_o}$

Cascode

- CS + CG



Cascode as a Single Stage

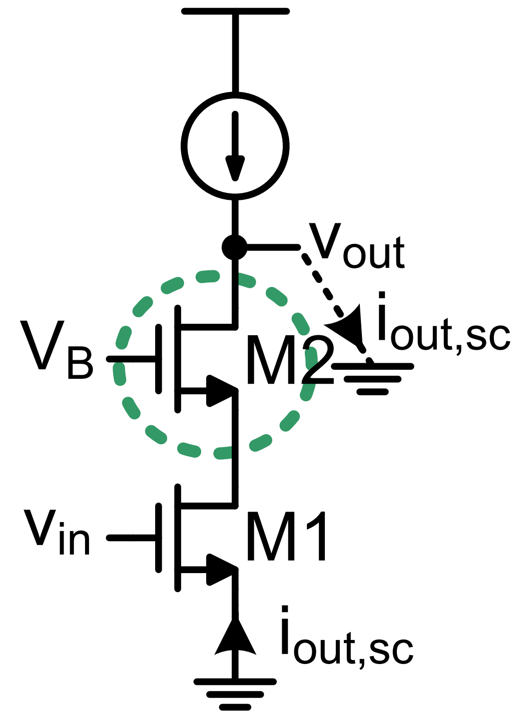
- Transconductance is always related to the input device (VCCS)

$$G_m \approx -g_{m1}$$

Same Gm of CS

$$R_{out} \approx r_{o2}[1 + (g_{m2} + g_{mb2})r_{o1}]$$
$$\approx r_{o2}(g_{m2} + g_{mb2})r_{o1}$$

Rout significantly boosted



- Assume all g_m and r_o are equal and neglect body effect

$$A_v = -(g_m r_o)^2$$

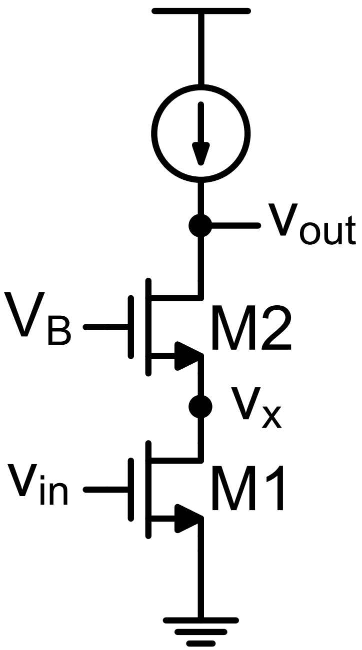
Cascode as CS + CG

$$CS:\ \frac{v_x}{v_{in}} = -g_{m1}(r_{o1}//\infty)$$

$$CG:\ \frac{v_o}{v_x} = (g_{m2} + g_{mb2})r_{o2}$$

$$A_v = \frac{v_x}{v_{in}} \cdot \frac{v_{out}}{v_x}$$

$$\approx -g_{m1}r_{o1}(g_{m2} + g_{mb2})r_{o2}$$

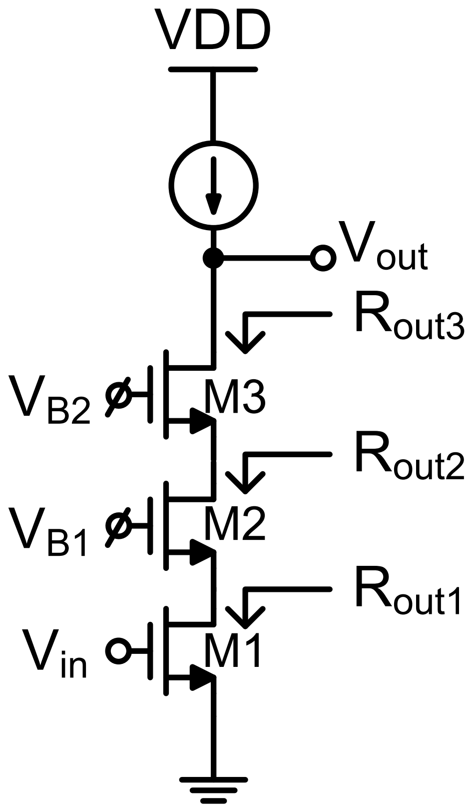


- Assume all g_m and r_o are equal and neglect body effect

$$A_v = -(g_m r_o)^2$$

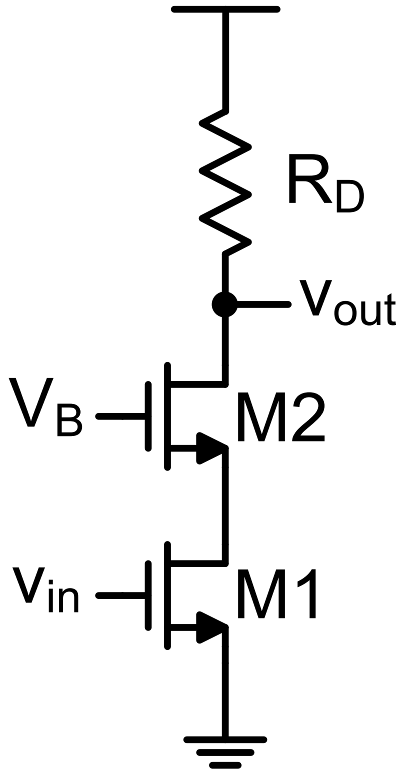
Q: Double Cascode

- Find the voltage gain. Assume all g_m and r_o are equal and neglect body effect.



What if R_D is small?

- ❑ Is this cascode useful?
  - – No for gain, but yes for BW



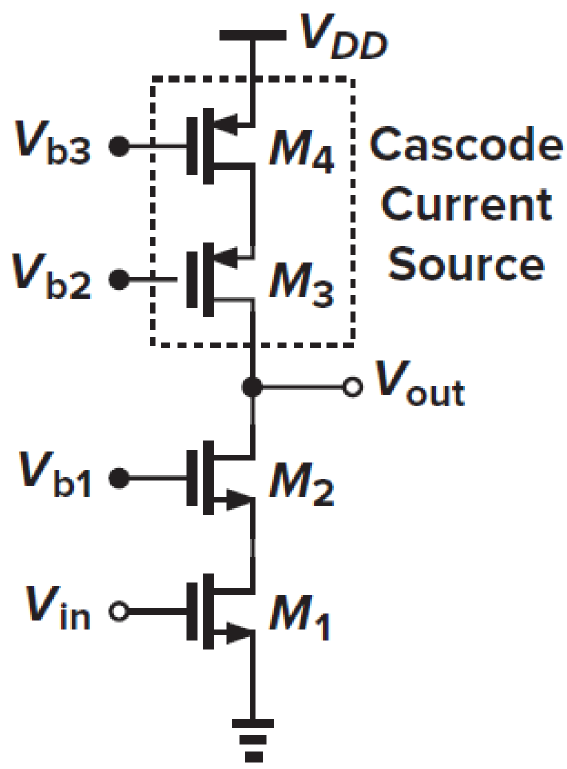
Cascode Load

- If you want to keep the large Rout, you must use cascode load

- Assume all g_m and r_o are equal and neglect body effect

$$A_v = -\frac{(g_m r_o)^2}{2}$$

- Output swing $\approx V_{DD} - 4V_{ov}$



Cascode Large Signal Analysis

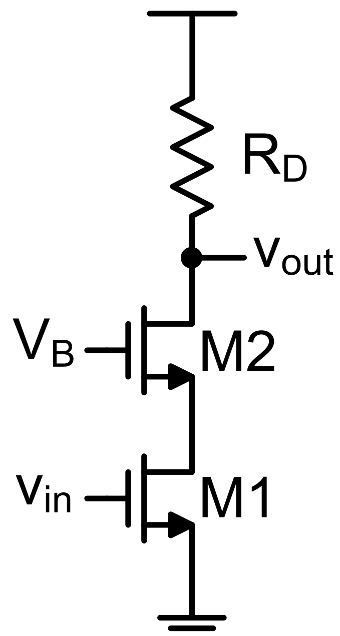
- Cascode bias voltage

$$V_B \geq V_{TH2} + V_{ov2} + V_{ov1}$$

- Input and output ranges are coupled oppositely (max vs min)

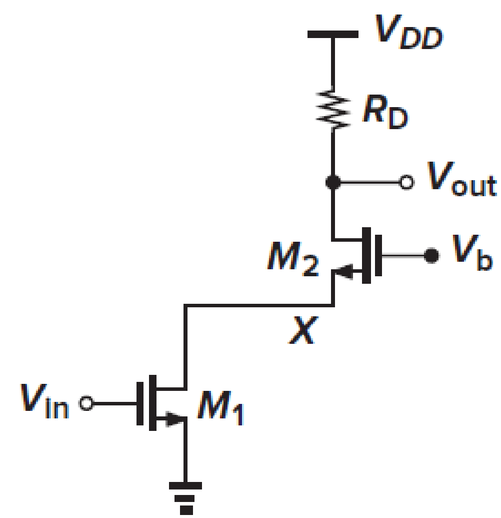
$$V_{in,max} = V_{TH1} + V_{DS1}$$

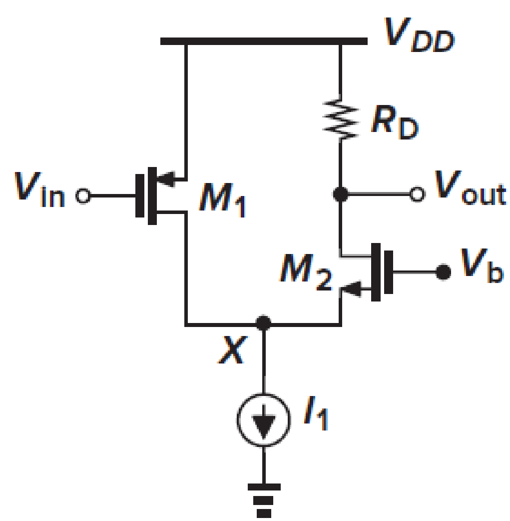
$$V_{out,min} = V_{ov2} + V_{DS1} = V_{ov2} + V_{in,max} - V_{TH1}$$

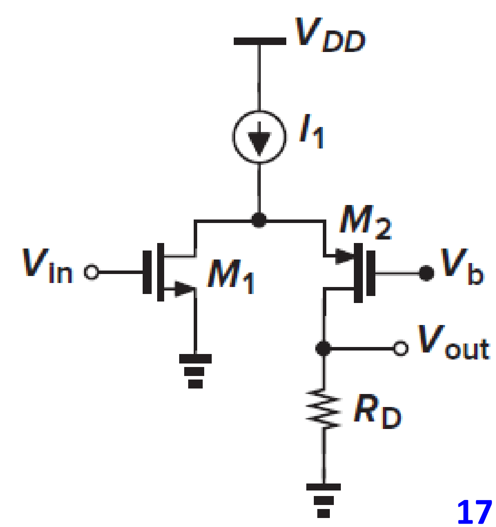


Telescopic vs Folded Cascode

- Telescopic: CS + CG (both NMOS or both PMOS)
  - Both CS and CG use same bias current
- Folded: CS + CG (NMOS-PMOS combination)
  - The small signal current is folded up or down
  - Extra bias current is needed
  - Rout is lower (due to IDC)
  - Why is it useful?







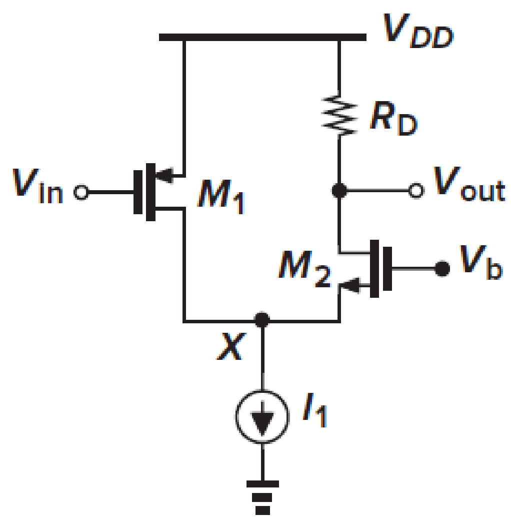
Folded Cascode

- Input and output ranges are NOT coupled oppositely

$$V_{in,min} = -|V_{TH1}| + V_{ISS}$$

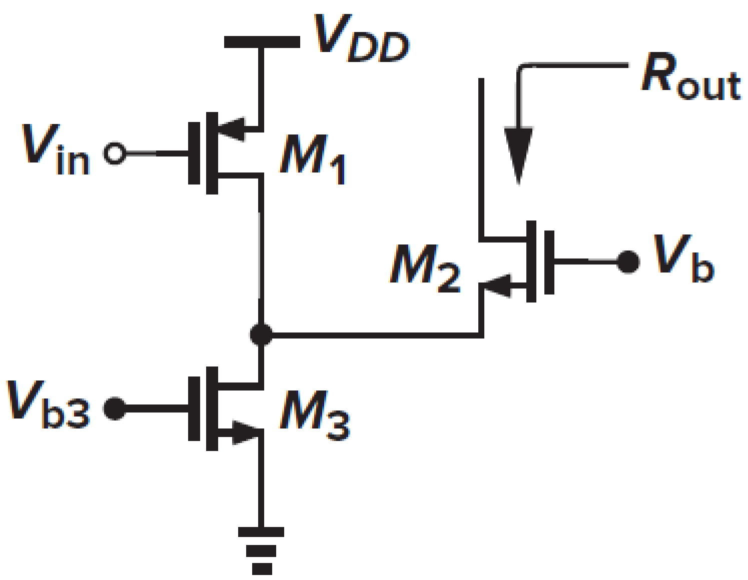
$$V_{out,min} = V_{ov2} + V_{ISS} = V_{ov2} + V_{in,min} + |V_{TH1}|$$

- More on this point when we study OTAs



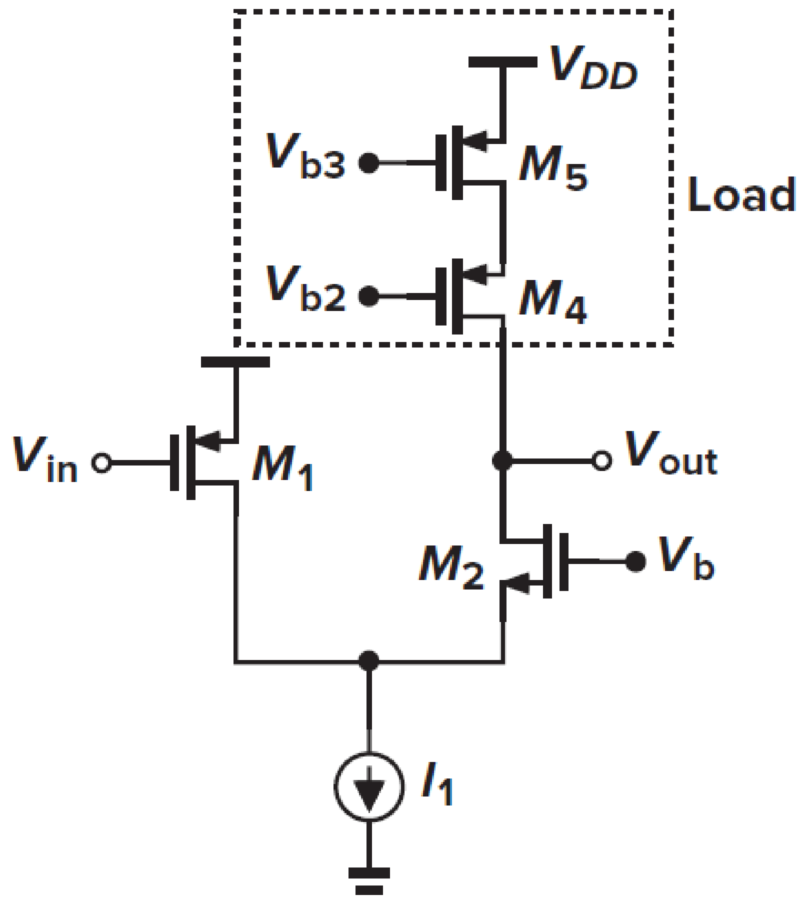
Q: Rout of Folded Cascode

- Assume all transistors have same gm and ro, and neglect body effect. Calculate Rout.



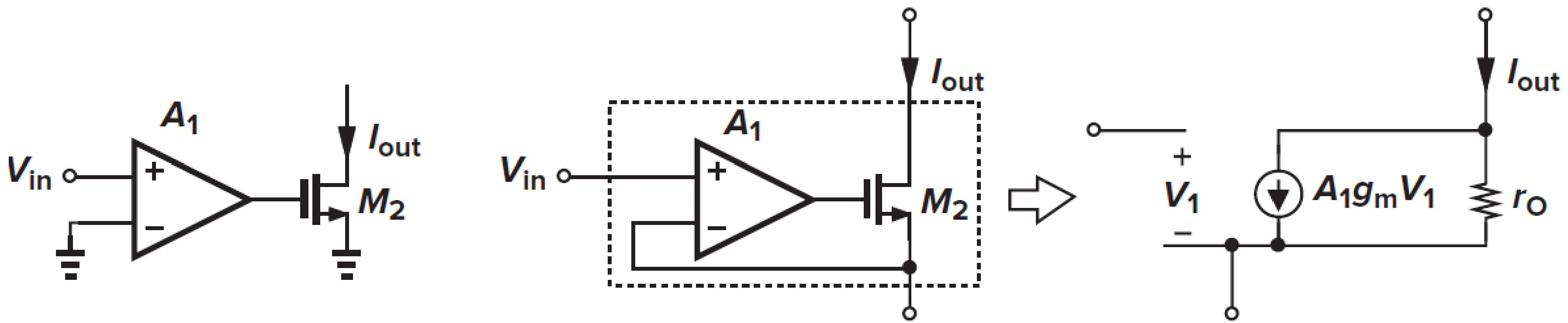
Folded Cascode With Cascode Load

- Calculate Av = GmRout. Assume all transistors have same gm and ro, and neglect body effect. Assume I1 is implemented using a single NMOS.



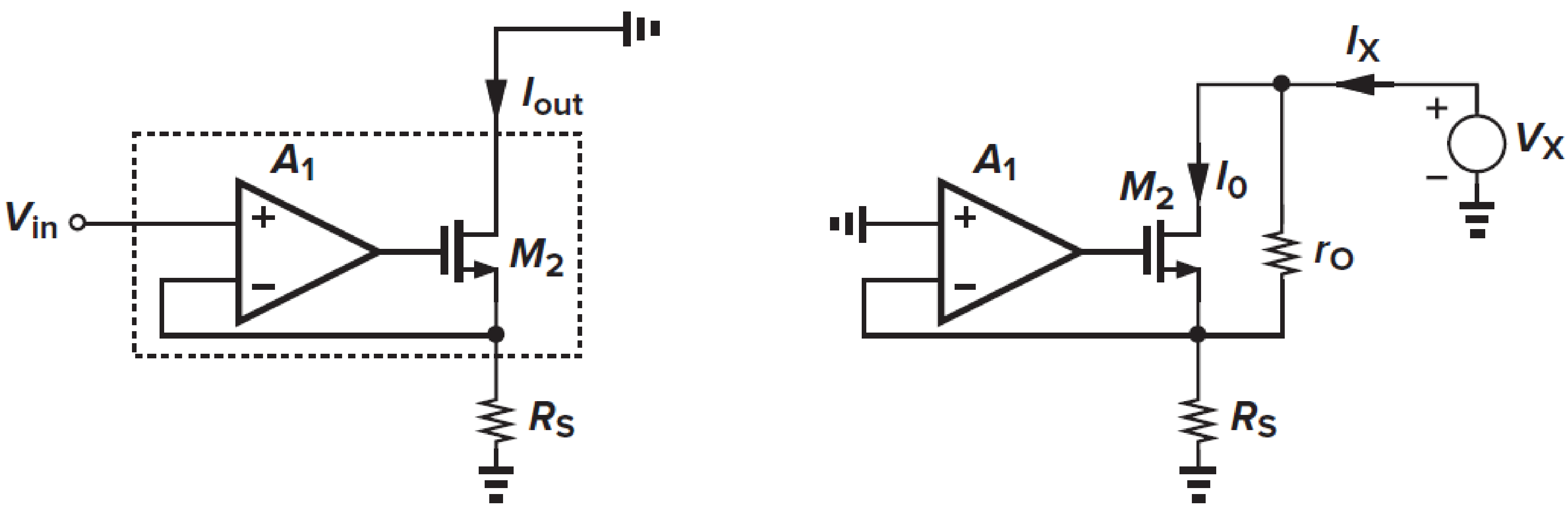
Gain Boosting: Super Transistor

- Assume $A_1 \gg 1$
- $g_{m,super} = A_1 g_m$
- $r_{o,super} = r_o$



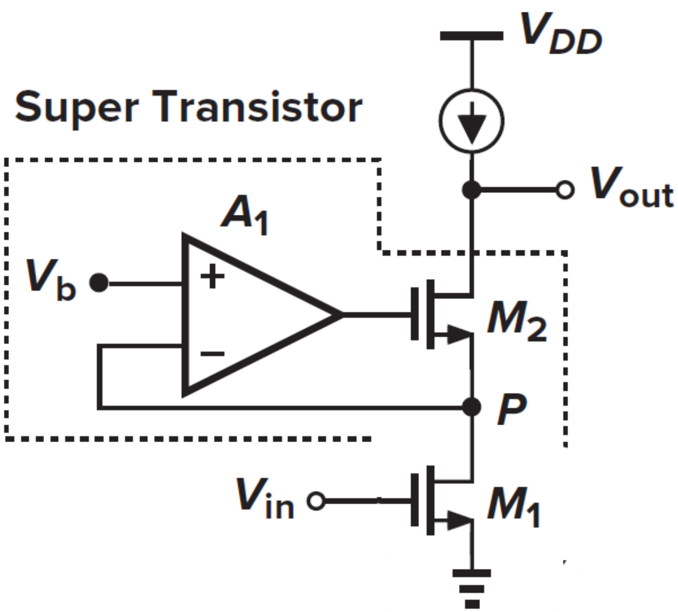
Gain Boosting: Super Transistor

- $G_m \approx \frac{g_{m,super}}{1+g_{m,super}R_S} \approx \frac{A_1 g_m}{1+A_1 g_m R_S} \approx \frac{1}{R_S}$
- $R_{out} = r_o\left(1 + g_{m,super}R_S\right) = r_o(1 + A_1 g_m R_S)$



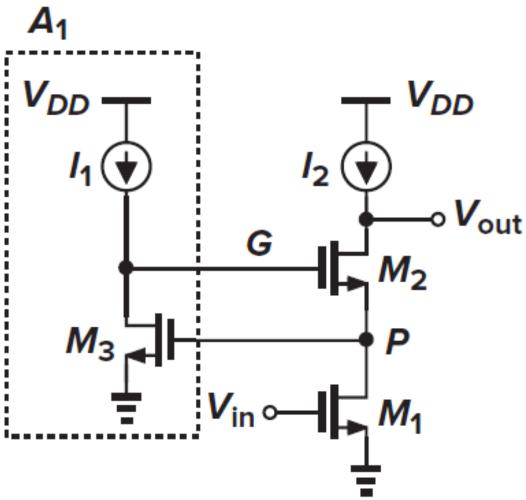
Super Cascode

- A.k.a. regulated cascode or gain boosted cascode
- $G_m \approx g_{m1}$
- $R_{out} = r_{o2}\left(1 + g_{m2,super} r_{o1}\right) = r_{o2}(1 + A_1 g_{m2} r_{o1})$
- $A_v \approx A_1(g_{m1} r_{o1})(g_{m2} r_{o2})$
- Gain is boosted while preserving headroom
- But more power and noise



Super Cascode Implementation

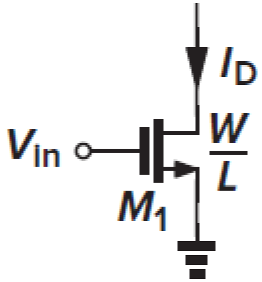
- NMOS CS
  - Headroom limitation
  - $V_P = V_{TH} + V_{ov3}$ instead of V_{ov1}

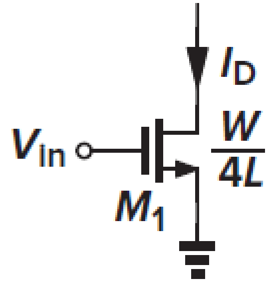


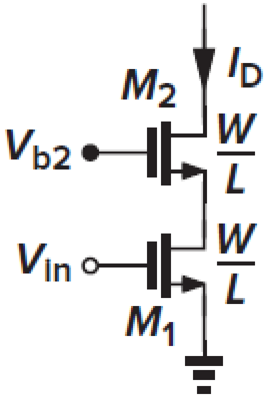
Thank you!

Cascode vs Longer Device

- Assuming same bias current and headroom requirement
- For single device
  - Double V_{ov} means 4 times L can be used ($I_D \propto (W/L)V_{ov}^2$)
  - $r_o = 1/\lambda I_D$ multiplied by 4, but g_m divided by 2 ($g_m = 2I_D/V_{ov}$)
  - Overall gain increases by a factor of 2
- For cascode
  - Rout multiplied by $g_m r_o$, and gm unchanged
  - Overall gain increases by a factor of $g_m r_o$
  - But we need extra bias voltage







Poor Man's Cascode

- Can we eliminate the extra bias voltage?

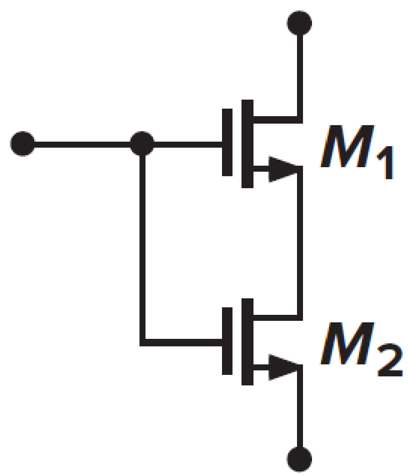
$$V_{DS2} = V_{GS2} - V_{GS1} = V_{ov2} - V_{ov1} < V_{ov2}$$

M2 ALWAYS in triode → Not a cascode, just twice the length

- But what if $V_{T2} > V_{T1}$ (devices with different threshold voltages)?

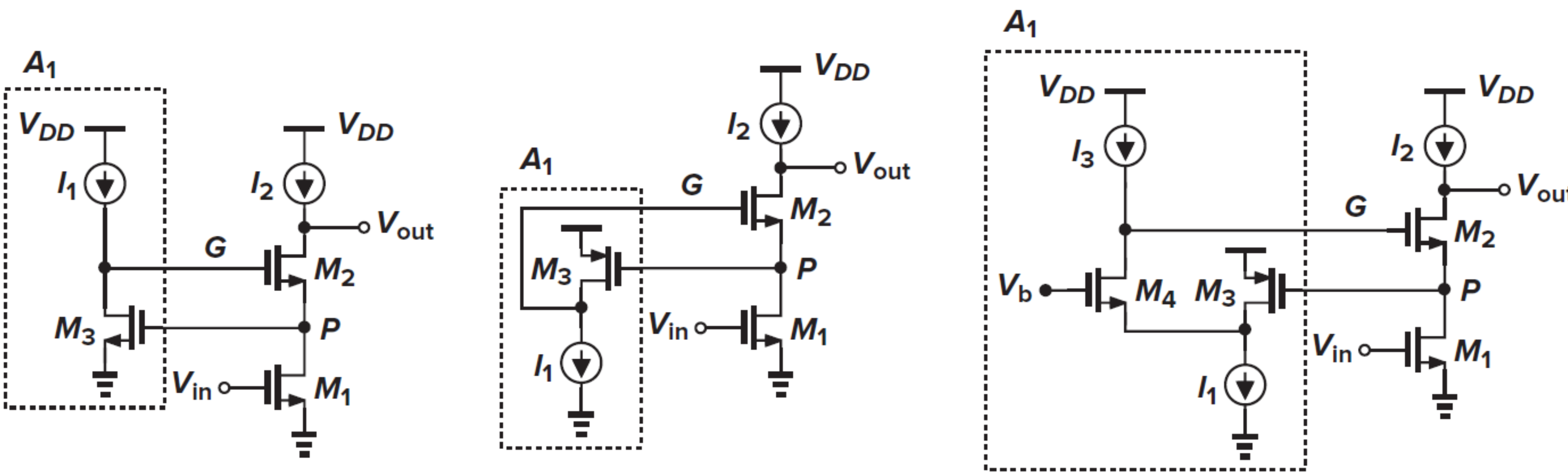
$$V_{DS2} = V_{GS2} - V_{GS1} = (V_{ov2} - V_{ov1}) + (V_{T2} - V_{T1}) > V_{ov2}$$

M2 in saturation if: $(\boldsymbol{V_{T2} - V_{T1}}) > \boldsymbol{V_{ov1}}$



Gain Boosting Implementation

- NMOS CS (a): headroom limitation
  - $V_P = V_{TH} + V_{ov3}$ instead of V_{ov1}
- PMOS CS (b): M3 will be in triode
  - $V_G - V_P > V_{TH}$
- Folded cascode (c): M4 provide level shift



(a) (b) (c)