Analog IC Design

Lecture 19
OTA Topologies

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Outline

- Recapping previous key results
- OTA/op-amp overview
- Comparison of OTA topologies
- Gain-boosted OTA
- OTA output range in CL configuration
  - Unity-gain buffer configuration
  - Fully-differential amplifier configuration

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MOSFET in Saturation

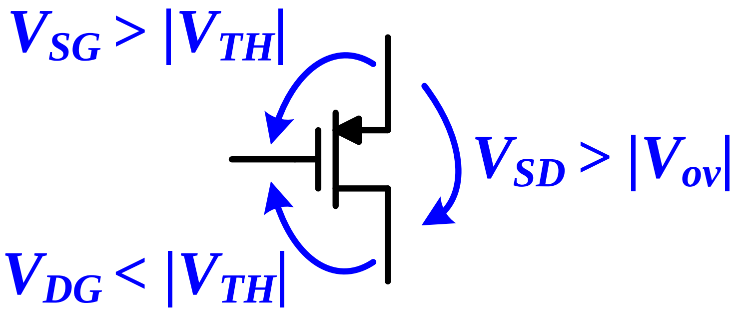
- The channel is pinched off if the difference between the gate and drain voltages is not sufficient to create an inversion layer

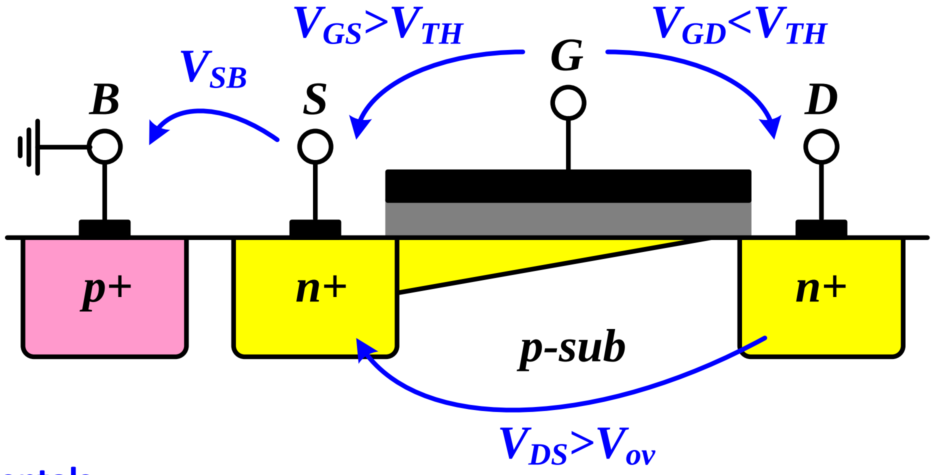
$$V_{GD} \le V_{TH} \quad or \quad V_{DS} \ge V_{ov}$$

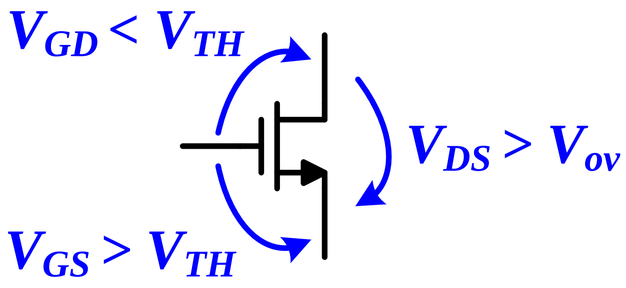
- Square-law (long channel MOS)

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

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







Regions of Operation Summary

OFF (Subthreshold)

$V_{GS} < V_{TH}$

ON

$V_{GS} > V_{TH}$

Triode

$V_{DS} < V_{ov}$

Or

$V_{GD} > V_{TH}$

Pinch-Off (Saturation)

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

Or

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

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

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

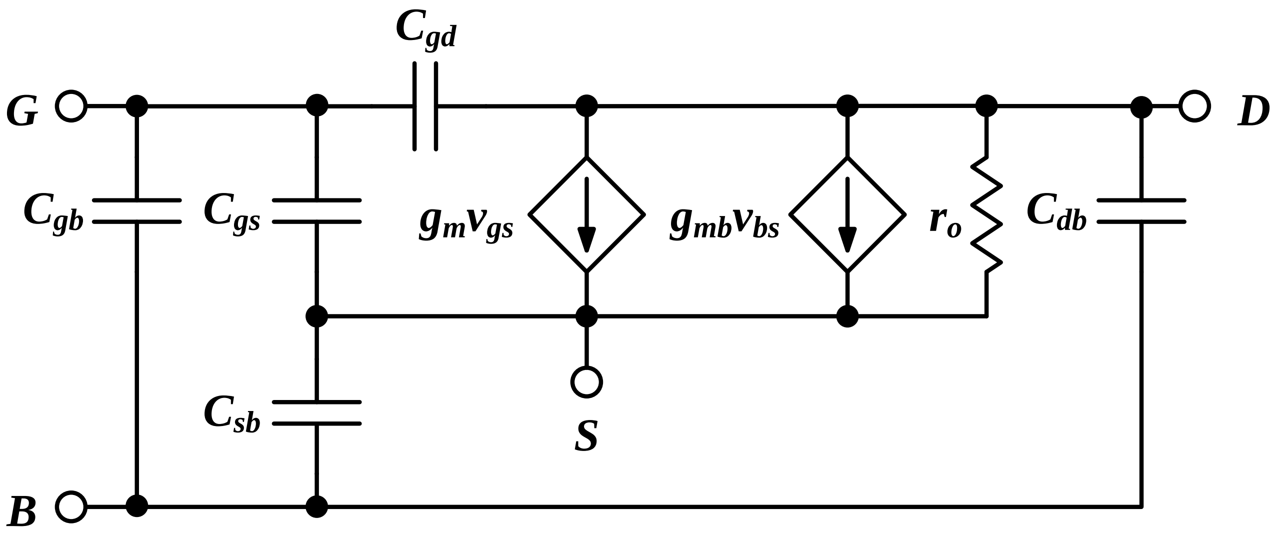
High Frequency Small Signal Model

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

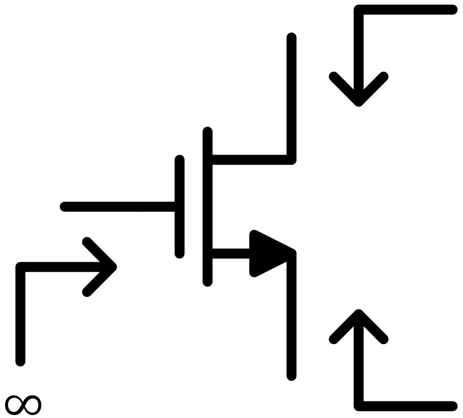
$$g_{mb} = \eta g_m \qquad \eta \approx 0.1 - 0.25$$

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

$$C_{gb} \approx 0 \qquad C_{gs} \gg C_{gd} \qquad C_{sb} > C_{db}$$



Rin/out Shortcuts Summary



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

H.I.N.

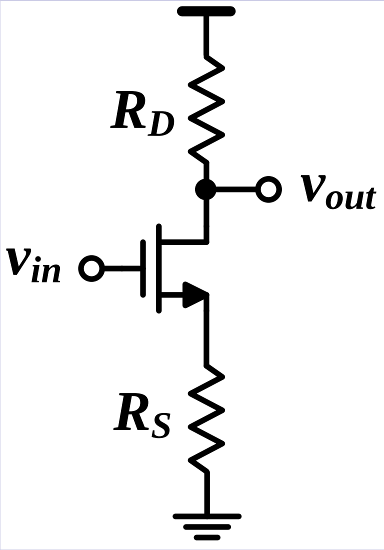
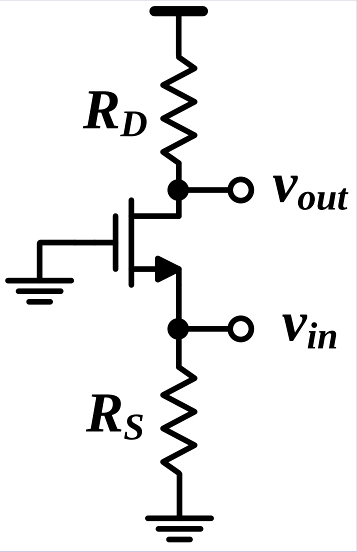
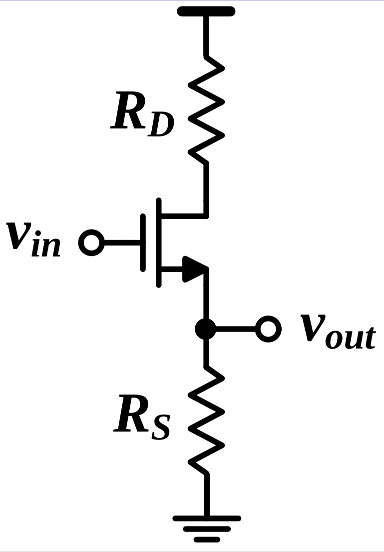
∞

At low frequencies **ONLY**

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

L.I.N.

Summary of Basic Topologies

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

Differential Amplifier

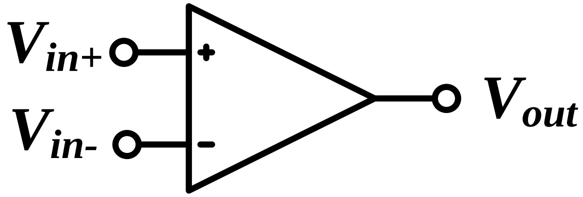
	Pseudo Diff Amp	Diff Pair (w/ ideal CS)	Diff Pair (w/ R_{SS})
A_{vd}	$-g_m R_D$	$-g_m R_D$	$-g_m R_D$
A_{vCM}	$-g_m R_D$	0	$\frac{-g_m R_D}{1 + 2(g_m + g_{mb})R_{SS}}$
A_{vd}/A_{vCM}	1	∞	$2(g_m + g_{mb})R_{SS} \gg 1$

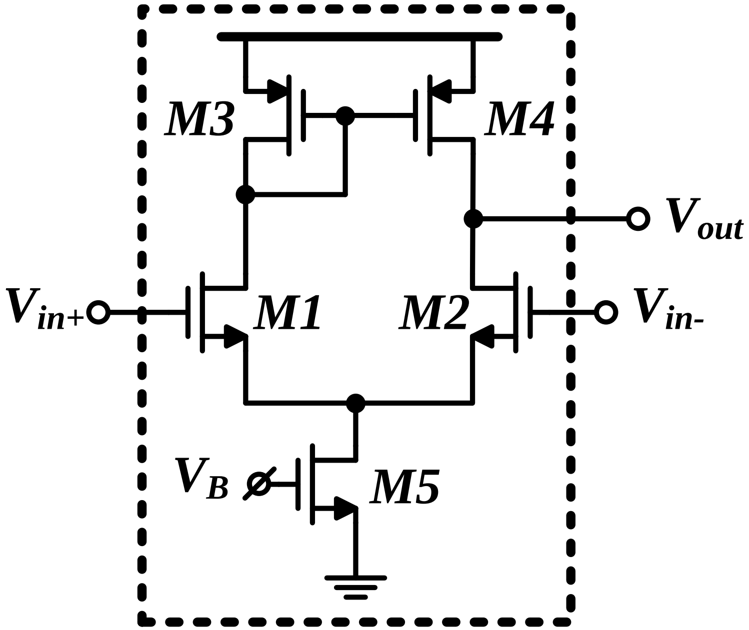
$$A_{vCM2d} = \frac{v_{od}}{v_{iCM}} \approx \frac{\Delta R_D}{2R_{SS}} + \frac{\Delta g_m R_D}{2 g_{m1,2} R_{SS}}$$

$$CMRR = \frac{A_{vd}}{A_{vCM2d}}$$

Op-Amp

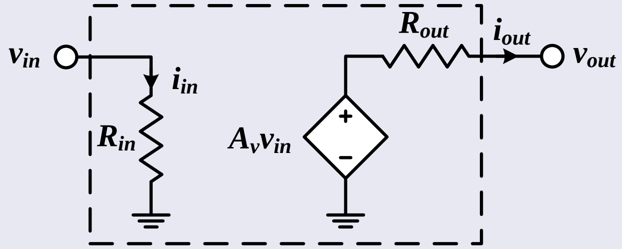
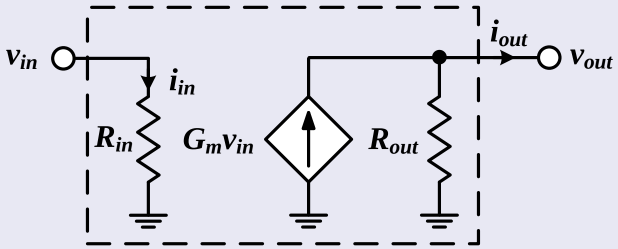
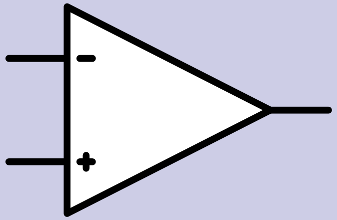
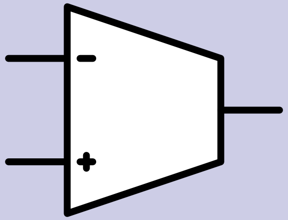
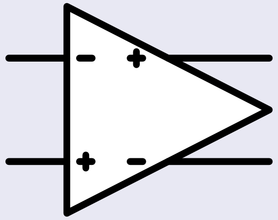
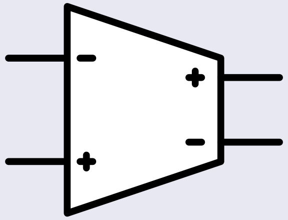
- An op-amp is simply a high gain differential amplifier
  - The gain can be increased by using cascodes and multi-stage amplification
- The diff amp is a key block in many analog and RF circuits
  - DEEP understanding of diff amp is ESSENTIAL





Op-Amp vs OTA

- In short, an OTA is an op-amp without an output stage (buffer)
- Some designers just use op-amp name and symbol for both

	Op-amp	OTA
Rout	**LOW**	**HIGH**
Model		
Diff input, SE output		
Fully diff		

V-star ($\boldsymbol{V^*}$)

- V-star (V^*) is inspired by V_{ov} but calculated from actual simulation data

$$g_m = \frac{2I_D}{V^*} \leftrightarrow V^* = \frac{2I_D}{g_m} = \frac{2}{g_m/I_D}$$

- Figures-of-merit in terms of V^*

$$g_m r_o = \frac{2I_D}{V^*} \cdot \frac{1}{\lambda I_D} = \frac{2}{\lambda V^*}$$

$$f_T = \frac{g_m}{2\pi C_{gg}} = \frac{1}{2\pi} \cdot \frac{2I_D}{V^*} \cdot \frac{1}{C_{gg}}$$

$$\frac{g_m}{I_D} = \frac{2}{V^*}$$

- The boundary between weak and strong inversion ($n = 1.2 \rightarrow 1.5$)

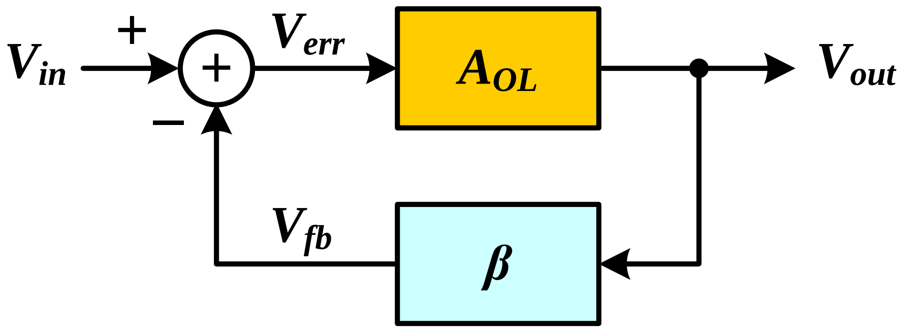
$$V_{ov}(SI) = V^*(WI) = 2nV_T \approx 60 \rightarrow 80mV$$

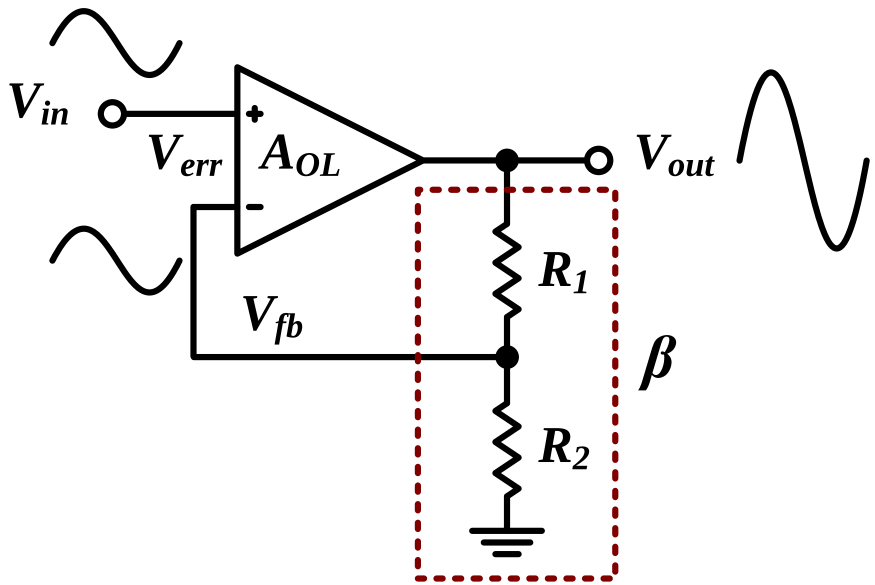
Negative Feedback

$$\beta = \frac{R_2}{(R_1 + R_2)}$$

$$A_{CL} = \frac{V_{out}}{V_{in}} = \frac{A_{OL}}{1 + \beta A_{OL}} = \frac{A_{OL}}{1 + \beta A_{OL}} \approx \frac{1}{\beta} = \frac{R_1 + R_2}{R_2} = 1 + \frac{R_1}{R_2}$$

$$\omega_{p,CL} = (1 + \beta A_{OLo})\omega_{P,OL}$$

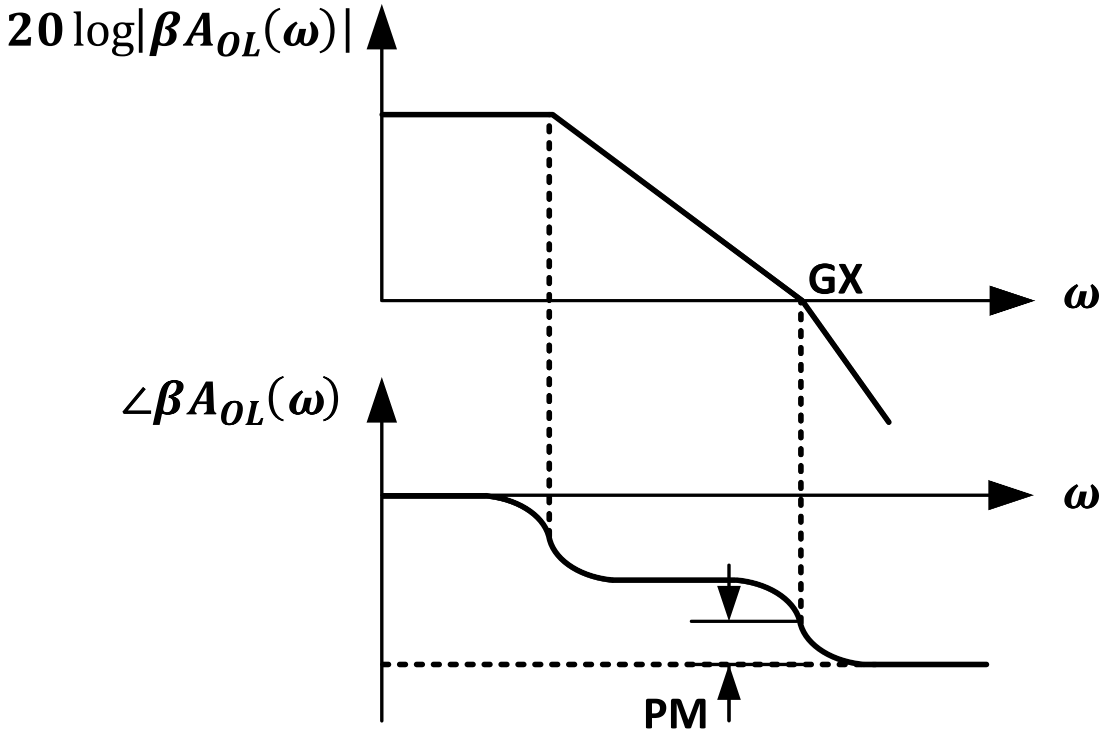




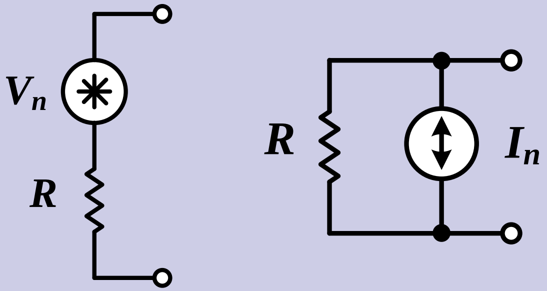
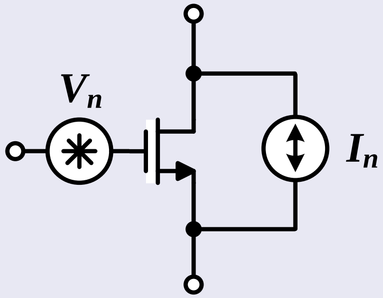
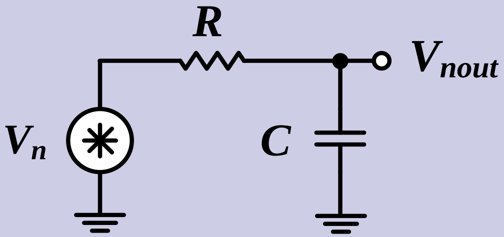
Phase Margin and the Ultimate GBW

- If $\omega_{p2} = \omega_u$: PM = 45°
  - Typically inadequate (peaking/ringing)
- Thus ω_{p2} should be $> \omega_u$→ $\omega_{p1} \ll \omega_u < \omega_{p2}$
  - ω_{p1} defines OL BW and ω_{p2} defines ultimate GBW (max CL BW)

Frequency domain peaking
→ noise amplification
Time domain ringing
→ poor settling time



Noise Models

Resistor thermal noise		$V_n(f) = \sqrt{4kTR} \approx \sqrt{\frac{R}{1\,k}} \times 4\frac{nV}{\sqrt{Hz}}$ $I_n(f) = \sqrt{\frac{4kT}{R}} \approx \sqrt{\frac{1\,k}{R}} \times 4\frac{pA}{\sqrt{Hz}}$
MOSFET thermal and flicker noise		$I_n^2(f) = 4kT\gamma g_m$ $V_n^2(f) = \frac{K}{C_{ox}WL}\frac{1}{f}$
RMS noise		$V_{noutrms}^2 = 4kTR \times B_N = \frac{kT}{C}$ $B_N = \frac{1}{4RC} = \frac{\pi}{2}f_p$ $V_{noutrms} \approx \sqrt{\frac{1\,p}{C}} \times 64\,\mu Vrms$

Noise Analysis Procedure

- Deactivate the input signal
- Identify the **dominant** noise sources → Model as $V_n^2(f)$ or $I_n^2(f)$
- Find the output noise density for each source: $V_{nout,x}^2(f)$
- Calculate the rms output noise of each source

$$V_{noutrms,x}^2 = V_{nout,x}^2(f) \times B_{N,x}$$

- Calculate total rms noise

$$V_{noutrms,tot}^2 = V_{nrms,1}^2 + V_{nrms,2}^2 + \cdots$$

- Calculate the input-referred rms noise voltage

$$V_{ninrms,tot}^2 = V_{noutrms,tot}^2 / A_v^2$$

- For low Z_{in}, input referred noise current must be added

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- ❑ Comparison of OTA topologies
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    - Unity-gain buffer configuration
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OTA / Op-Amp

- Integral part of many analog and mixed-signal systems
  - Amplification
  - Filtering
  - Any form of "signal-conditioning"
  - Voltage regulation
  - Reference generation
- Challenges
  - Complex interdependence between different specs
  - Supply voltage scaling
  - Channel length scaling
  - Energy efficiency

Finite Gain

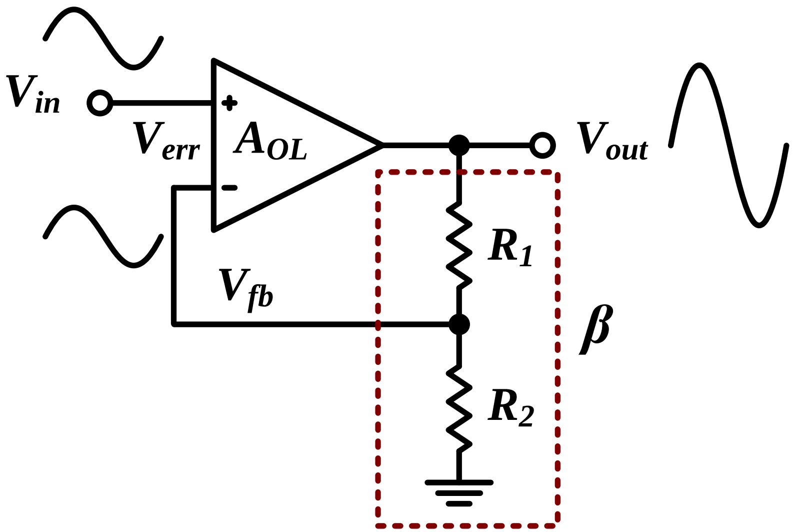
- Negative feedback: Gain set by ratio of matched components
  - Very low sensitivity to PVT, load, and input variations

$$A_{CL} = \frac{V_{out}}{V_{in}} = \frac{A_{OL}}{1+\beta A_{OL}} \approx \frac{1}{\beta}$$

- Open-loop gain is finite: still small dependence on OL gain
  - Static gain error $\epsilon_s = \left|\frac{A_{CLi}-A_{CL}}{A_{CLi}}\right| = \left|1-\frac{A_{CL}}{A_{CLi}}\right|$

$$\epsilon_s \approx 1-\beta \times \frac{A_{OL}}{\beta A_{OL}}\left(1-\frac{1}{\beta A_{OL}}\right) = \frac{1}{LG}$$

- Example: $A_{CL} = 10$ and $\epsilon_s < 1\%$
  - $A_{OL} > 1000 = 60dB$



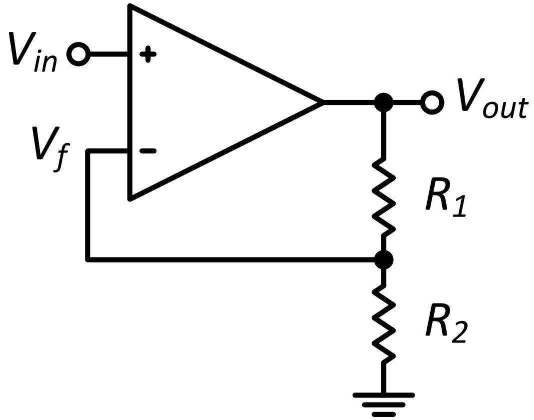
Finite Small-Signal Bandwidth

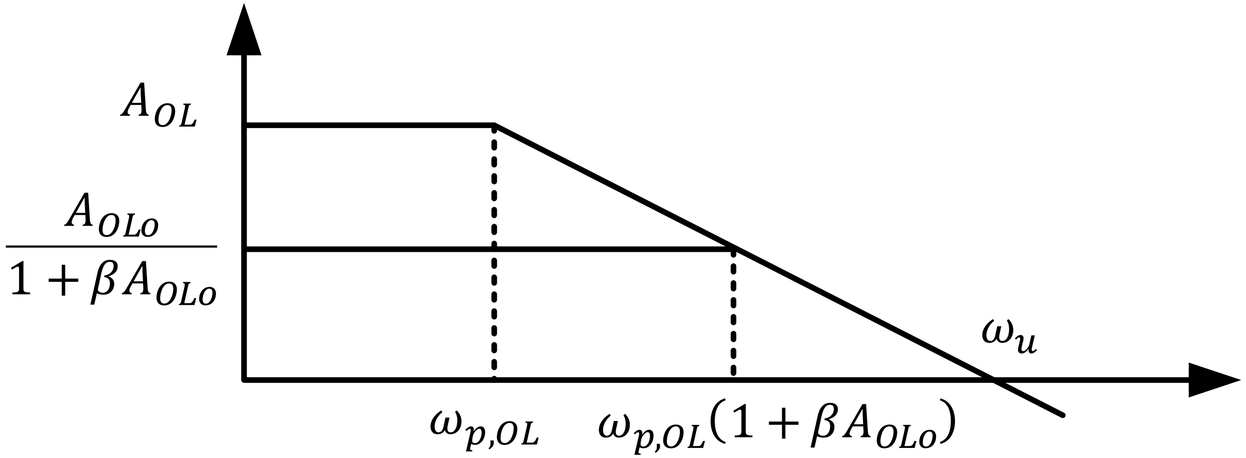
- How much bandwidth / speed is required by your application?

$$\omega_u = A_{OL}\omega_{p,OL} = A_{CL}\omega_{p,CL}$$

$$\tau_{OL} = \frac{1}{\omega_{p,OL}} = \frac{A_{OL}}{\omega_u}$$

$$\tau_{CL} = \frac{1}{\omega_{p,CL}} = \frac{A_{CL}}{\omega_u}$$





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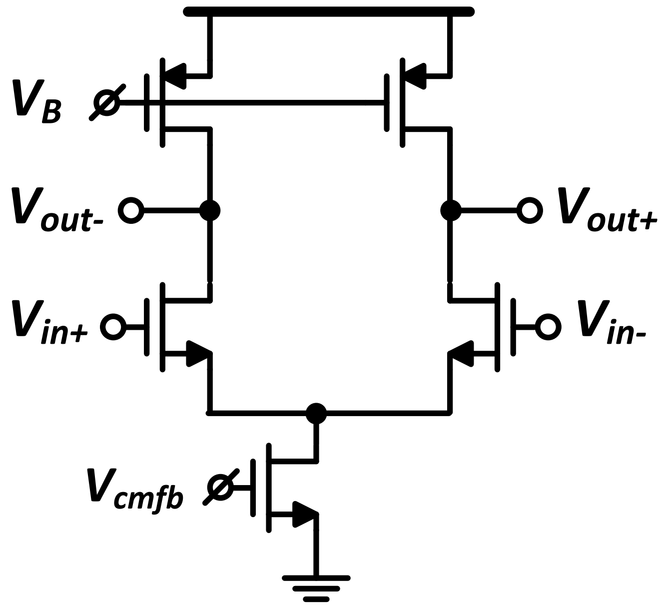
Popular OTA Topologies

- Single-stage OTAs
  - 5T OTA
  - Telescopic cascode OTA
  - Folded cascode OTA
- Two-stage OTA
- Three-stage OTA
- Gain-Boosted OTA

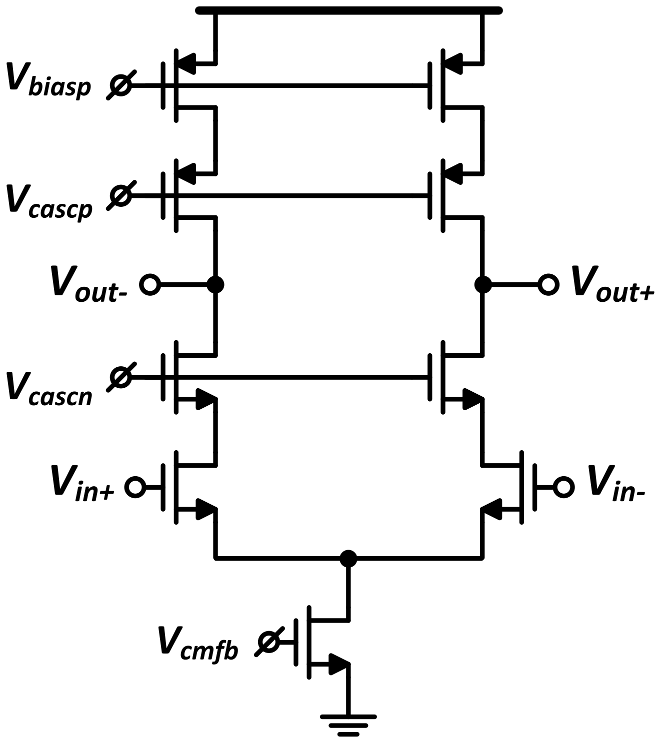
Fully-Differential (FD) 5T OTA

- Gain $\sim \frac{g_m r_o}{2}$
- Max output swing $\sim 2(V_{DD} - 3V^*)$
- $V_{in,max}$ and $V_{out,min}$ oppositely coupled
  - Fixed CM input @ max output swing
- Efficiency ~ 100%
  - FoM $= \frac{GBW \cdot C_L}{I_{total}}$ $[MHz.pF/mA]$ ~ ?
- Noise: $\alpha \sim 2$
- Single pole



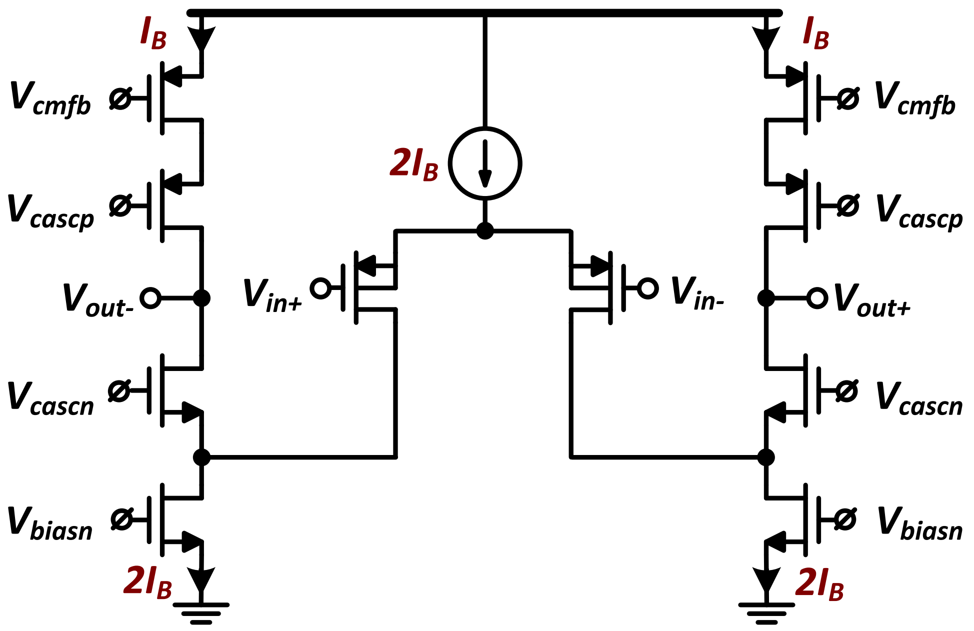
FD Telescopic Cascode OTA

- Gain $\sim \frac{(g_m r_o)^2}{2}$
- Max output swing $\sim 2(V_{DD} - 5V^*)$
  - Practically less (why?)
- $V_{in,max}$ and $V_{out,min}$ oppositely coupled
  - Fixed CM input @ max output swing
- Efficiency $\left(\frac{GBW \cdot C_L}{I_{total}}\right) \sim 100\%$
- Noise: $\alpha \sim 2$
- $\omega_{p2} \sim \frac{\omega_T}{2}$

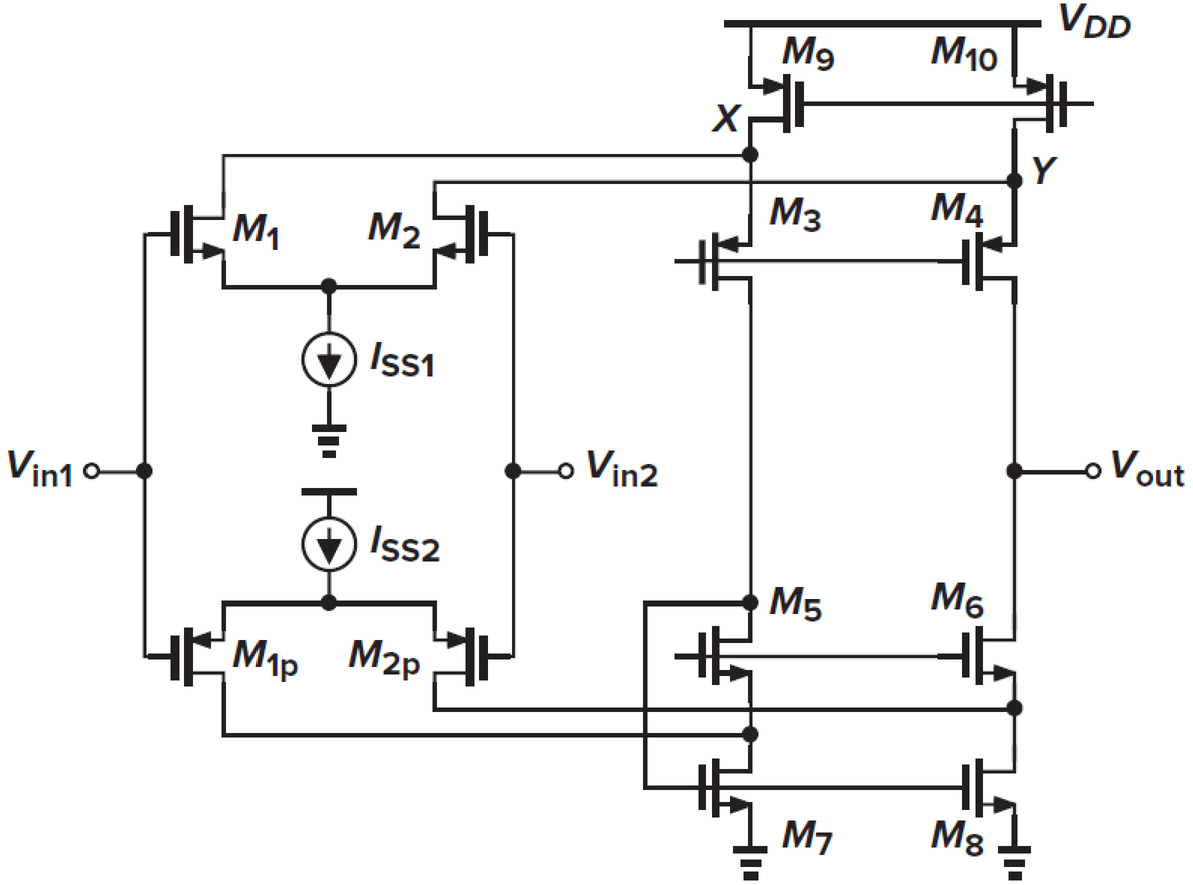


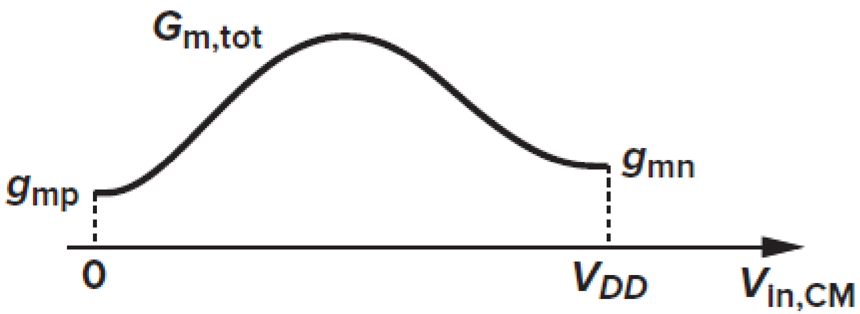
FD Folded Cascode OTA

- Gain $\sim \frac{(g_m r_o)^2}{4}$
- Max output swing $\sim 2(V_{DD} - 4V^*)$
  - Practically less (why?)
- Flexible CMIR
- Efficiency $\left(\frac{GBW \cdot C_L}{I_{total}}\right) \sim 50\%$
- Noise: $\alpha \sim 3$
- $\omega_{p2} \sim \frac{\omega_T}{3}$
- The most popular OTA due to flexible CMIR benefit



Folded Cascode with Rail-to-Rail CMIR

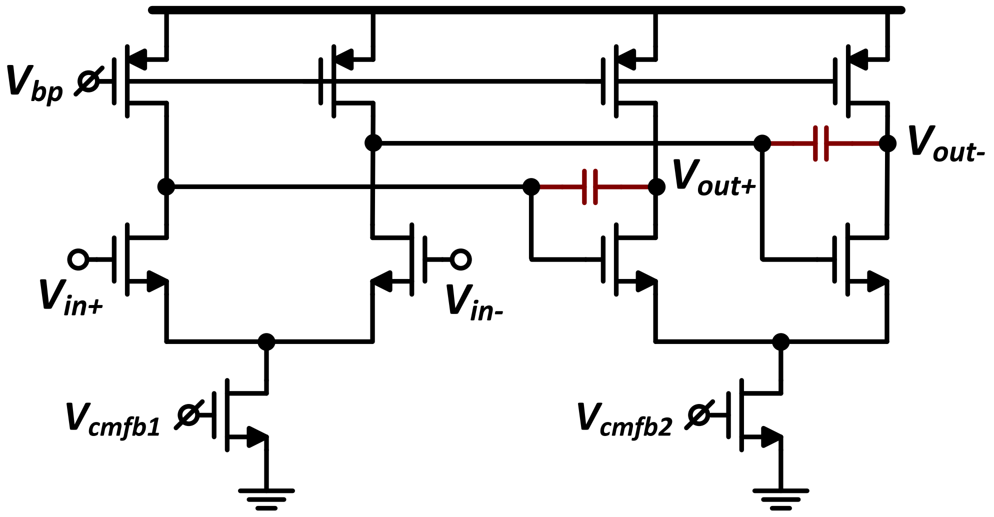




[Razavi, 2017]

FD Two-Stage Miller OTA

- Gain $\sim \frac{(g_m r_o)^2}{4}$
- Higher gain if first stage is telescopic/folded cascode
- Max output swing $\sim 2(V_{DD} - 3V^*)$
- CMIR better than 5T OTA (why?)
- Efficiency $\left(\frac{GBW \cdot C_L}{I_{total}}\right) < 50\%$
- Noise: $\alpha \sim 2 + 2\beta$
- $\omega_{p2} \sim \frac{G_{m2}}{C_{Ltot}}$



OTAs Comparison

Spec	Best			Worst
DC gain				
Swing				
CMIR				
Efficiency $\left(\frac{GBW \cdot C_L}{I_{total}}\right)$				
Noise				
Stability				

OTAs Comparison

Spec	Best			Worst
DC gain	Miller	Telescopic	Folded	5T
Swing	Miller	5T	Folded	Telescopic
CMIR	Folded	Miller	5T	Telescopic
Efficiency $\left(\frac{GBW \cdot C_L}{I_{total}}\right)$	5T	Telescopic	Folded	Miller
Noise	5T	Telescopic	Folded	Miller
Stability	5T	Telescopic	Folded	Miller

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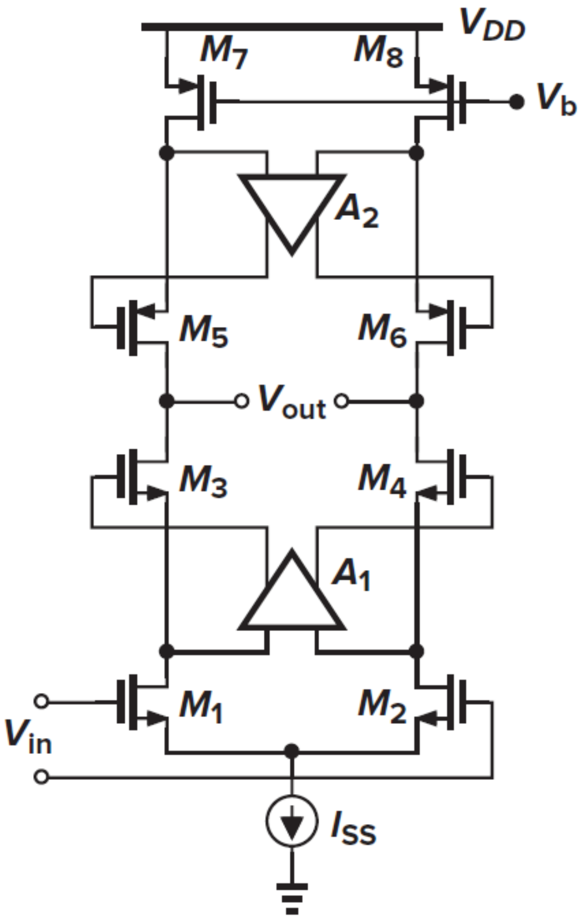
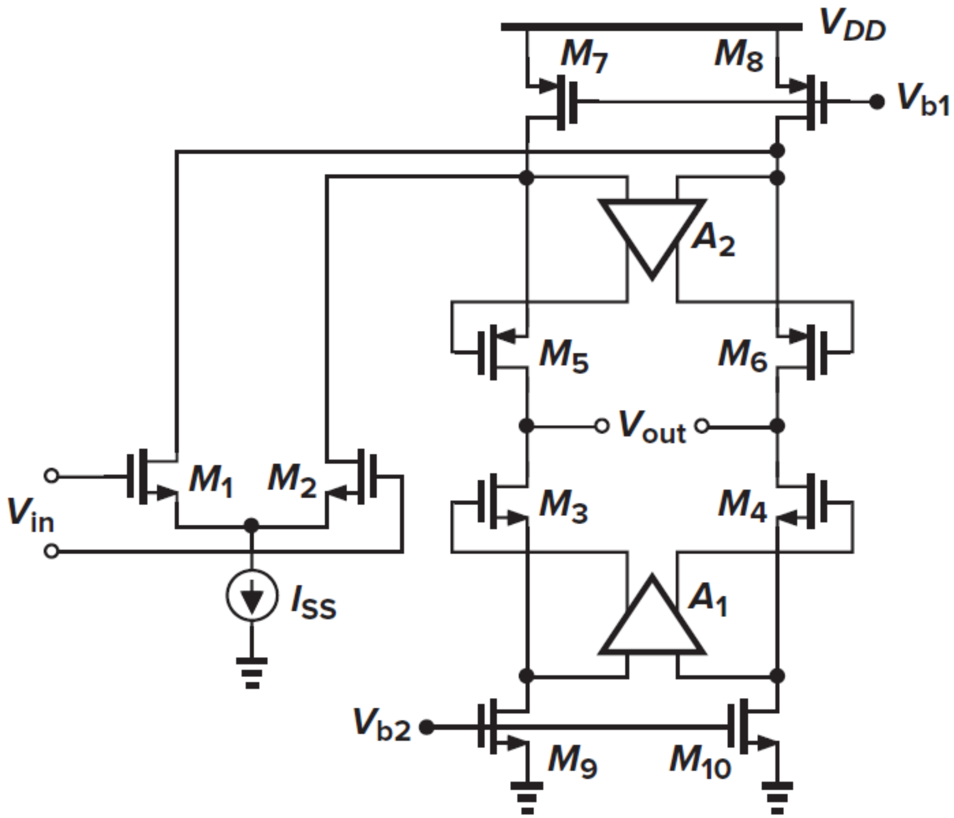
- OTA output swing in feedback amplifier configuration

Gain-Boosted OTA

- Very high gain and good output swing
- But higher noise, higher power (less efficient), complicated stability (many poles), and slow settling (pole-zero doublets)

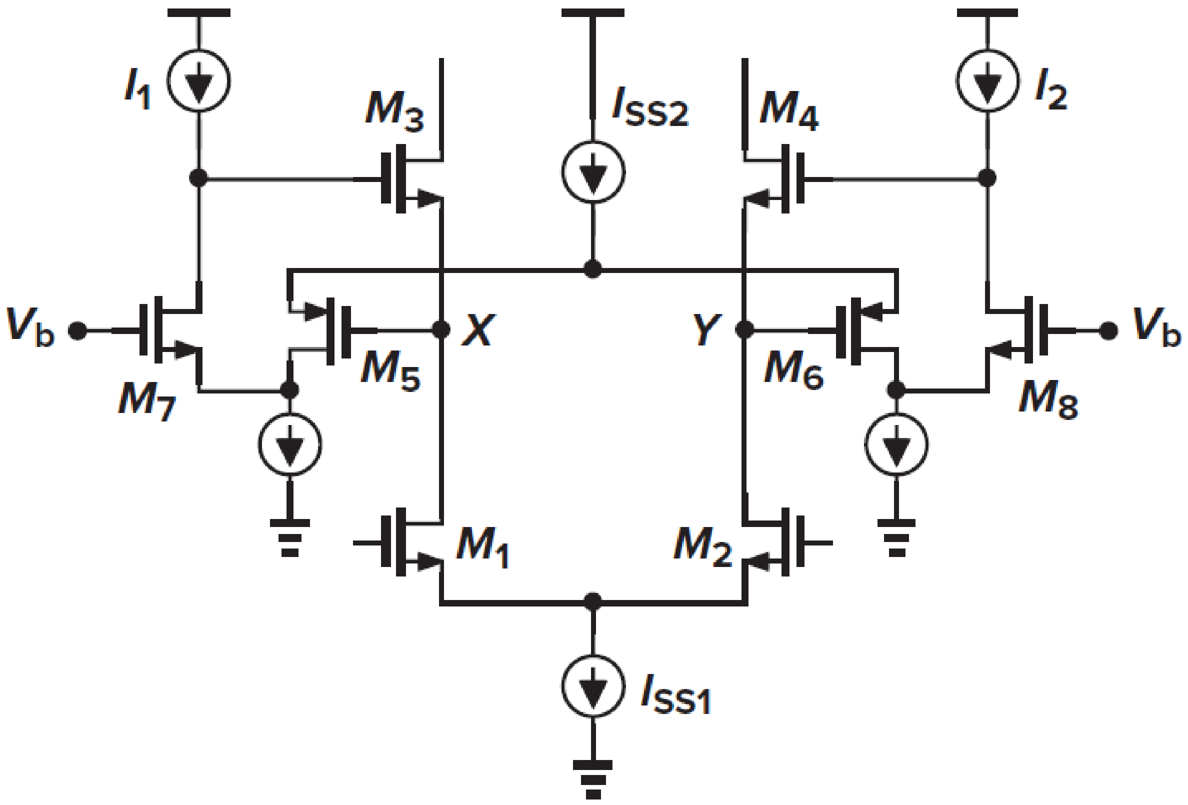




[Razavi, 2017]

Gain-Boosted OTA: Auxiliary Amplifier

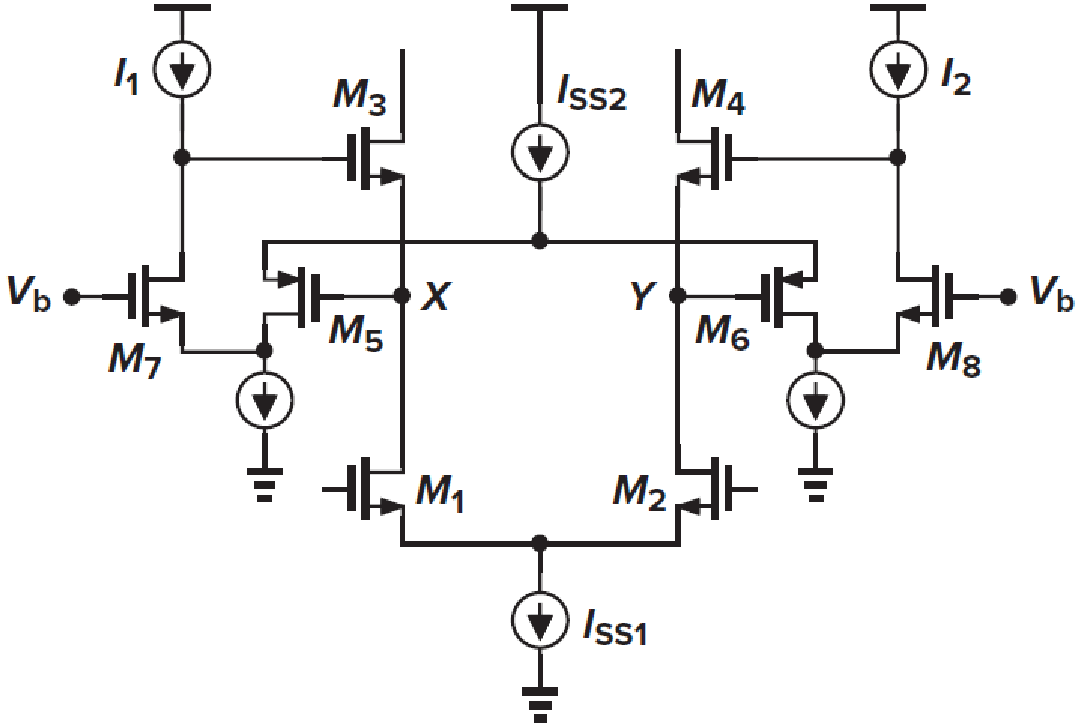
- Folded-cascode used as auxiliary amplifier
- No headroom limitation
  - $V_{X,Y} \geq V_{ov1} + V_{ISS1}$

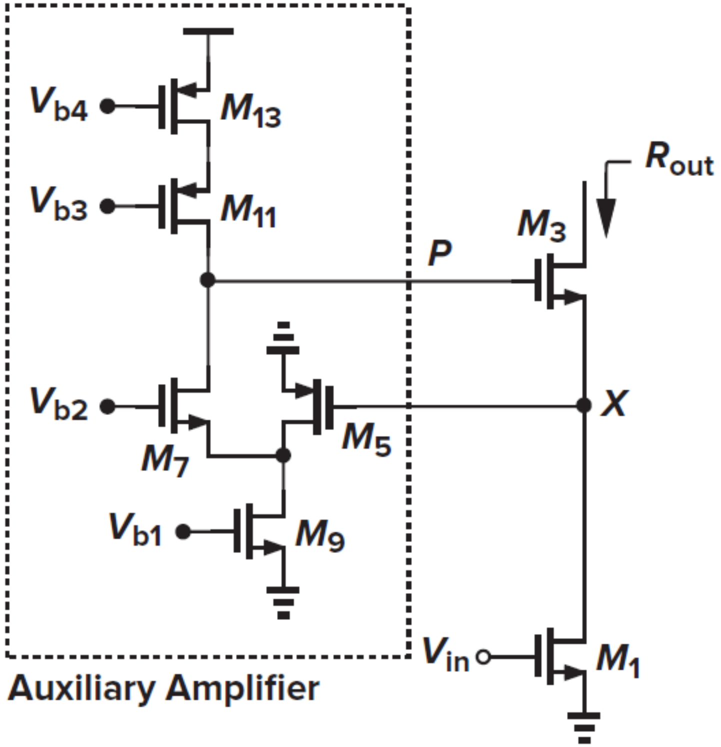


[Razavi, 2017]

Quiz: Gain-Boosted OTA

- ❑ Calculate the voltage gain. Assume all transistors have the same gm and ro. Assume the load is identical to R_{out} (not drawn).

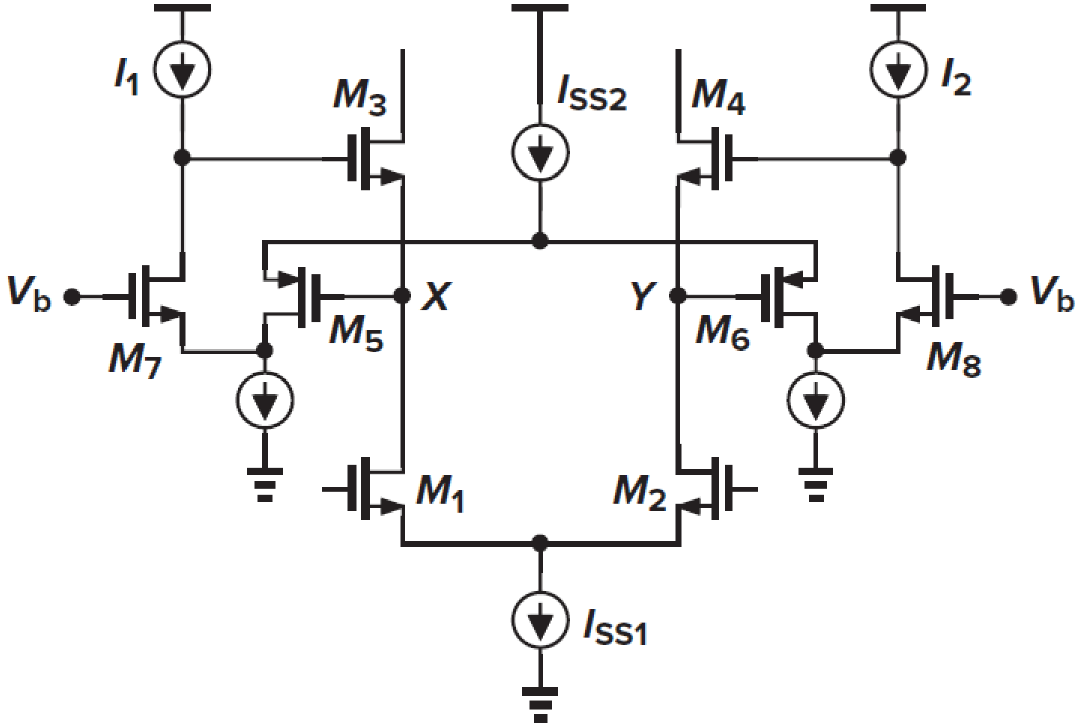


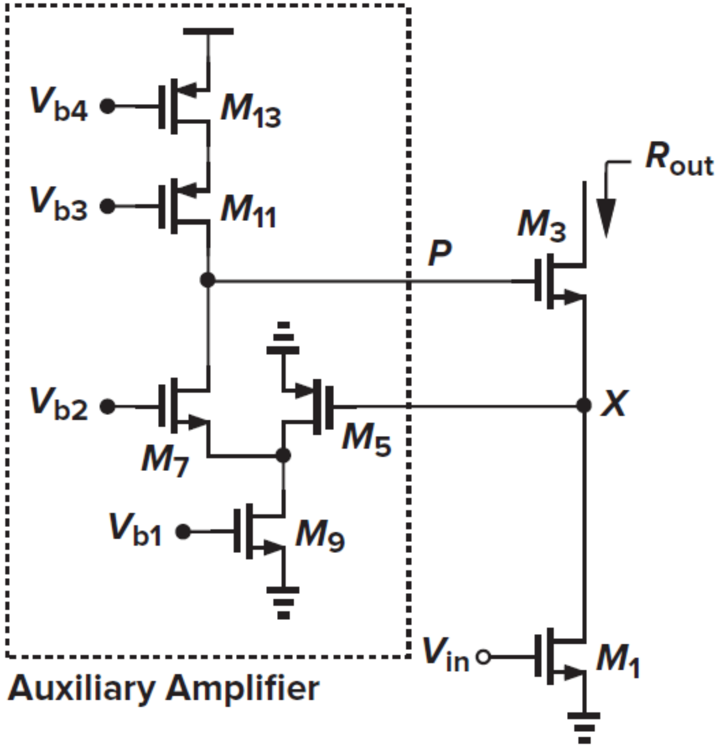


[Razavi, 2017]

Quiz: Gain-Boosted OTA

- $G_m \approx g_{m1}$
- $R_{out} \approx r_{o3}(1 + g_{m3,super} r_{o1}) \approx r_{o3}(A_1 g_{m3} r_{o1})$
- $A_1 \approx g_{m5}[g_{m11} r_{o11} r_{o13} || g_{m7} r_{o7}(r_{o5} || r_{o9})]$
- $A_v \approx \frac{1}{6}(g_m r_o)^4$ → quadruple cascode





Auxiliary Amplifier

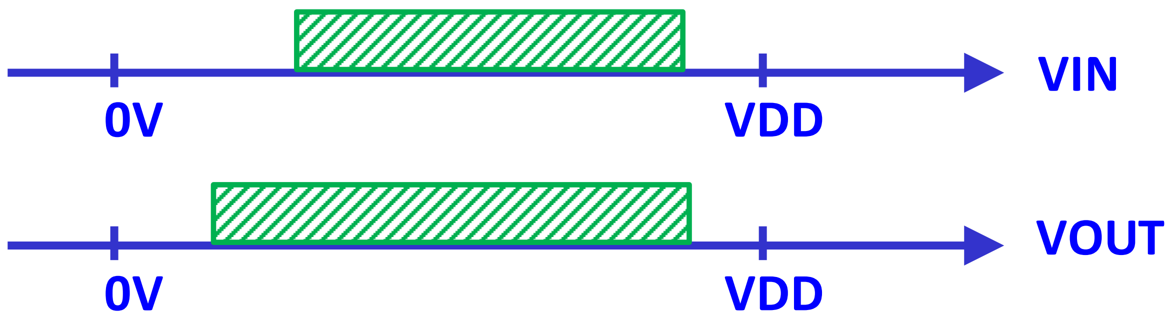
[Razavi, 2017]

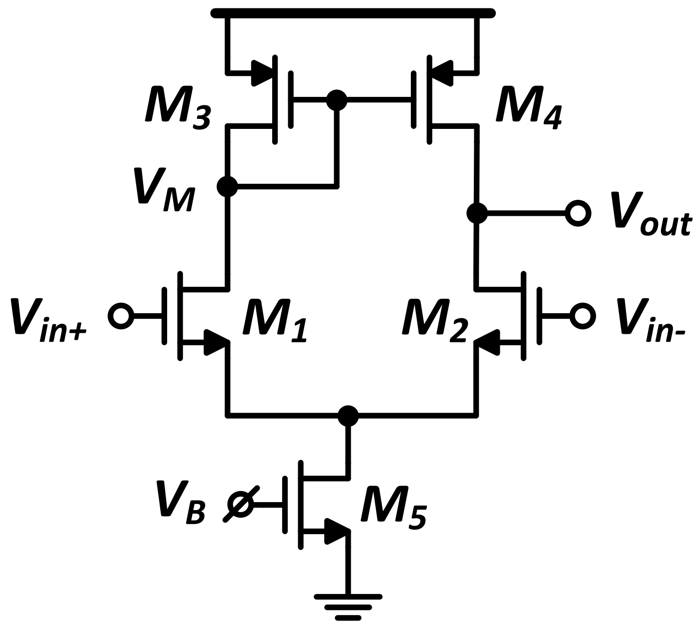
Outline

- Recapping previous key results
- OTA/op-amp overview
- Comparison of OTA topologies
- Gain-boosted OTA
- OTA output range in CL configuration
  - Unity-gain buffer configuration
  - Fully-differential amplifier configuration

5T OTA as a Buffer

- V_{in} OL: $V_T + V_{ov1,2} + V_{ov5} < V_{in} < V_{DD} - V_{ov3,4}$
- V_{out} OL: $V_{ov1,2} + V_{ov5} < V_{out} < V_{DD} - V_{ov3,4}$

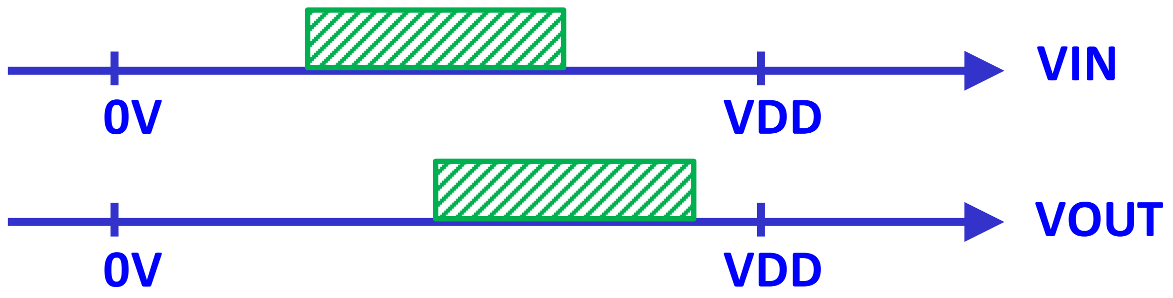




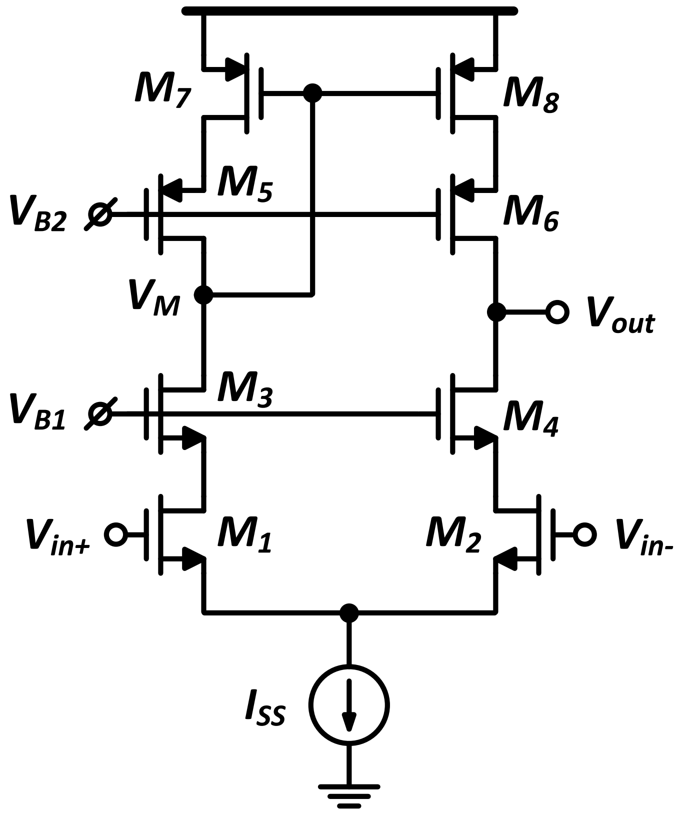
- Max swing ~ $(V_{DD} - V_T - 3V^*)$
- Example: $V_{DD} = 1.2\ V, V_T = 0.3\ V,$ and $V_{ov} = 0.1\ V$
  - $V_{in}\ (V_{out}) = 0.5 \rightarrow 1.1\ V$
  - Max swing $=\ 0.6\ V$

Telescopic Cascode as a Buffer

- ❑ V_{in} OL: $V_T + V_{ov1,2} + V_{ISS} < V_{in} < \boldsymbol{V_{B1}} - V_{ov3}$
- ❑ V_{out} OL: $\boldsymbol{V_{B1}} - V_T < V_{out} < V_{B2} + V_T$

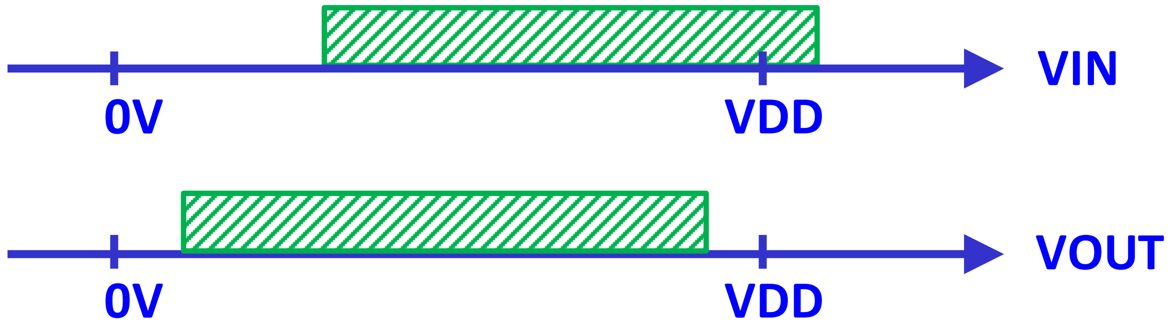


- ❑ Max swing ~ $(V_T - V_3^*)$
  - **Independent of $\boldsymbol{V_{DD}}$!**
- ❑ Example: $V_{DD} = 1.2\ V, V_T = 0.3\ V,$
  and $V_{ov} = 0.1\ V$
  - $V_{in}\ (V_{out}) = (V_{B1} - 0.3) \rightarrow (V_{B1} - 0.1)$
  - Max swing $=\ 0.2\ V$

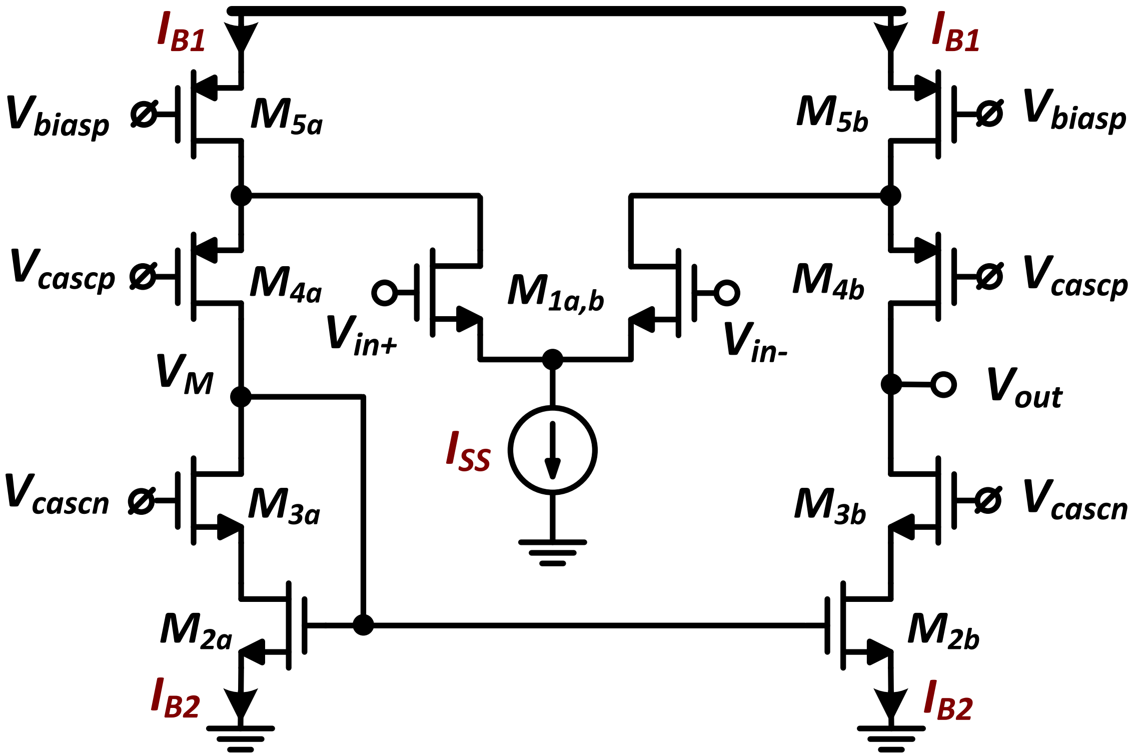


Folded Cascode as a Buffer

- V_{in} OL: $V_T + V_{ov1,2} + V_{ISS1} < V_{in} < V_{DD} + V_T - V_{ov5,6}$
- V_{out} OL: $V_{cascn} - V_T < V_{out} < V_{cascp} + V_T$



- Max swing ~ $(V_{DD} - 4V^* - V_T)$
  - Depends on V_{DD}
- Example: $V_{DD} = 1.2\ V$, $V_T = 0.3\ V$, and $V_{ov} = 0.1\ V$
  - Max swing $= 0.5\ V$



Outline

- Recapping previous key results
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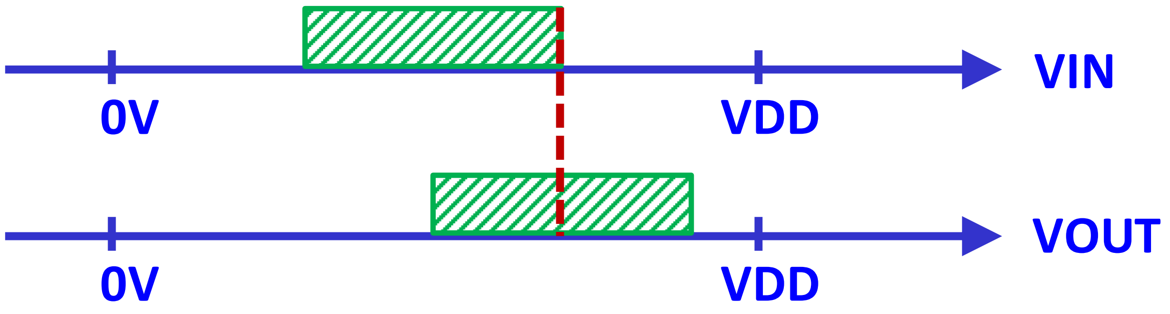
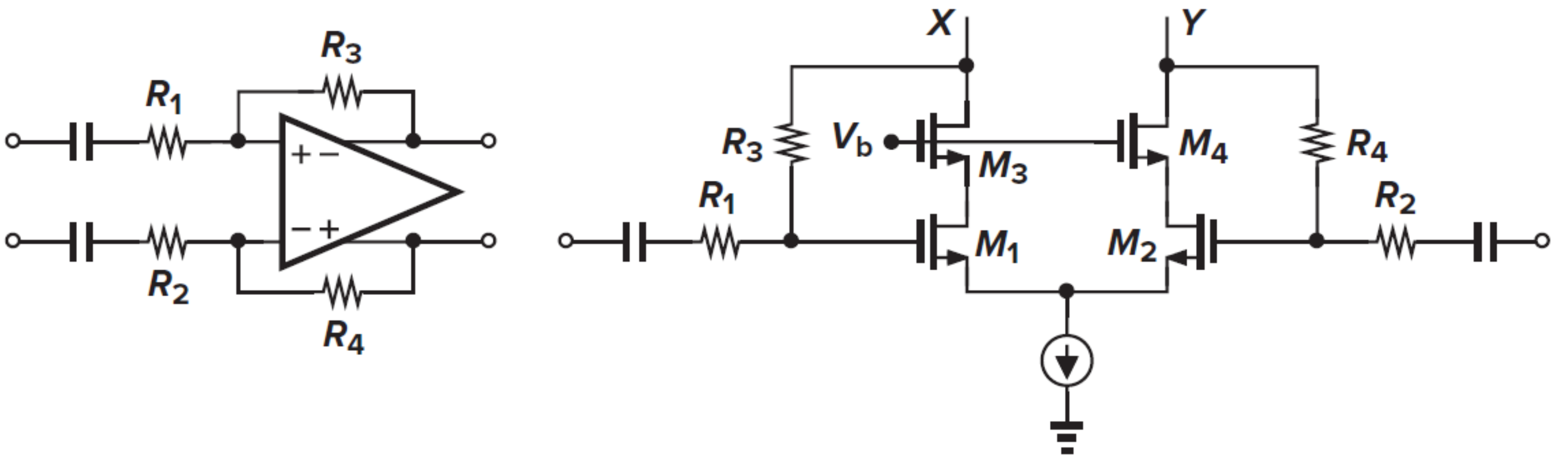
Telescopic Cascode Output Swing (CL)

- Input and output CM levels are equal (why?) → Same as buffer
- Input swing is negligible (why?)



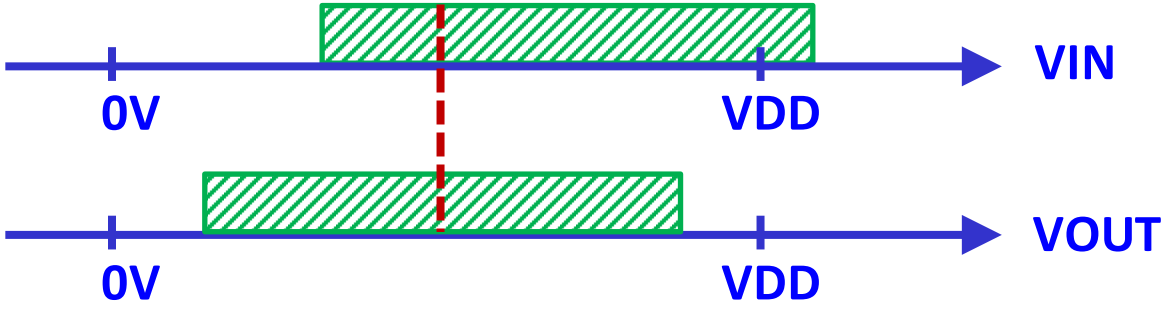
- Set CM level at its max value w.r.t. V_{in}: $V_{CM} = V_b - V_3^*$
- Max Diff Swing $= 2 \times 2 \times (V_T - V_3^*) = 0.8V$



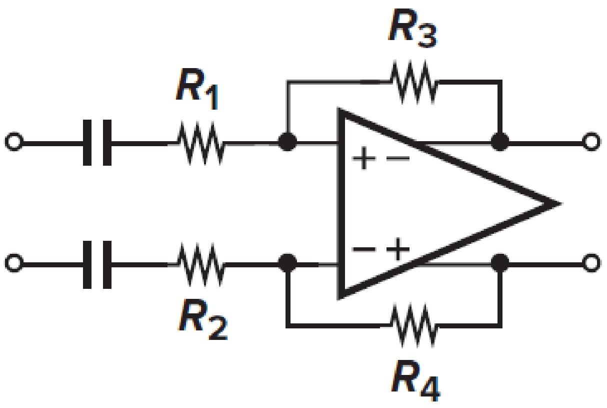
[Razavi, 2017]

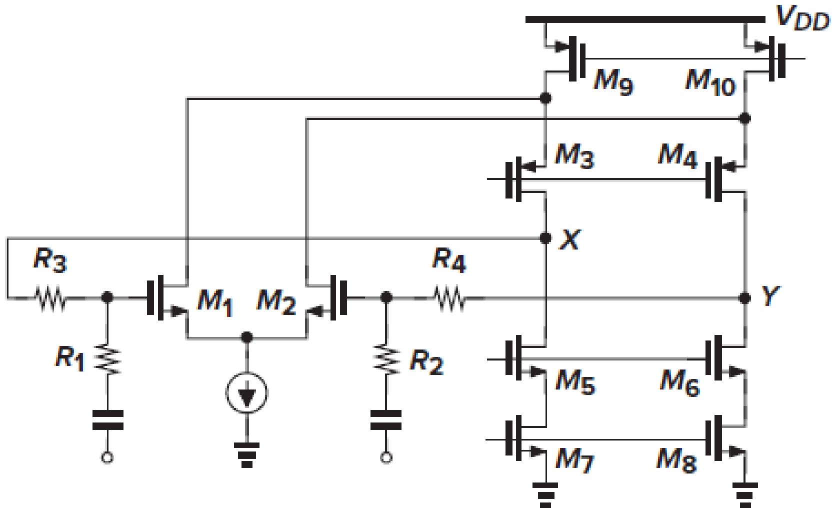
Folded Cascode Output Swing (CL)

- Input and output CM levels are equal (why?) → Same as buffer
- Input swing is negligible (why?)



- V_{in} and V_{out} ranges NOT oppositely coupled → Set CM to $V_{DD}/2$
- Max Diff Swing = $2(V_{DD} - 4V^*) = 1.6V$





[Razavi, 2017]

Thank you!

References

- B. Razavi, “Design of Analog CMOS Integrated Circuits,” McGraw-Hill, 2nd ed., 2017.
- T. C. Carusone, D. Johns, and K. W. Martin, “Analog Integrated Circuit Design,” 2nd ed., Wiley, 2012.
- B. Murmann, EE214 Course Reader, Stanford University.

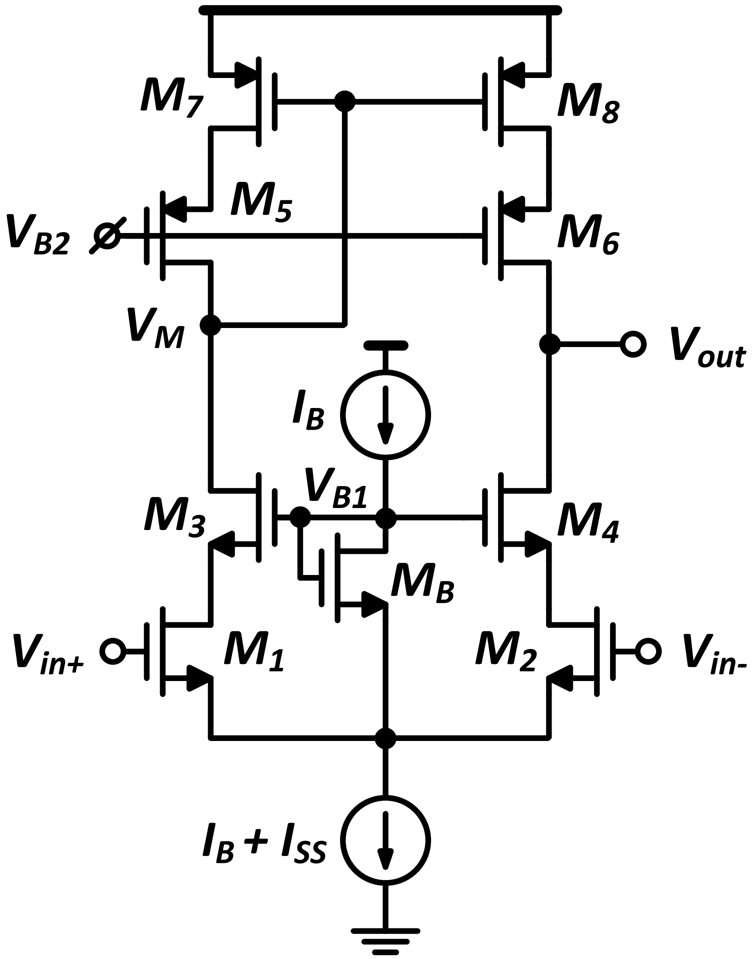
SE 5T OTA Trade-offs Matrix

- **Note**: In simulations and interviews, you will usually encounter the case of constant W rather than constant gm/ID

Spec	I_{SS}	L_{12}	$\left(\frac{g_m}{I_D}\right)_{12}$	L_{34}	$\left(\frac{g_m}{I_D}\right)_{34}$	L_5	$\left(\frac{g_m}{I_D}\right)_5$
DC gain ↑							
GBW ↑							
Thermal Noise ↓							
Flicker Noise ↓							
PM ↑							
C_{in} ↓ (Fanout ↑)							
Output swing							
CMRR @DC ↑							

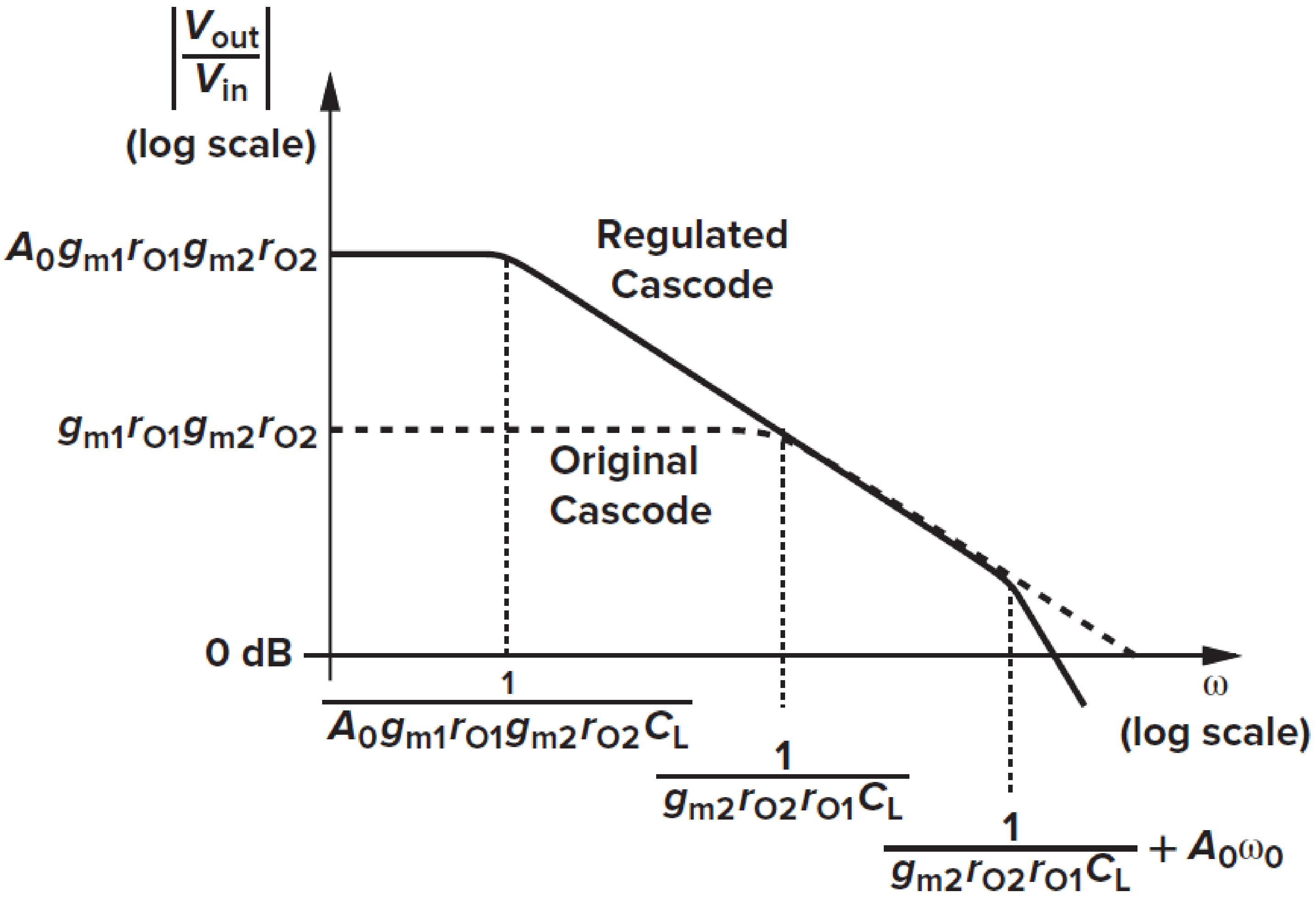
Clever Telescopic Cascode Biasing

- V_{B1} tracks V_{inCM}
- V_{in} OL: $V_T + V_{ov1,2} + V_{ISS} < V_{in} < \boldsymbol{V_{B1}} - V_{ov3,4}$
- V_{out} OL: $\boldsymbol{V_{B1}} - V_T < V_{out} < V_{B2} + V_T$
- Set $V_{B1} \geq V_{in,CM} + V_{ov3} \rightarrow \quad V_{ovB} \geq V_{ov1,2} + V_{ov3,4}$
- Input/output ranges extended



Gain-Boosted OTA Frequency Response

- See [Razavi, 2017] Section 9.4.3



[Razavi, 2017]