Analog IC Design

Lecture 07
Cascode Amplifiers

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Outline

- Recapping previous key results
- Cascode amplifier
- Telescopic vs folded cascode
- Super cascode

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MOSFET in Saturation

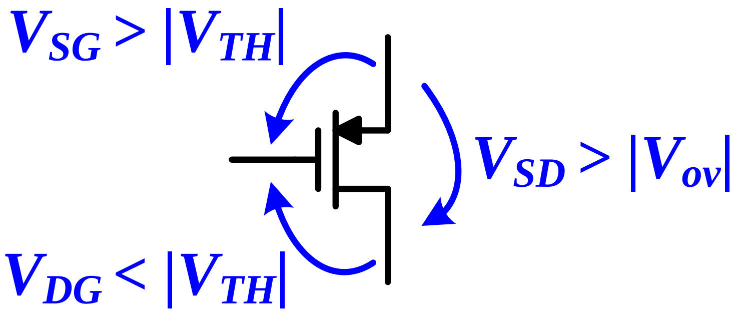
- The channel is pinched off if the difference between the gate and drain voltages is not sufficient to create an inversion layer

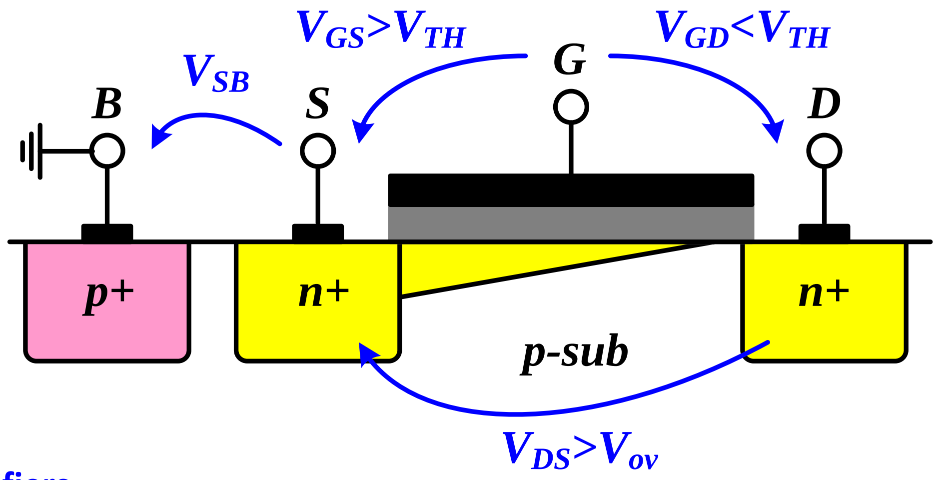
$$V_{GD} \le V_{TH} \quad OR \quad V_{DS} \ge V_{ov}$$

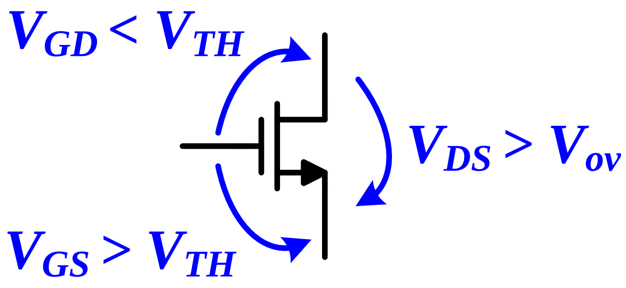
- Square-law (long channel MOS)

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

$$V_{SB} \uparrow \;\Rightarrow\; V_{TH} \uparrow$$







Regions of Operation Summary

OFF (Subthreshold)

$V_{GS} < V_{TH}$

ON

$V_{GS} > V_{TH}$

Triode

$V_{DS} < V_{ov}$

Or

$V_{GD} > V_{TH}$

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

Pinch-Off (Saturation)

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

Or

$V_{GD} \leq V_{TH}$

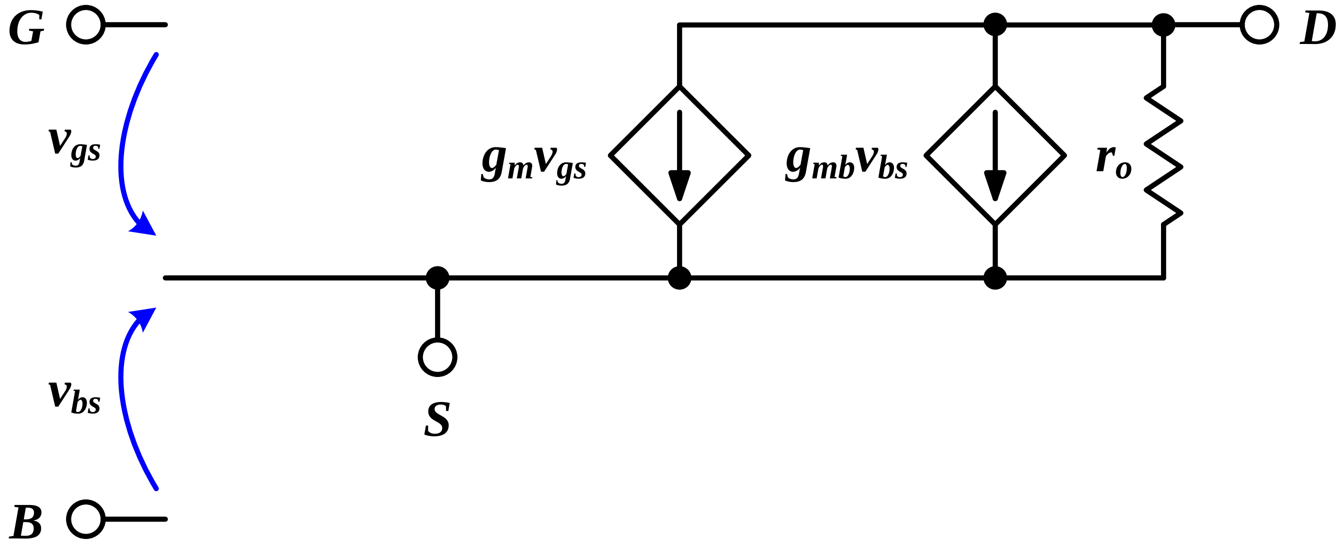
$$I_D = \frac{\mu C_{ox}}{2}\frac{W}{L}V_{ov}^2(1 + \lambda V_{DS})$$

Low-Frequency Small-Signal Model

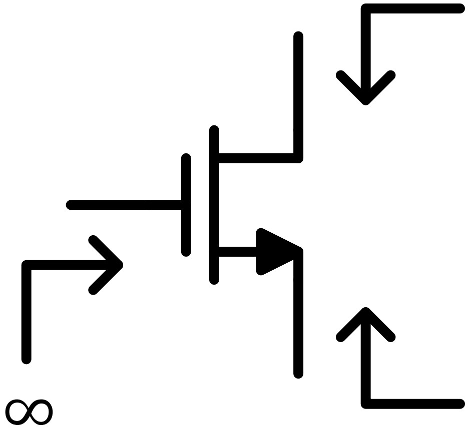
$$g_m = \frac{\partial I_D}{\partial V_{GS}} = \mu C_{ox}\frac{W}{L}V_{ov} = \sqrt{\mu C_{ox}\frac{W}{L}\cdot 2I_D} = \frac{2I_D}{V_{ov}}$$

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

$$r_o = \frac{1}{\partial I_D/\partial V_{DS}} = \frac{V_A}{I_D} = \frac{1}{\lambda I_D} \qquad V_A \propto L \leftrightarrow \lambda \propto \frac{1}{L} \qquad V_{DS}\uparrow V_A\uparrow$$



Rin/out Shortcuts Summary



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

H.I.N.

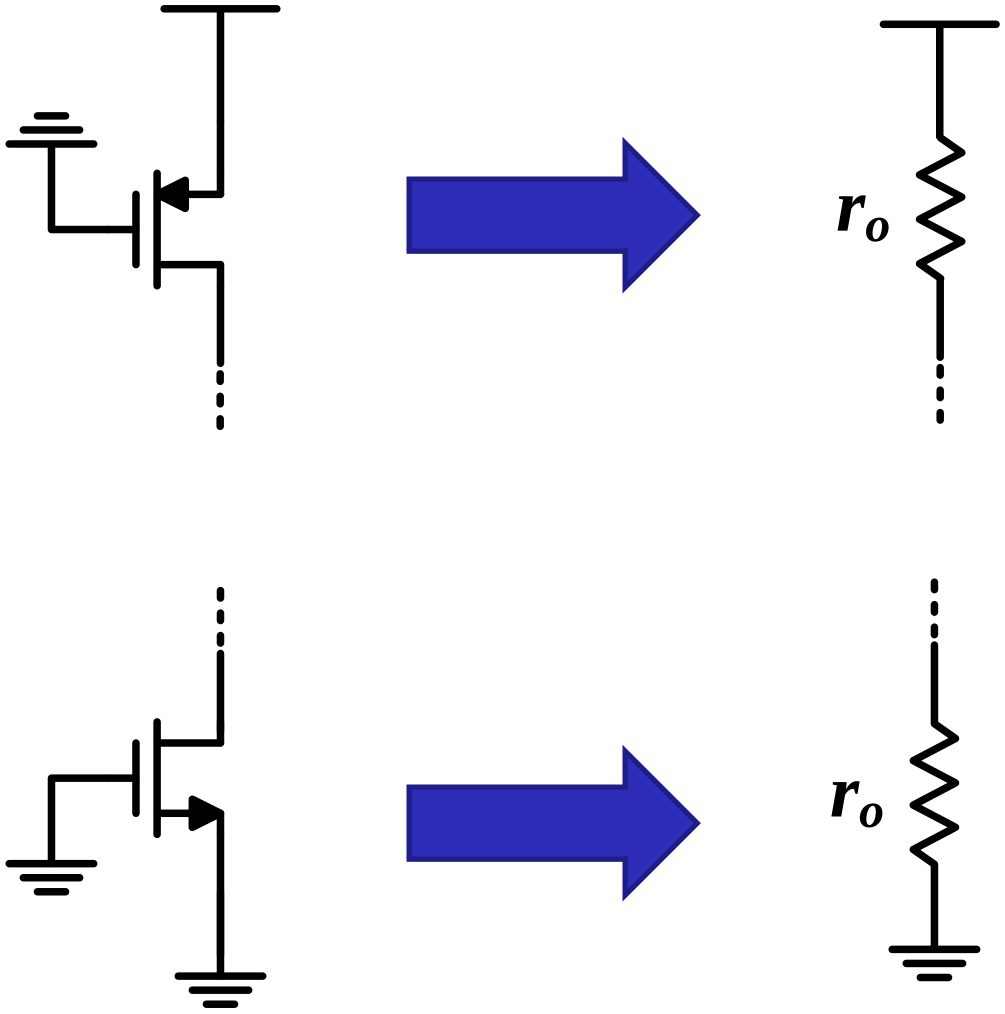
∞

At low frequencies **ONLY**

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

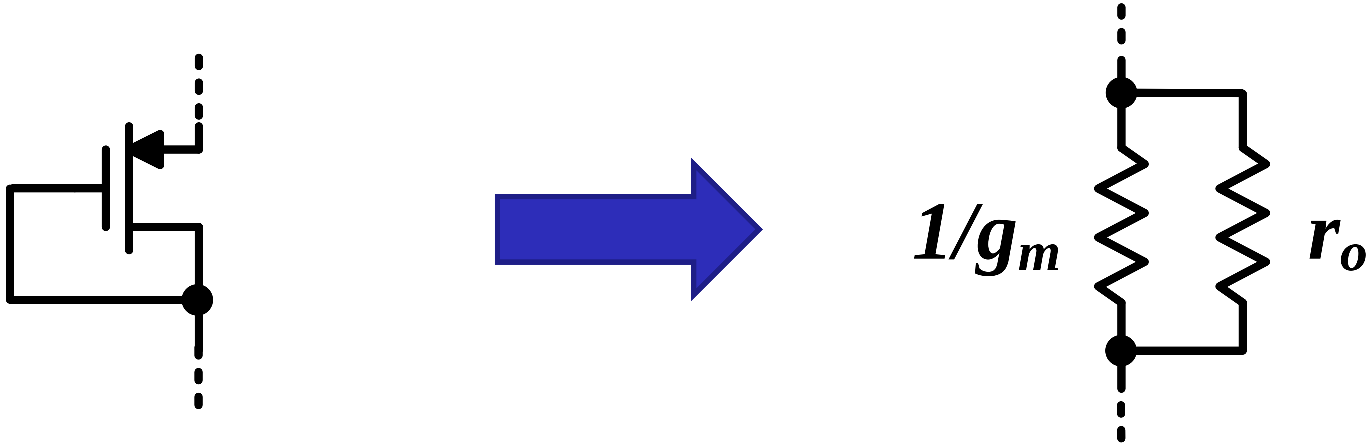
L.I.N.

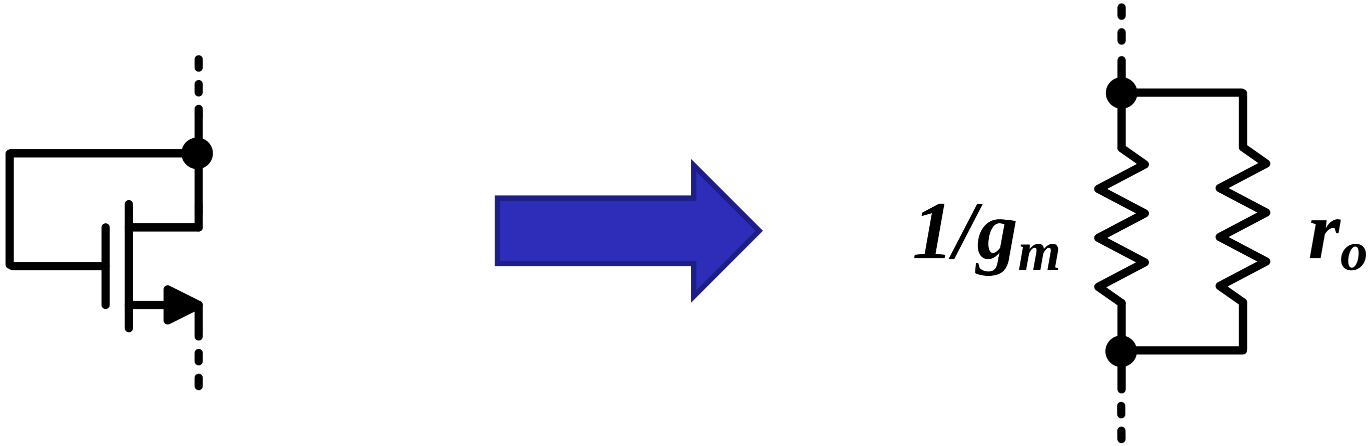
Active Load (Source OFF)



Diode Connected (Source Absorption)

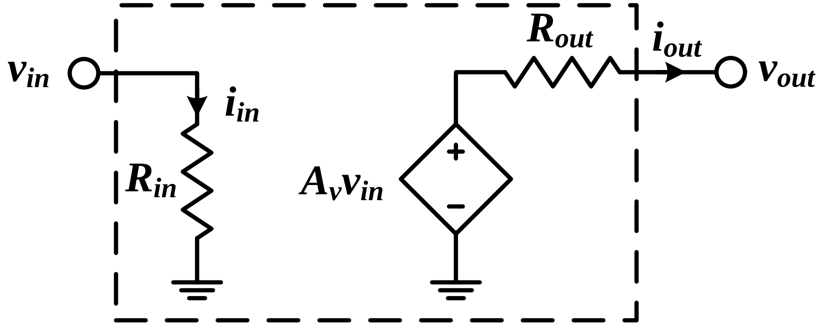
- Always in saturation ($V_{DS} = V_{GS} > V_{ov}$)
- Body effect: $g_m \rightarrow g_m + g_{mb}$ (if G is ac gnd)

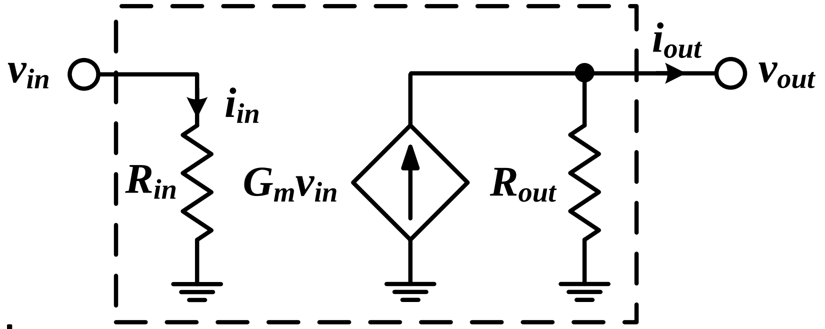




Why GmRout?

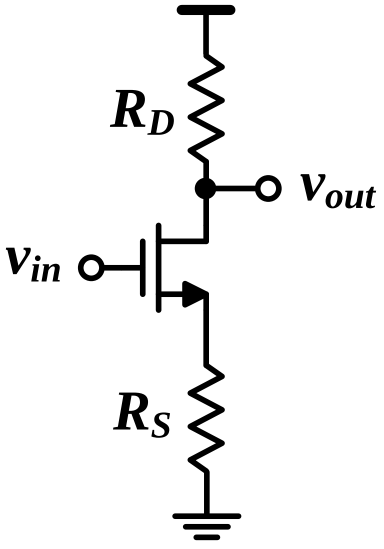
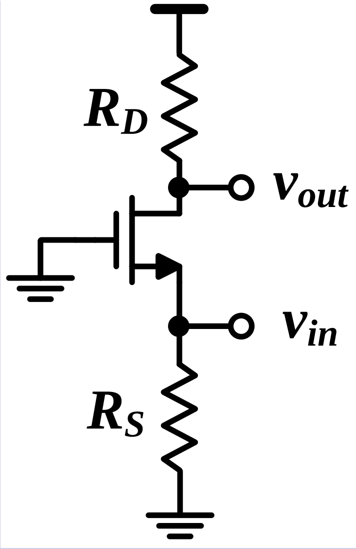
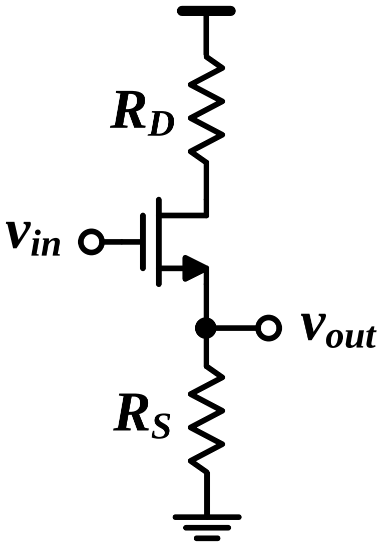
$$R_{in} = v_{in}/i_{in}$$
$$R_{out} = v_x/i_x \ @\ v_{in} = 0$$
$$G_m = i_{out,sc}/v_{in}$$
$$A_v = G_m R_{out}$$
$$A_i = G_m R_{in}$$





- Divide and conquer
  - Rout simplified: $v_{in} = 0$
  - Gm simplified: $v_{out} = 0$
  - We already need Rin/out and Gm
  - We can quickly and easily get Rin/out from the shortcuts

Summary of Basic Topologies

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

Outline

- ❑ Recapping previous key results
- ❑ Cascode amplifier
- ❑ Telescopic vs folded cascode
- ❑ Super cascode

Boosting Voltage Gain

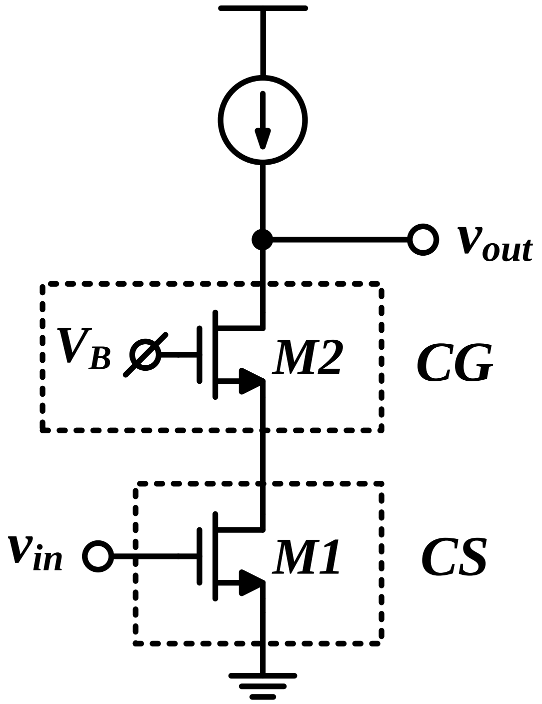
- The max gain of a single transistor amplifier is the intrinsic gain (body effect may add).

$$A_i = g_m r_o$$

- $g_m r_o$ is quite small for modern deep submicron technologies.
  - May be less than 10!
  - But we need high voltage gain to design an op-amp.
- How to boost the gain?
  - Both CS and CG stages provide voltage gain.
  1. Use a cascade of CS stages: CS + CS + CS + …
  2. Use a cascode amplifier: CS + CG + CG + …
     - Single cascode: CS + CG
     - Double cascode: CS + CG + CG
     - …

Cascode

- CS + CG



Cascode Gain Using GmRout

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

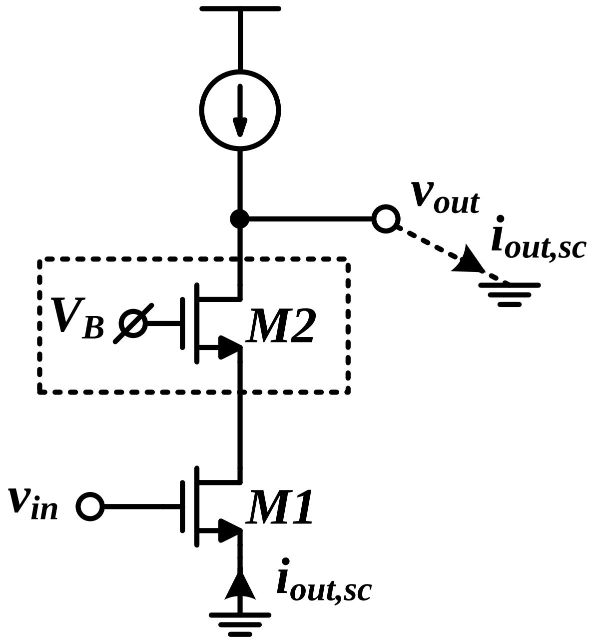
$$i_{out,sc} \approx -g_{m1} v_{in}$$

$$G_m = \frac{i_{out,sc}}{v_{in}} \approx -g_{m1}$$

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



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

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

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

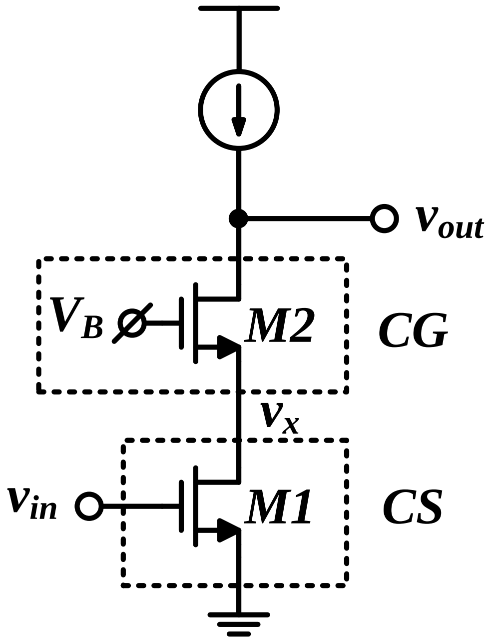
Cascode as CS + CG

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

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

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

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

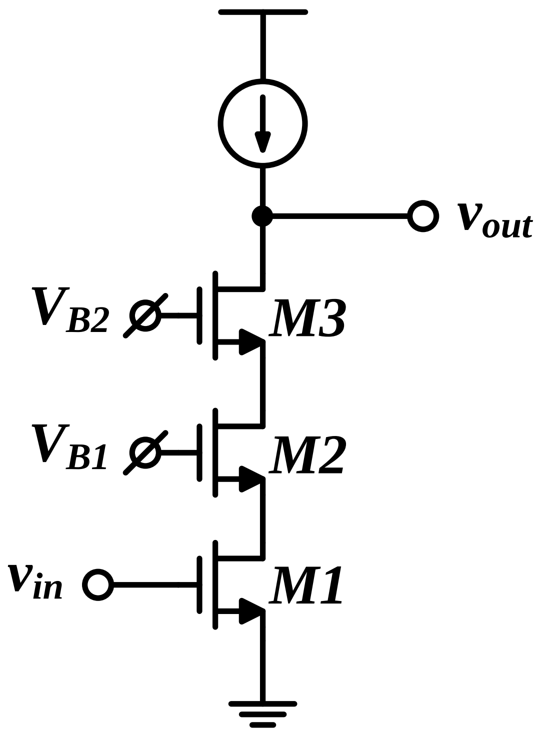


- Assume all g_m and r_o are equal and neglect body effect

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

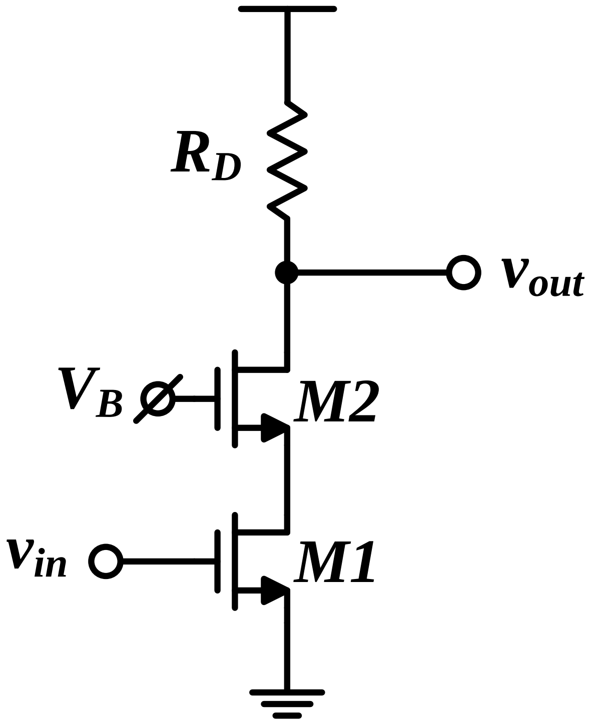
Quiz

- The circuit below shows a 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?
  - Not useful for boosting the gain
  - But useful for boosting the BW (more about this later)



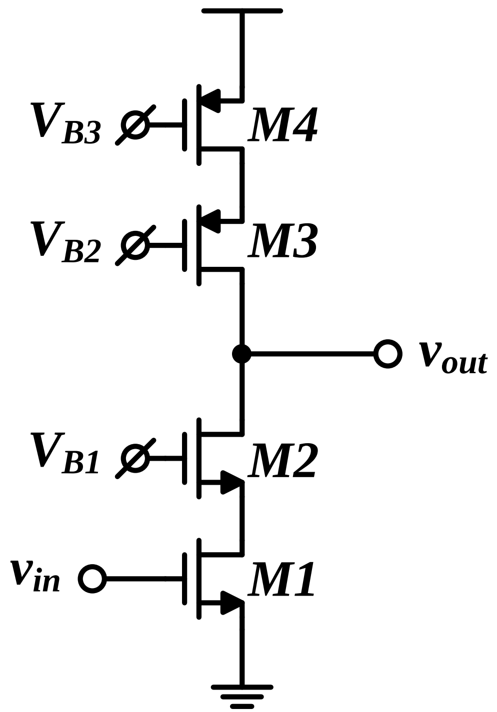
Cascode Load

- 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 Bias Voltage

- Keep M1 in sat

$$V_B > V_{GS2} + \left(V_{in,max} - V_{TH1}\right)$$

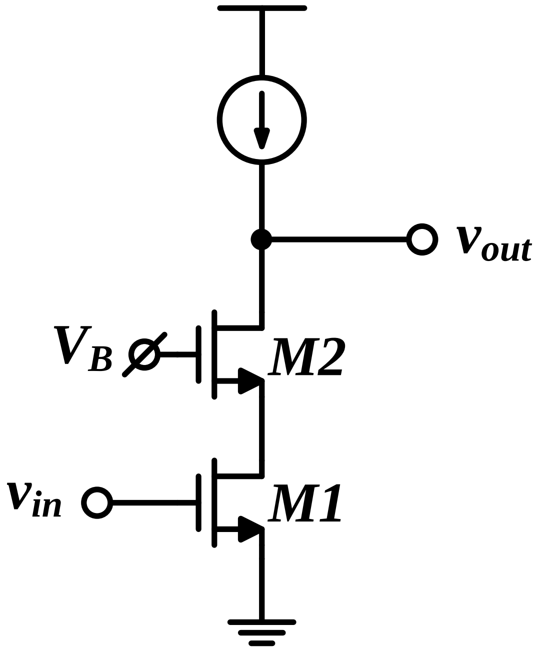
$$V_{in,max} < V_{TH1} + \boldsymbol{V_B} - V_{GS2}$$

- Keep M2 in sat

$$V_B < V_{TH2} + V_{out,min}$$

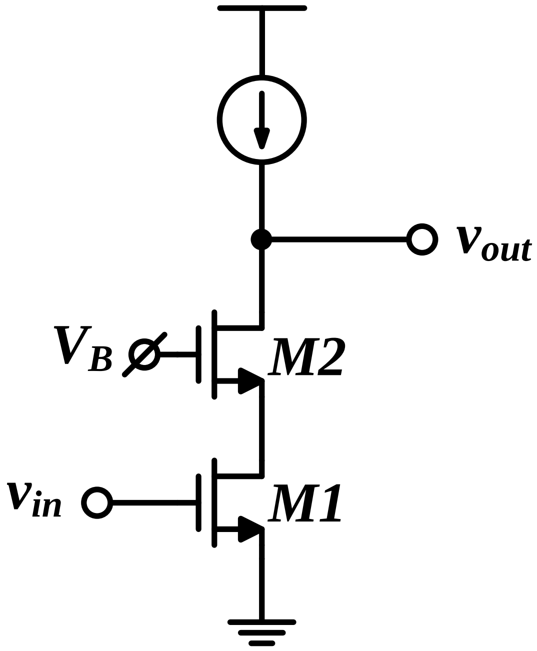
$$V_{out,min} > \boldsymbol{V_B} - V_{TH2}$$

- Increasing/decreasing V_B either hurts V_{in} range or V_{out} range
  - Input and output ranges are coupled oppositely



Quiz: Cascode Bias Voltage

- Assume $V_{TH} = 0.4\ V$ and $V_{ov} = 0.1\ V$.
- Find minimum V_B.
- If V_B is set at $0.1\ V$ above the minimum value, find $V_{in,max}$ and $V_{out,min}$.



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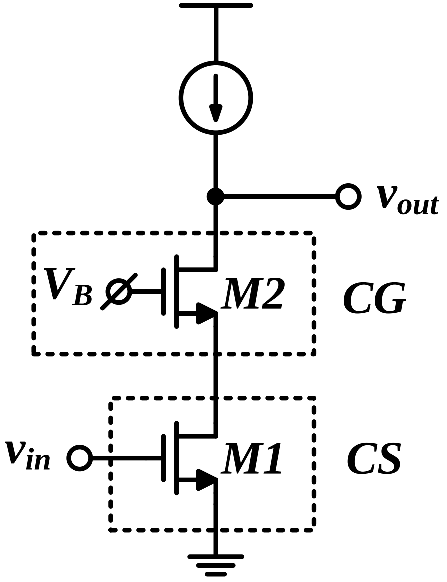
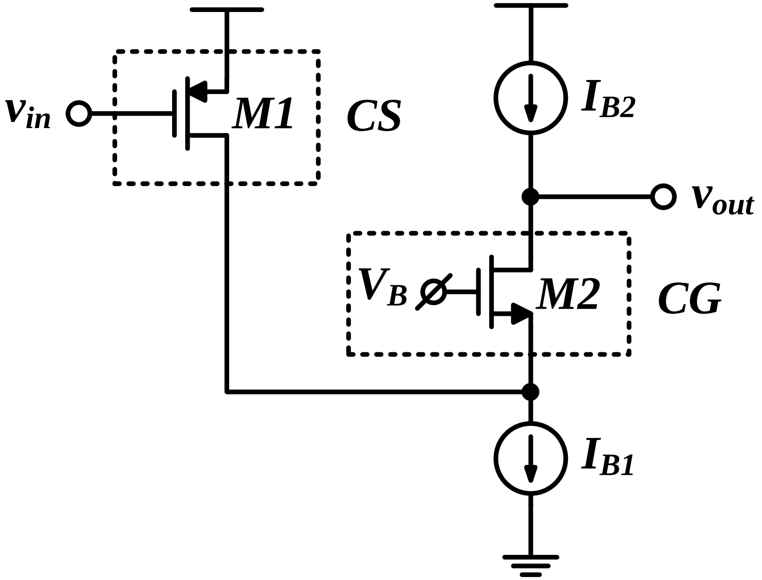
Telescopic vs Folded Cascode

- 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 I_{B1})
  - Why is it useful?





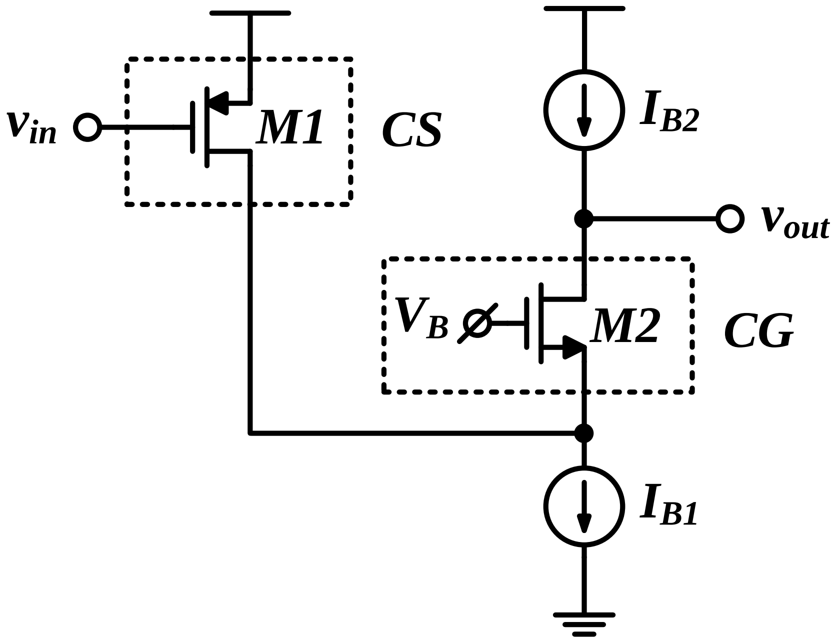
Folded Cascode Bias Voltage

- Input and output ranges are NOT coupled oppositely

$$V_{in,min} > -|V_{TH1}| + \boldsymbol{V_B} - V_{GS2}$$

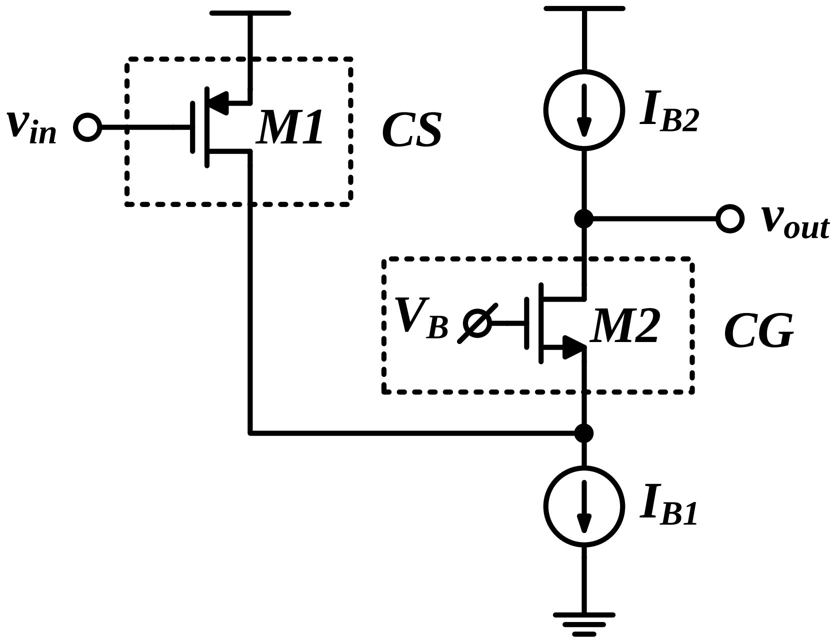
$$V_{out,min} > \boldsymbol{V_B} - V_{TH2}$$

- Choosing small V_B extends both V_{in} and V_{out} ranges
  - Just bias I_{B1} in saturation
- More on this point when we study operational amplifier design



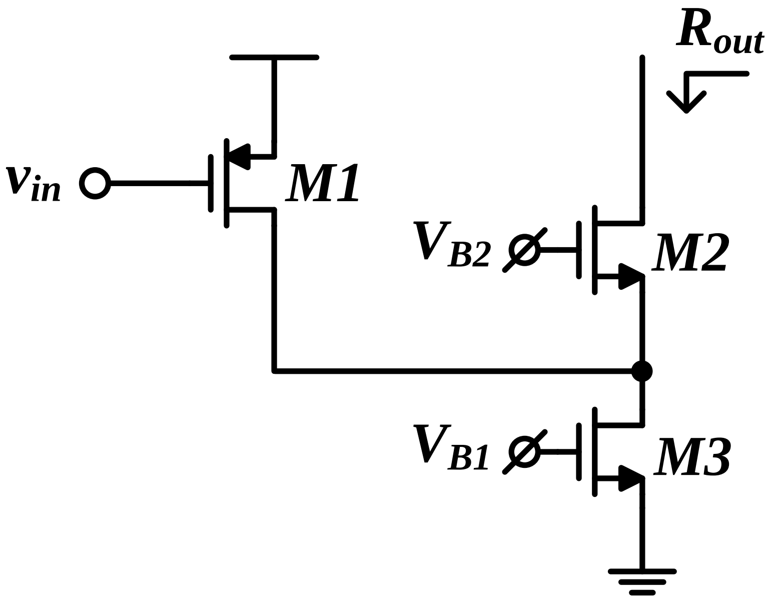
Quiz: Folded Cascode Bias Voltage

- Assume I_{B1} is implemented using a MOSFET, $V_{TH} = 0.4\ V$, and $V_{ov} = 0.1\ V$.
- Find minimum V_B.
- If V_B is set at $0.1\ V$ above the minimum value, find $V_{in,min}$ and $V_{out,min}$.



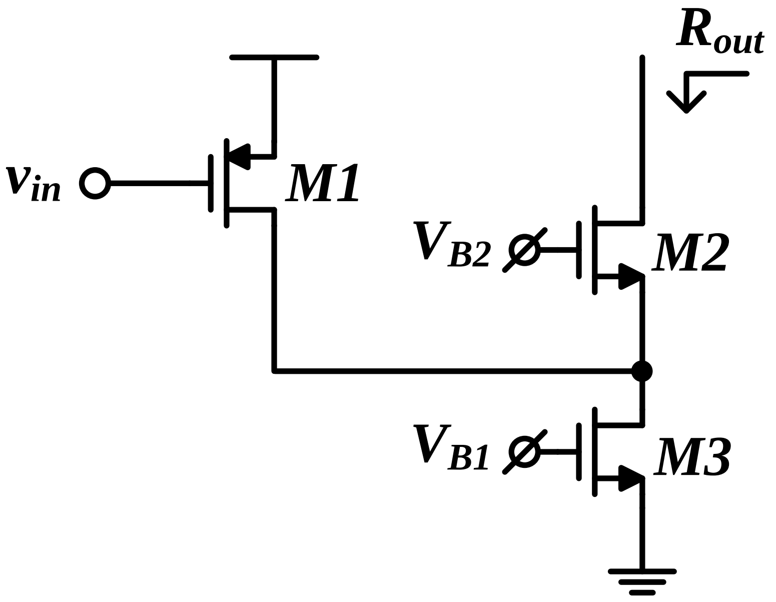
Quiz: Rout of Folded Cascode

- Assume all transistors have the same g_m and r_o, and neglect body effect. Calculate Rout.



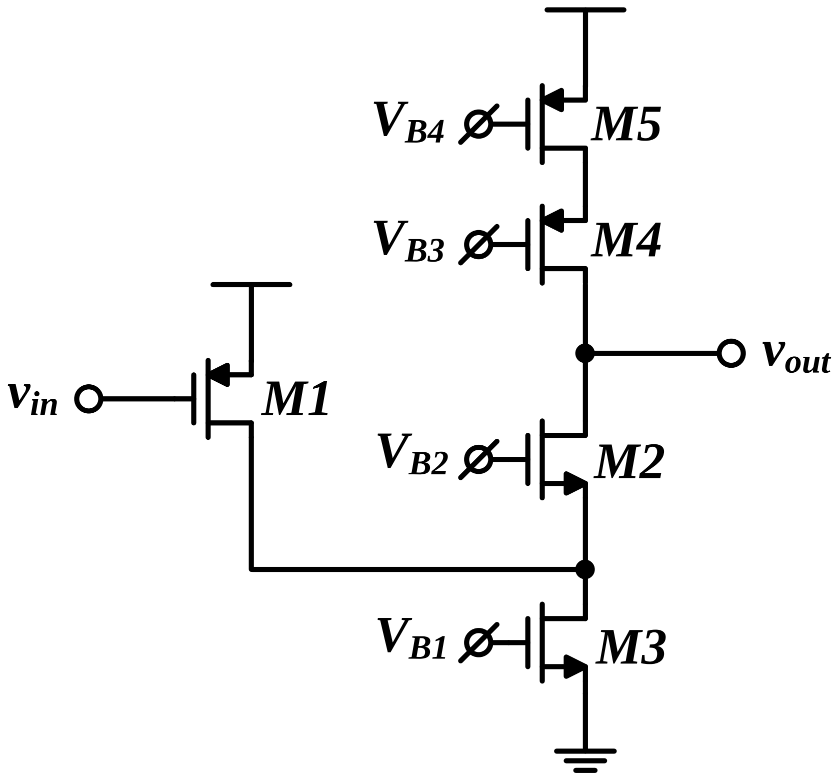
Quiz: Rout of Folded Cascode

- Assume all transistors have the same V_{ov} and L, CS and CG have the same bias current, and neglect body effect. Calculate Rout in terms of g_m and r_o of M1.



Quiz: Gain of Folded Cascode

- Calculate Av = GmRout. Assume all transistors have the same g_m and r_o, and neglect body effect.



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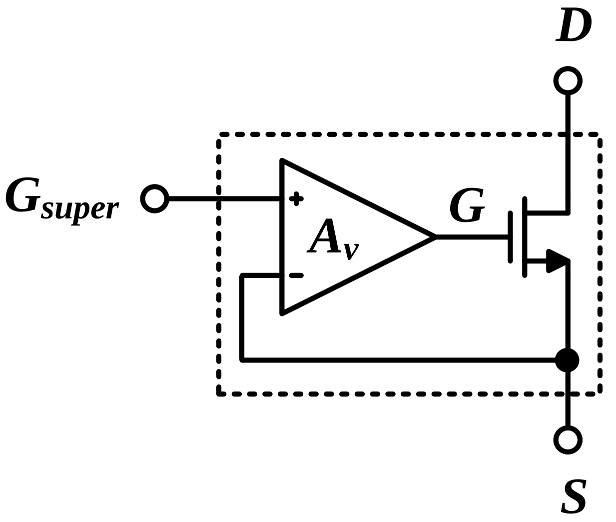
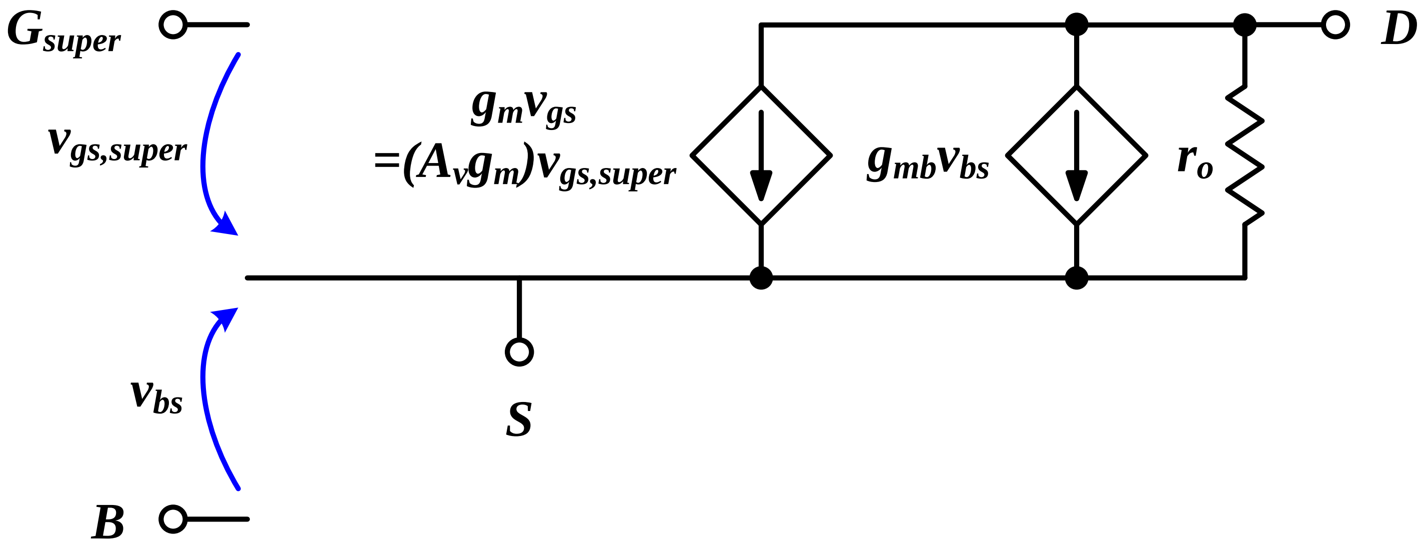
Gain Boosting: Super Transistor

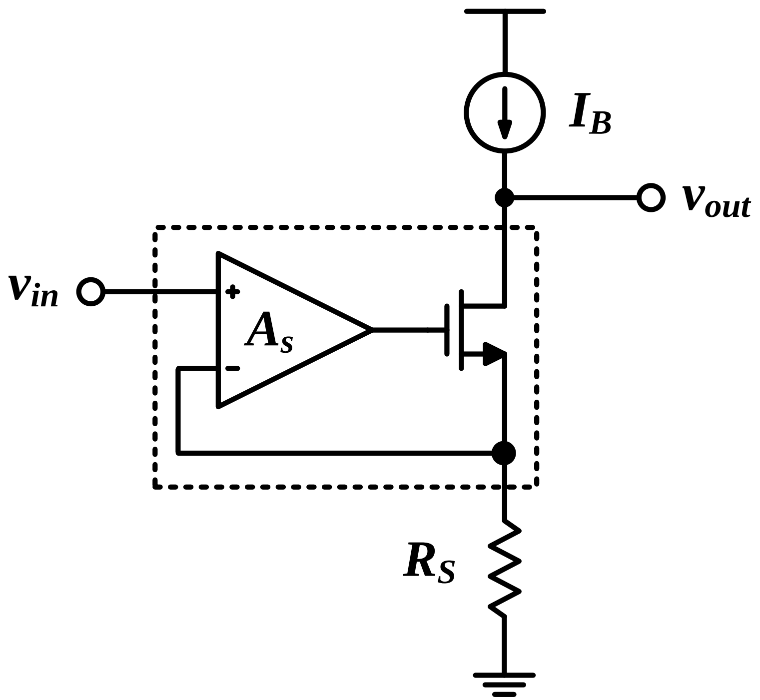
- $g_{m,super} = A_v g_m$
- $r_{o,super} = r_o$





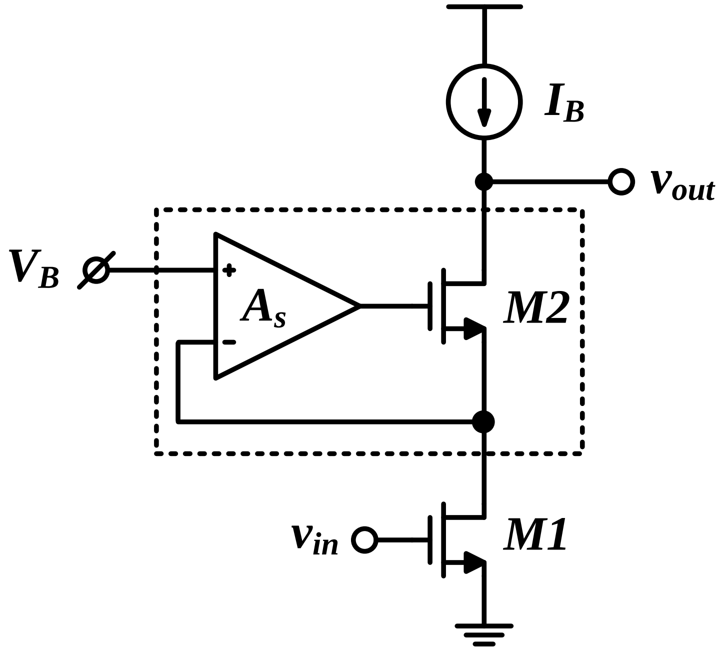
Gain Boosting: Super Transistor

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



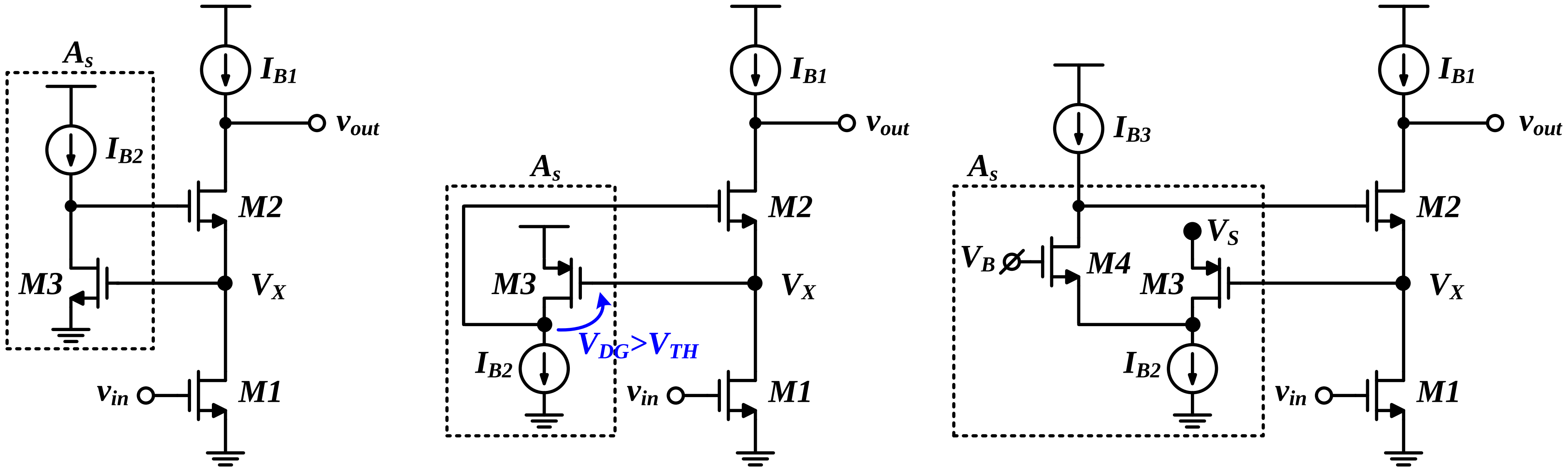
Super Cascode

- A.k.a. regulated cascode or gain boosted cascode
- $G_m \approx g_{m1}$
- $R_{out} = r_{o2}\left(1 + g_{m2,super} r_{o1}\right) = r_{o2}(1 + A_s g_{m2} r_{o1})$
- $A_v \approx A_s (g_{m1} r_{o1})(g_{m2} r_{o2})$
- Gain is boosted while preserving headroom (no extra stacking)
- But more power, noise, and complexity



Gain Boosting Implementation

- NMOS CS: headroom limitation
  - $V_X = V_{GS3} = V_{TH3} + V_{ov3}$ instead of V_{ov1}
- PMOS CS: M3 in triode
  - $V_{DG3} = V_{GS2} > V_{TH}$
- Folded cascode: M4 provides level shift
  - Can bias the circuit such that $V_{out,min} = V_{ov2} + V_{ov1}$



Thank you!

References

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- B. Razavi, "Fundamentals of Microelectronics," Wiley, 2nd ed., 2014
- B. Razavi, "Design of Analog CMOS Integrated Circuits," McGraw-Hill, 2nd ed., 2017