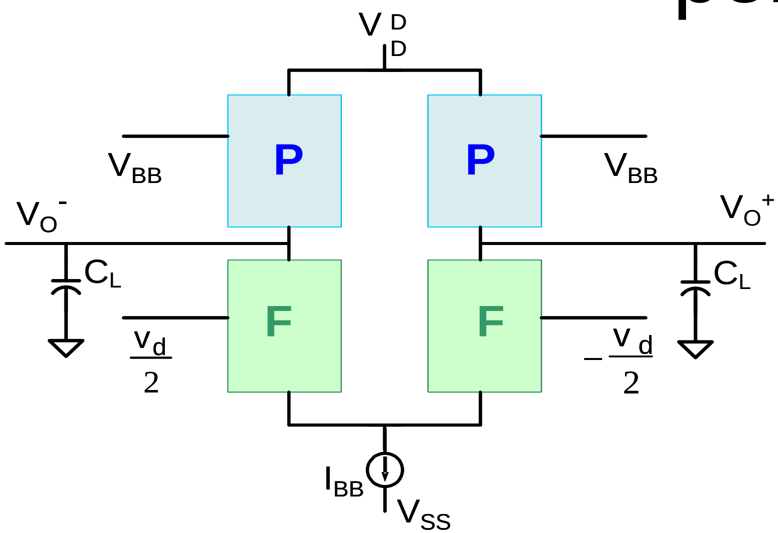
EE 435

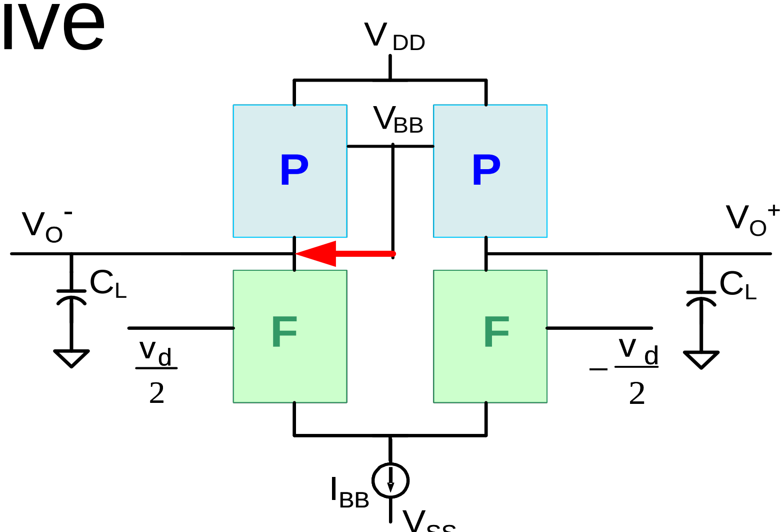
Lecture 6:

- Signal Swing
- Measurement/Simulation of High Gain Circuits
- Offset Voltage
- High Gain Single-Stage Op Amps

Review from last lecture:

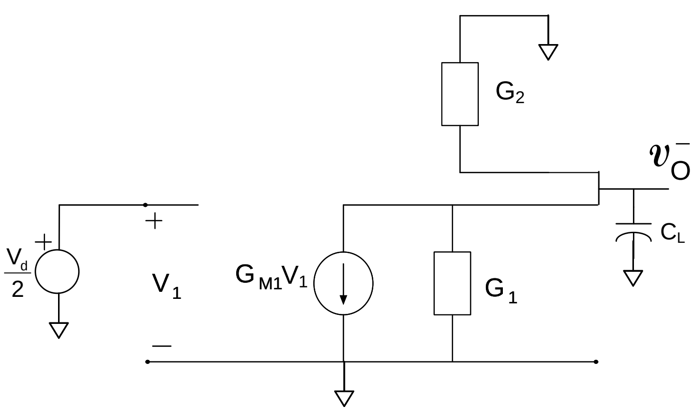
Operation of Op Amp – A different perspective





If the input impedance to the counterpart circuit is infinite and the quiescent values of the left and right drain voltages are the same, connecting the bias port of the quarter circuit to V_0^- instead of to V_{BB} will cause the signal current in the right counterpart circuit to be equal to that in the left counterpart circuit

Small signal differential half-circuit



This will double the signal current steered to V_o^+ and thus double the voltage gain !

This will also eliminate the need for a CMFB circuit !

Review from last lecture:

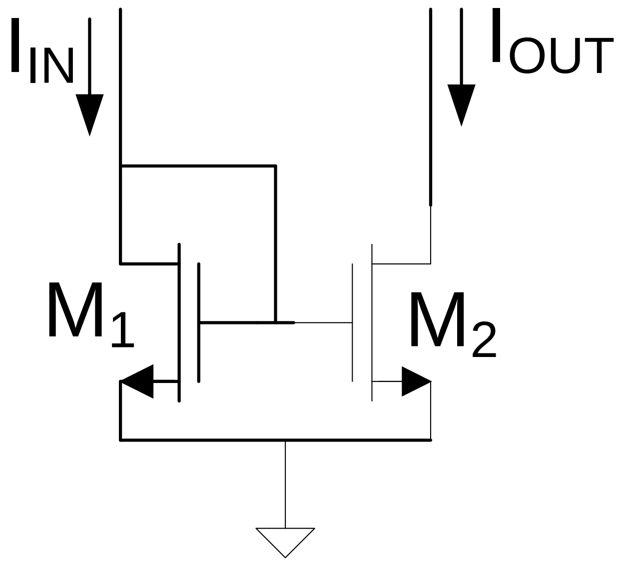
Amplifier Comparison

Small Signal Parameter Domain			
Reference Op Amp (single-ended ouput) (5T Op Amp)	$A_{VO}=\frac{1}{2}\frac{g_{m1}}{g_{O1}+g_{O3}}$	$GB=\frac{g_{m1}}{2C_L}$	$SR=\frac{g_{01}}{\lambda C_L}$
Practical Parameter Domain			
Reference Op Amp (single-ended ouput) (5T Op Amp)	$A_{V0}=\left[\frac{1}{\lambda_1+\lambda_3}\right]\left(\frac{1}{V_{EB1}}\right)$	$GB=\left(\frac{P}{2V_{DD}C_L}\right)\bullet\left[\frac{1}{V_{EB1}}\right]$	$\mathbf{SR}=\frac{\mathbf{P}}{\mathbf{2V_{DD}C_L}}$

Small Signal Parameter Domain			
Op Amp with CM Load and M_1 QC (5T Op Amp wCM)	$A_{VO}=\frac{g_{m1}}{g_{O1}+g_{O3}}$	$GB=\frac{g_{m1}}{C_L}$	$SR=2\frac{g_{01}}{\lambda C_L}$
Practical Parameter Domain			
Op Amp with CM Load and M_1 QC (5T Op Amp wCM)	$A_{V0}=\left[\frac{2}{\lambda_1+\lambda_3}\right]\left(\frac{1}{V_{EB1}}\right)$	$GB=\left(\frac{P}{V_{DD}C_L}\right)\bullet\left[\frac{1}{V_{EB1}}\right]$	$SR=\frac{P}{V_{DD}C_L}$

Review from last lecture:

Basic Current Mirror



n-channel

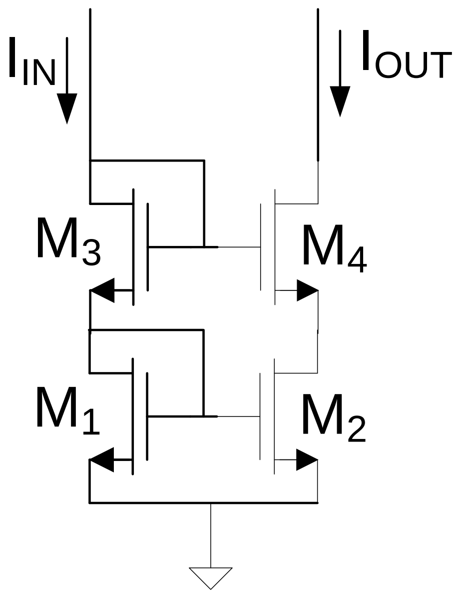
$$I_{IN}=\frac{\mu C_{OX}W_1}{2L_1}\left(V_{GS1}-V_T\right)^2$$

$$I_{OUT}=\frac{\mu C_{OX}W_2}{2L_2}\left(V_{GS2}-V_T\right)^2$$

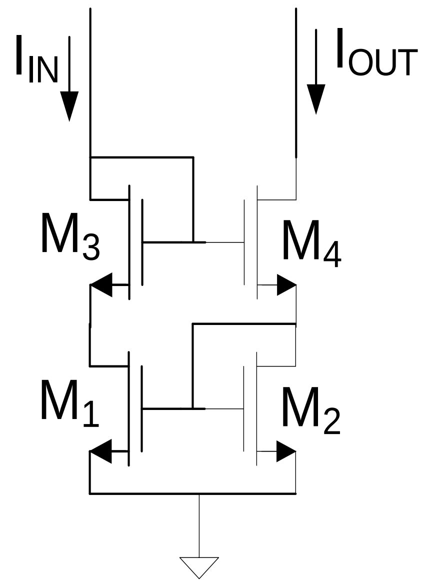
$$\frac{I_{OUT}}{I_{IN}}=\frac{W_2}{W_1}\frac{L_1}{L_2}$$

Review from last lecture:

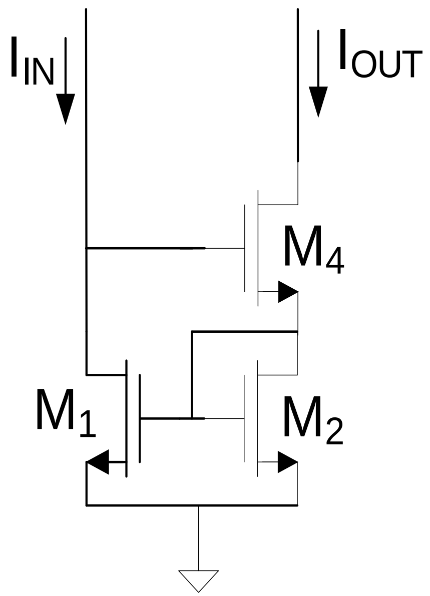
More Advanced Current Mirrors



Cascode Current Mirror



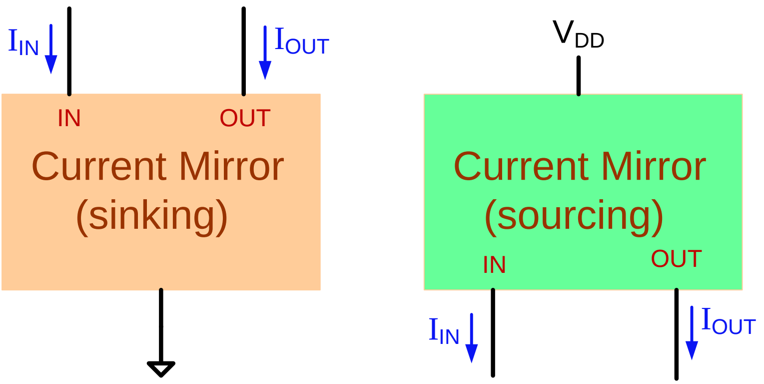
Modified Wilson Current Mirror



Wilson Current Mirror

Review from last lecture:

USPTO search on Feb 2, 2021



612 patents with “current and mirror” in title since 1976

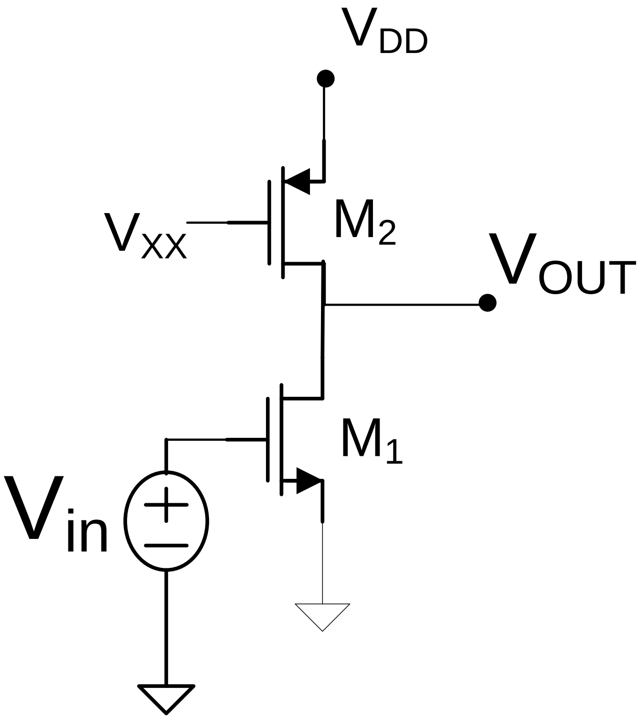
26 patents with “current and mirror” in title from 2018 and 2020 searches

Number of patents/decade is about at the 3-decade average

Is there still an opportunity to contribute to the current mirror field?

Signal Swing

Consider single-input amplifier first



To keep M_1 out of Triode Region

$\mathcal{L}_1$: $V_{OUT} > V_{iN} - V_{Tn}$

To keep M_1 out of Cutoff

$\mathcal{L}_2$: $V_{iN} > V_{Tn}$

To keep M_2 out of Triode Region

$\mathcal{L}_3$: $|V_{OUT} - V_{DD}| > |V_{XX} - V_{DD} - V_{Tp}|$

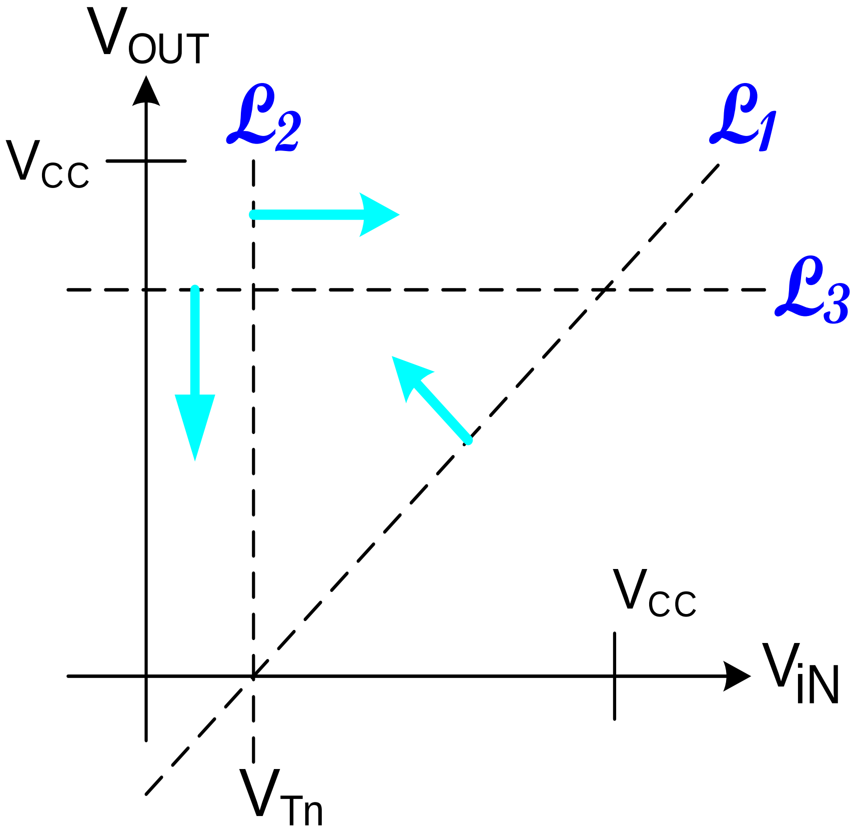
$$V_{XX} - V_{Tp} > V_{OUT}$$

Signal Swing

$\mathcal{L}_1$: $V_{OUT} > V_{iN} - V_{Tn}$

$\mathcal{L}_2$: $V_{iN} > V_{Tn}$

$\mathcal{L}_3$: $V_{XX} - V_{Tp} > V_{OUT}$

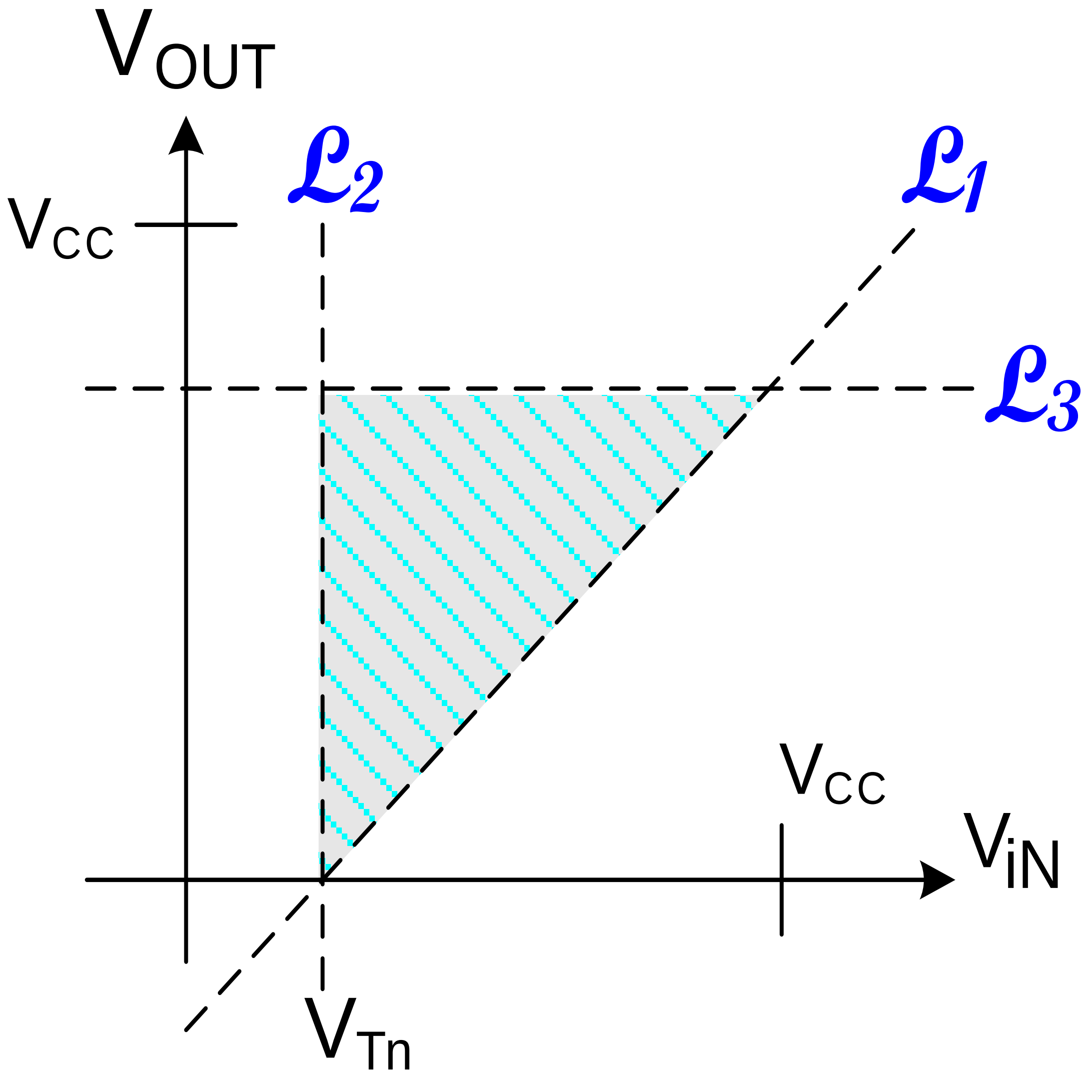


Signal Swing

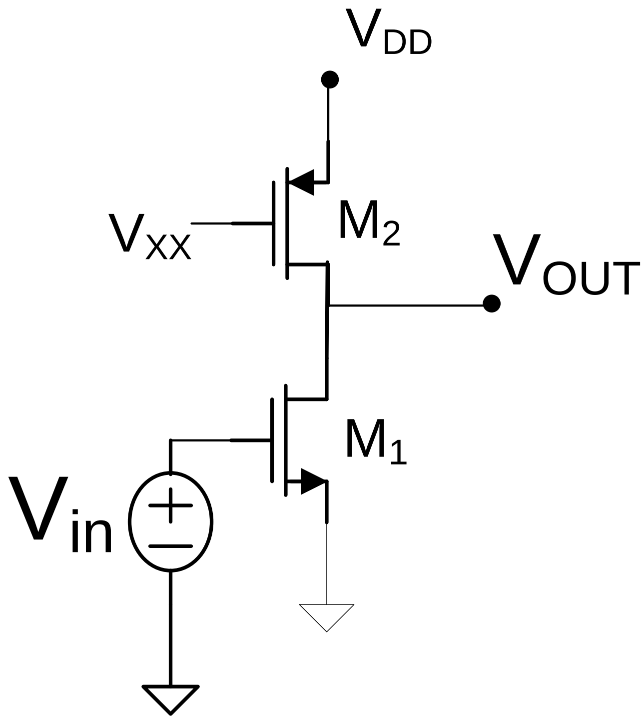
$\mathcal{L}_1$: $V_{OUT} > V_{iN} - V_{Tn}$

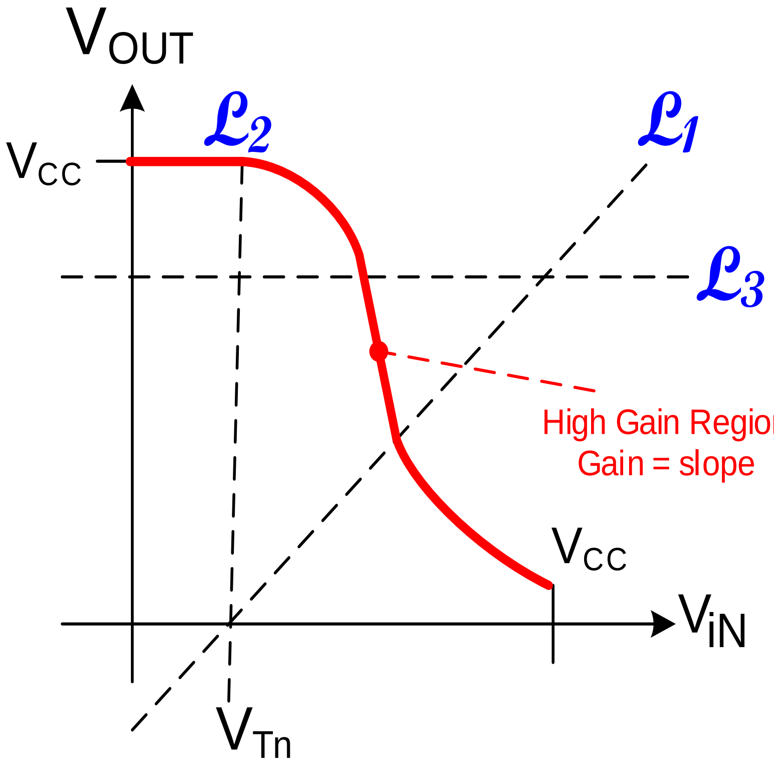
$\mathcal{L}_2$: $V_{iN} > V_{Tn}$

$\mathcal{L}_3$: $V_{XX} - V_{Tp} > V_{OUT}$



Signal Swing





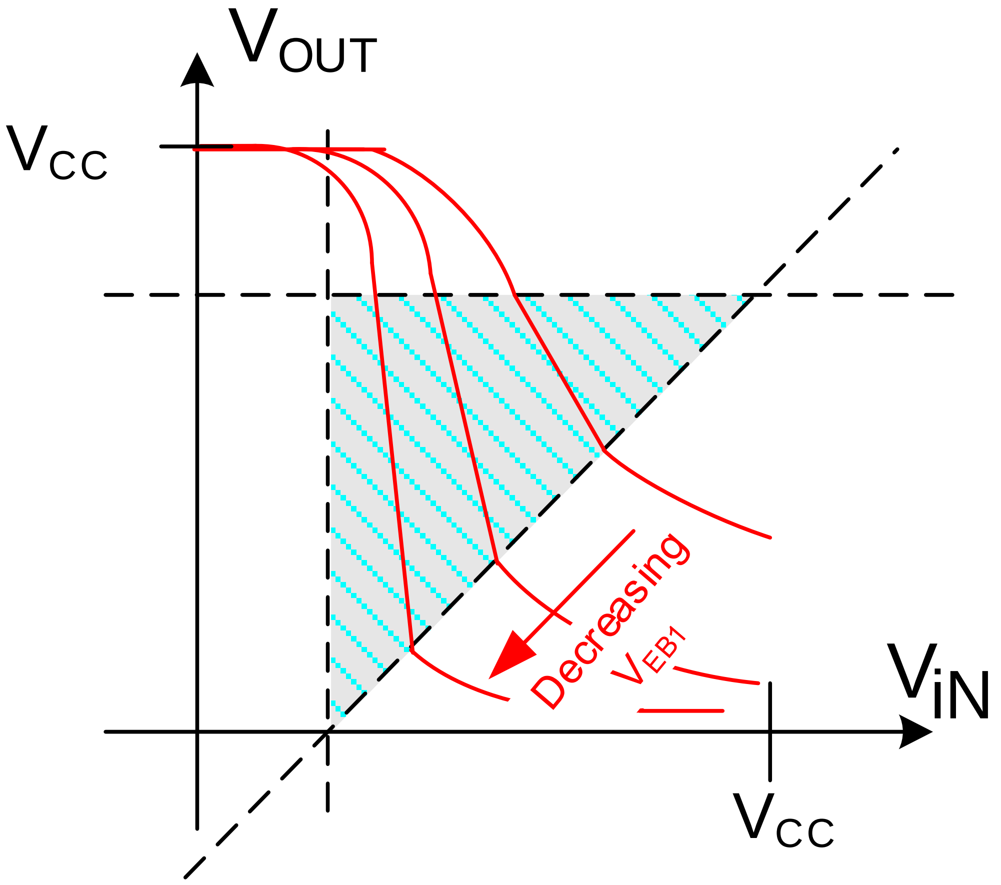
Transfer Characteristics of amplifier

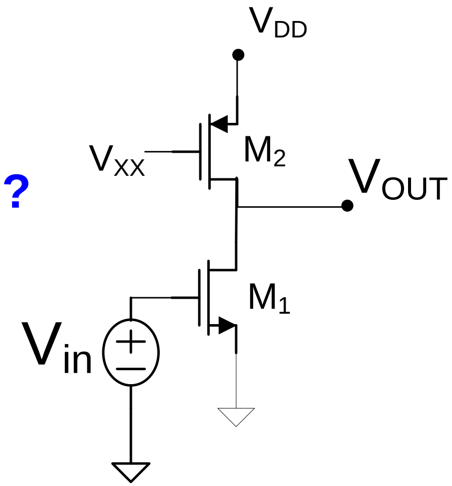
How do the transfer characteristics relate to the signal swing ?

Observe signal swing boundaries are same as operating region changes for transfer characteristics

Signal Swing

How do the transfer characteristics relate to the signal swing ?





For this circuit, high gain and large output signal swing for small V_{EB1}

Amplifier Comparison

Small Signal Parameter Domain			
Reference Op Amp (single-ended ouput) (5T Op Amp)	$A_{VO} = \frac{1}{2}\frac{g_{m1}}{g_{O1}+g_{O3}}$	$GB = \frac{g_{m1}}{2C_L}$	$SR = \frac{g_{01}}{\lambda C_L}$

Practical Parameter Domain			
Reference Op Amp (single-ended ouput) (5T Op Amp)	$A_{V0} = \left[\frac{1}{\lambda_1+\lambda_3}\right]\left(\frac{1}{V_{EB1}}\right.$		

Small Signa			
Op Amp with CM Load and M_1 QC (5T Op Amp wCM)	$A_{VO} = \frac{g_{m1}}{g_{O1}+g_{O3}}$		λC_L

Practical Parameter Domain			
Op Amp with CM Load and M_1 QC (5T Op Amp wCM)	$A_{V0} = \left[\frac{2}{\lambda_1+\lambda_3}\right]\left(\frac{1}{V_{EB1}}\right)$	$GB = \left(\frac{P}{V_{DD}C_L}\right)\bullet\left[\frac{1}{V_{EB1}}\right]$	$SR = \frac{P}{V_{DD}C_L}$

$$I_D = \frac{\mu C_{OX} W}{2L}\left(V_{GS}-V_{TH}\right)^2\left(1+\lambda V_{DS}\right)$$

$$g_0 = \lambda I_{DQ}$$

λ not a BSIM Parameter

Output Impedance Calculation

- g_o is a critical parameter that appears in the small-signal models of high-gain circuits

- With a square-law Spice Level 2 or Level 3 model of the transistor,

$$I_D = \frac{\mu C_{OX} W}{2L} \left(V_{GS} - V_{TH}\right)^2 \left(1 + \lambda V_{DS}\right)$$

$$g_0 = \left.\frac{\partial I_D}{\partial V_{DS}}\right|_{Q-PT} = \left.\left(\frac{\mu C_{OX} W}{2L} \left(V_{GS} - V_{TH}\right)^2 \lambda\right)\right|_{Q-PT} \simeq \lambda I_{DQ}$$

- But λ is not a parameter in a BSIM model and λ is often not even given in measured data such as that from MOSIS

- And $g_0 = \left.\frac{\partial I_D}{\partial V_{DS}}\right|_{Q-PT}$ depends somewhat on L

Output Impedance Calculation

How to obtain g_0

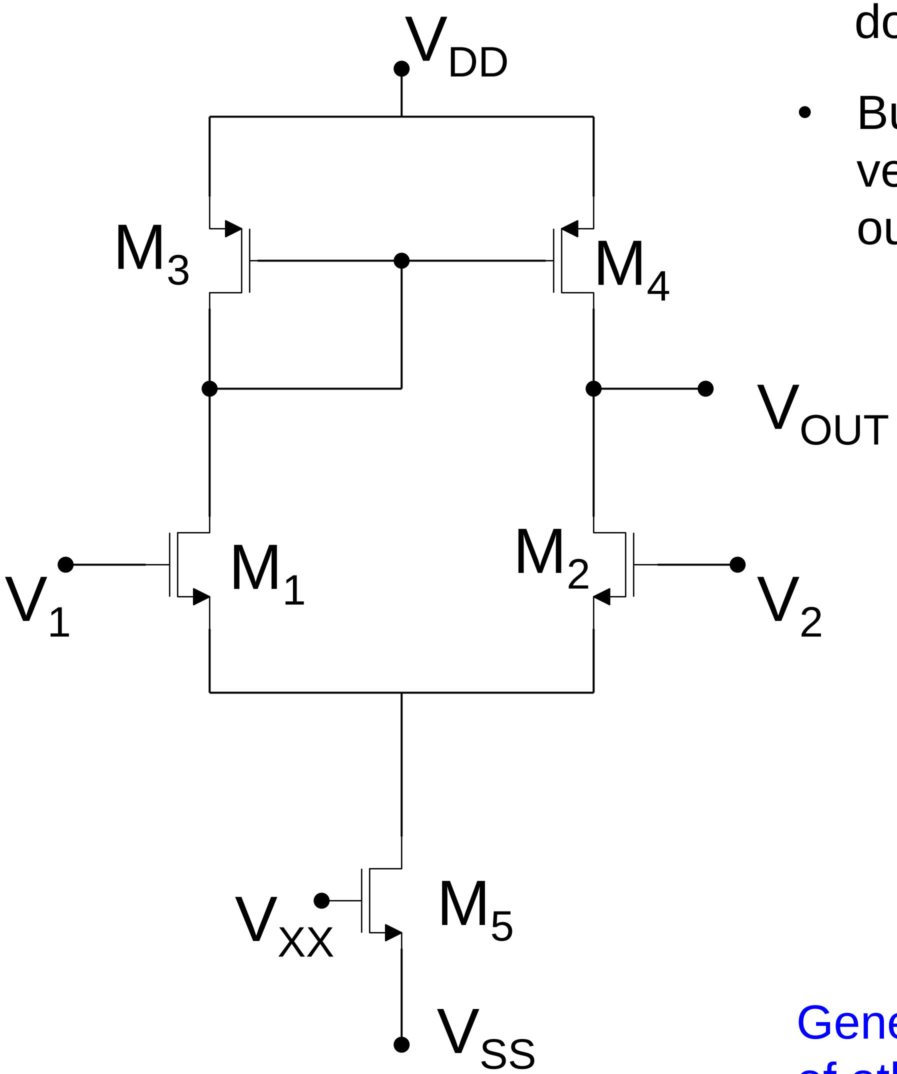
- Simulate single-transistor circuit with dimensions and operating point close to that of device used and obtain $g_0 = \left.\frac{\partial I_D}{\partial V_{DS}}\right|_{Q-PT}$

- If desired, define $\lambda \simeq \frac{\left.\frac{\partial I_D}{\partial V_{DS}}\right|_{Q-PT}}{I_{DQ}}$ (though actually g_0 is what is needed to obtain small-signal gain)

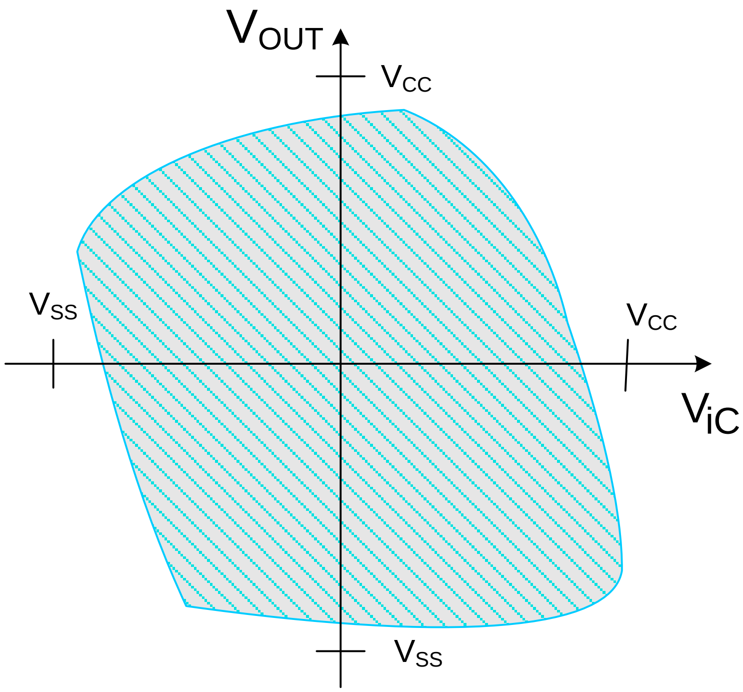
- Make a table of g_0 (or λ) for different L values in a given process

- g_0 is, however, still a model parameter

Signal Swing of Single-Stage Op Amp



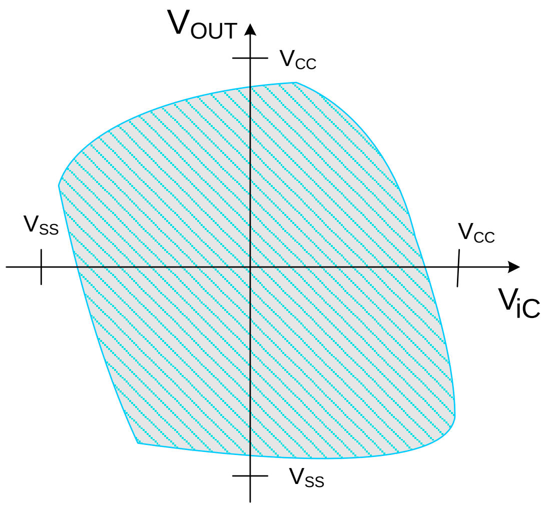
- Interested in region in $\{V_{iC}, V_d, V_{OUT}\}$ domain where op amp operates
- But for high-gain amplifiers, V_d is inherently very small so are only concerned about output signal swing vs V_{iC}



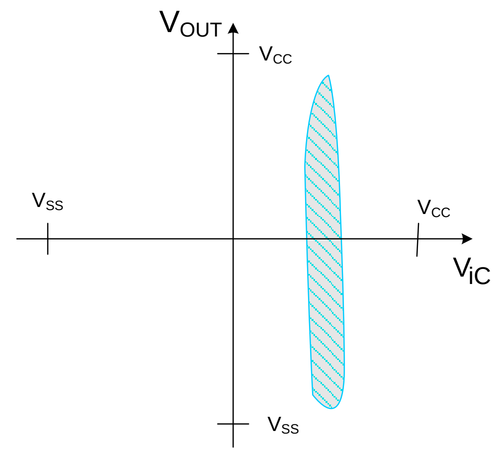
Generally large swings come at expense of other desirable characteristics

Signal Swing of Single-Stage Op Amp

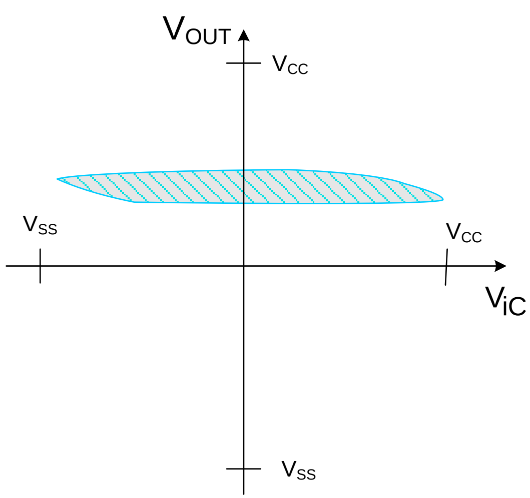
What type of signal swing is needed ?



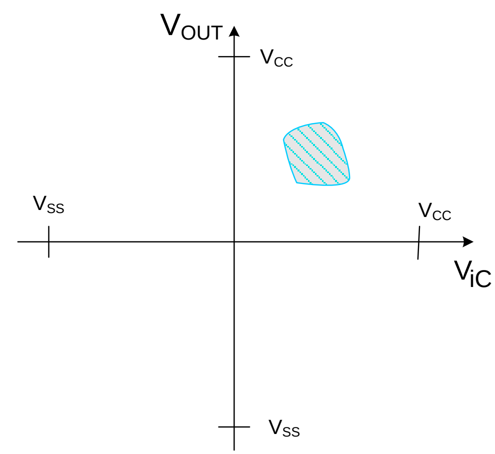
Wide V_{iC} and V_{OUT} range



Narrow V_{iC} and wide V_{OUT} range



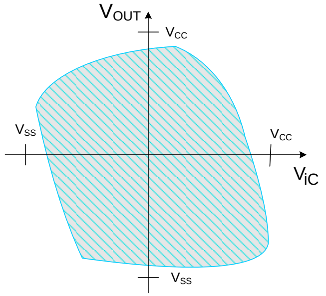
Narrow V_{OUT} and wide V_{iC} range



Narrow V_{iC} and V_{OUT} range

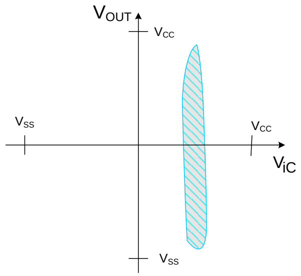
Signal Swing of Single-Stage Op Amp

What type of signal swing is needed ?



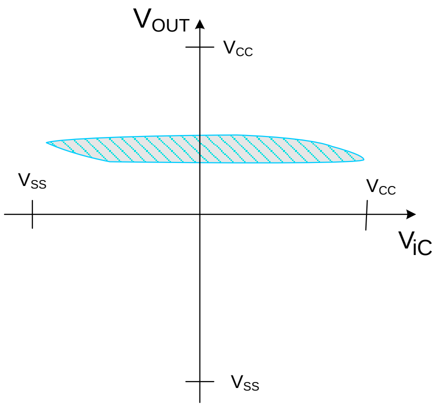
Wide V_{iC} and V_{OUT} range

Expected for catalog parts and overall I/O in many applications



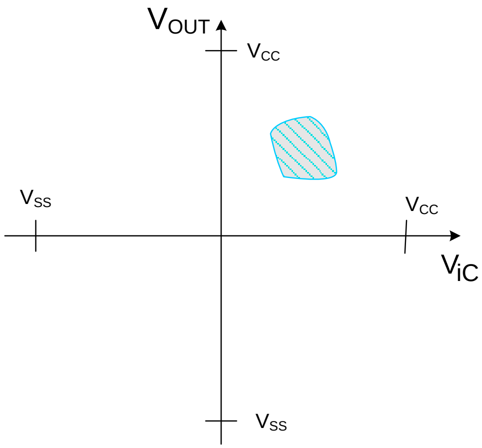
Narrow V_{iC} and wide V_{OUT} range

Acceptable when ViC is fixed



Narrow V_{OUT} and wide V_{iC} range

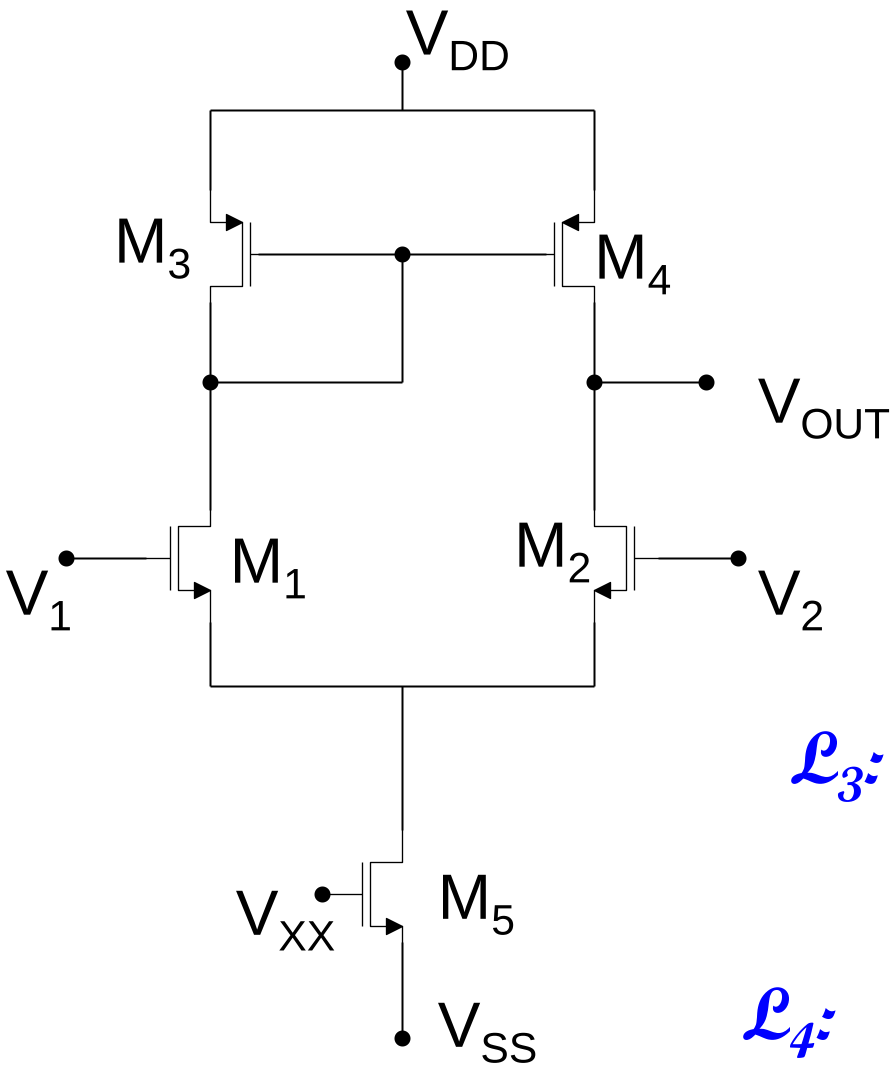
Acceptable when followed by high-gain stage



Narrow V_{iC} and V_{OUT} range

Acceptable when V_{iC} fixed and followed by high-gain stage

Signal Swing of Single-Stage 5T Op Amp



Constraining Equations:

To keep M_2 in Saturation:

$\mathcal{L}_1$: $$V_{OUT} > V_{ic} - V_{T2}$$

To keep M_4 in Saturation:

$\mathcal{L}_2$: $$V_{OUT} < V_{DD} - |V_{EB4}|$$

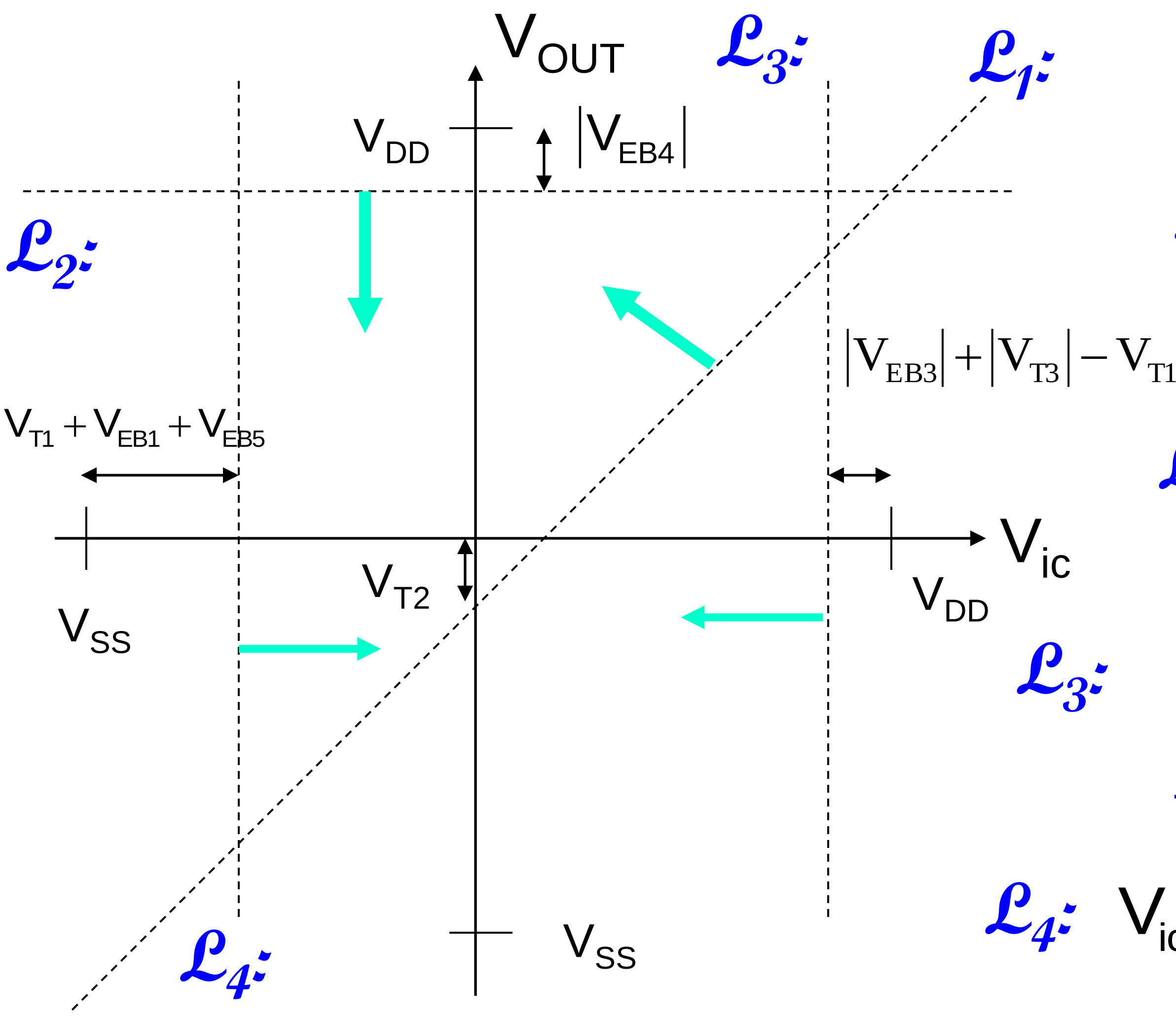
To keep M_1 in Saturation:

$\mathcal{L}_3$: $$V_{iC} < V_{DD} + V_{T1} - |V_{T3}| - |V_{EB3}|$$

To keep M_5 in Saturation:

$\mathcal{L}_4$: $$V_{ic} > V_{T1} + V_{EB1} + V_{EB5} + V_{SS}$$

Signal Swing of Single-Stage 5T Op Amp



To keep M_2 in Saturation:

$\mathcal{L}_1$: $V_{OUT} > V_{ic} - V_{T2}$

To keep M_4 in Saturation:

$\mathcal{L}_2$: $V_{OUT} < V_{DD} - |V_{EB4}|$

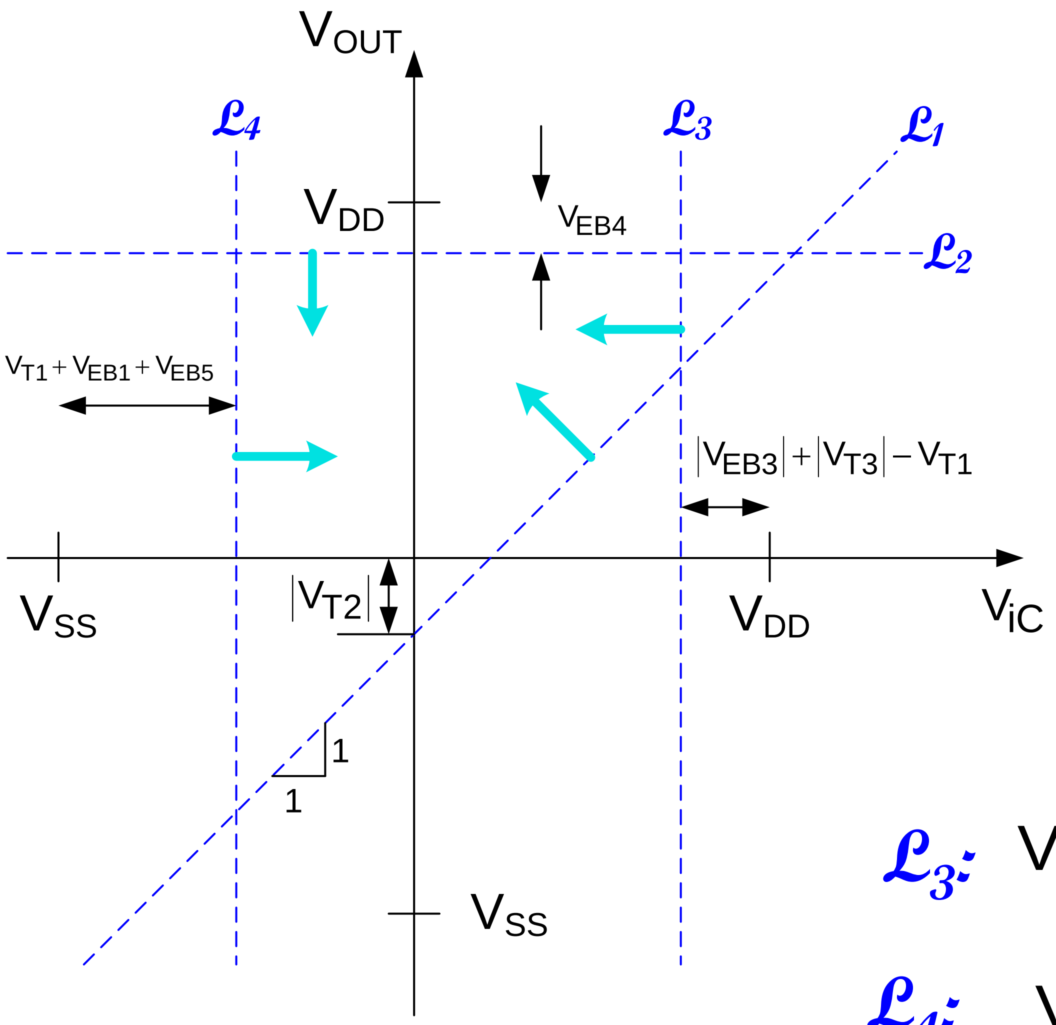
To keep M_1 in Saturation:

$\mathcal{L}_3$: $V_{iC} < V_{DD} + V_{T1} - |V_{T3}| - |V_{EB3}$

To keep M_5 in Saturation:

$\mathcal{L}_4$: $V_{ic} > V_{T1} + V_{EB1} + V_{EB5} + V_{SS}$

Signal Swing of Single-Stage 5T Op Amp



Constraining Equations:

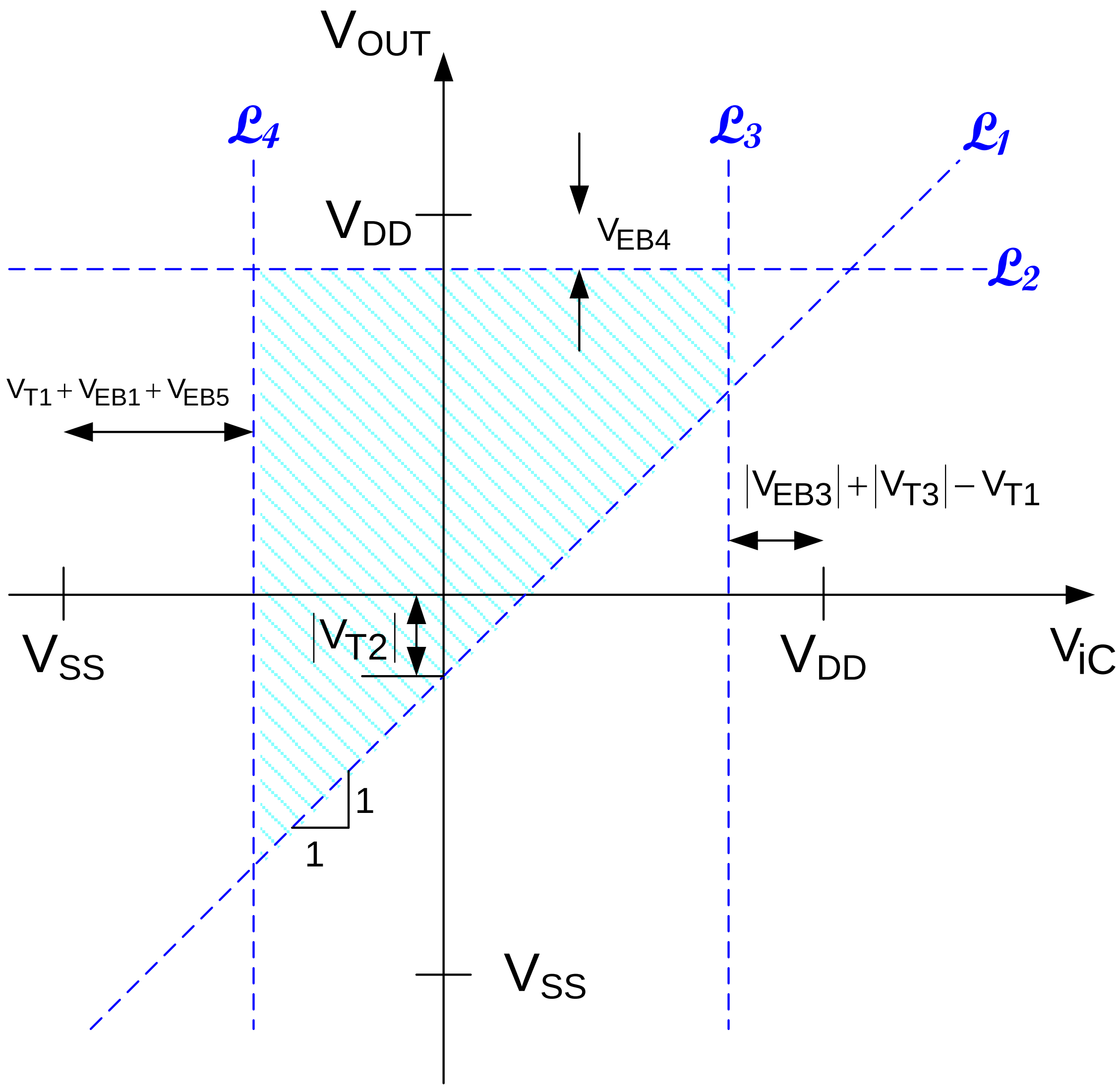
ℒ1: $V_{OUT} > V_{ic} - V_{T2}$

ℒ2: $V_{OUT} < V_{DD} - |V_{EB4}|$

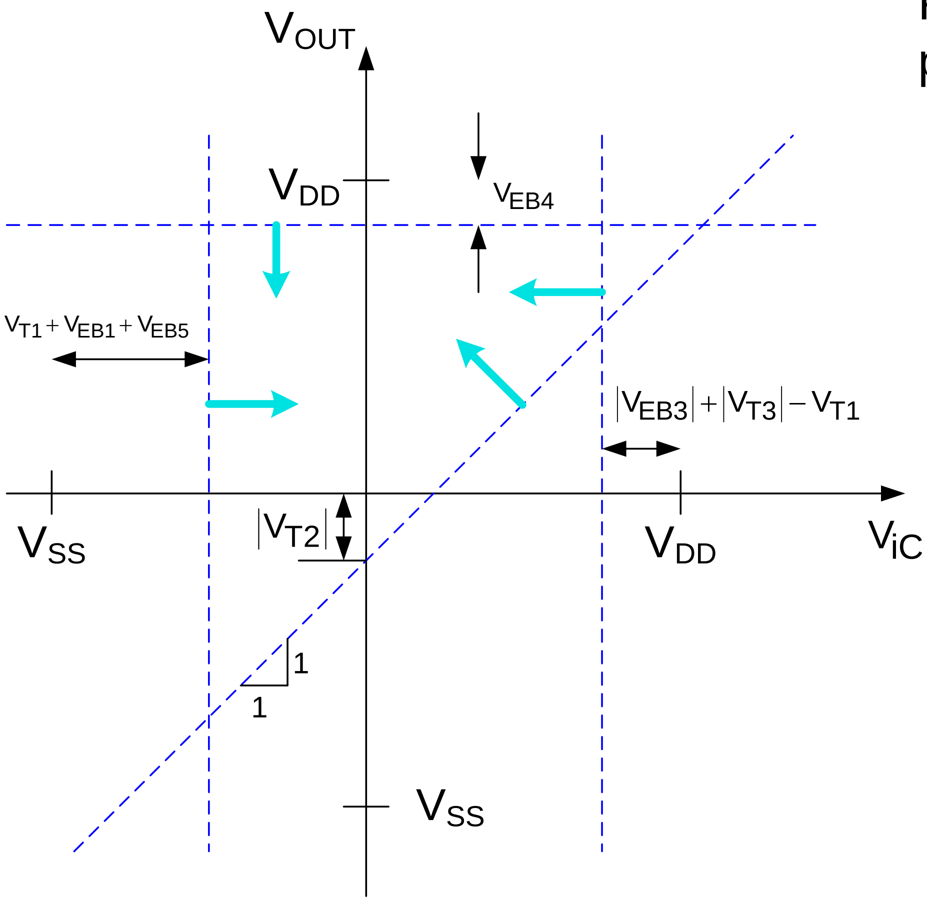
ℒ3: $V_{iC} < V_{DD} + V_{T1} - |V_{T3}| - |V_{EB3}|$

ℒ4: $V_{ic} > V_{T1} + V_{EB1} + V_{EB5} + V_{SS}$

Signal Swing of Single-Stage 5T Op Amp



Signal Swing of Single-Stage Op Amp



Preemptive comment: practical parameter domain for 5T Op Amp

$\{V_{EB1}\ V_{EB3}\ V_{EB5}\ \ P\}$

Constraining Equations:

$$V_{OUT} > V_{ic} - V_{T2}$$

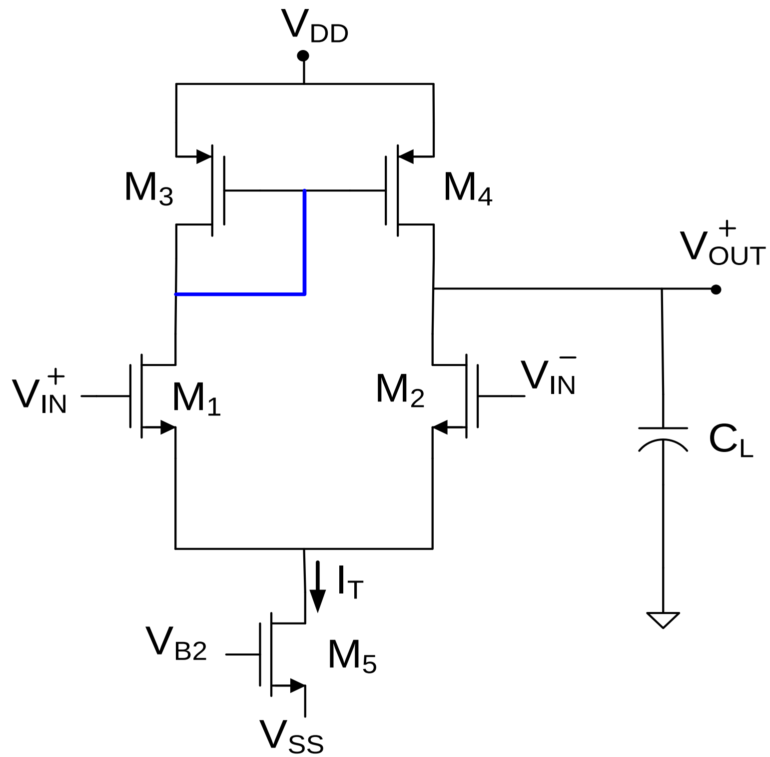
$$V_{OUT} < V_{DD} - |V_{EB4}|$$

$$V_{iC} < V_{DD} + V_{T1} - |V_{T3}| - |V_{EB3}|$$

$$V_{ic} > V_{T1} + V_{EB1} + V_{EB5} + V_{SS}$$

- Signal swings are Important Performance Parameters !!
- Signal swing parameters are naturally in practical parameter domain
- Since $V_{EB3}=V_{EB4}$, small V_{EB3} improves both output swing and V_{iC} swing

Design space for single-stage CM 5T op amp



How many independent design variables and how many constraints does this circuit have (assuming symmetry)?

Assume V_{SS}, V_{DD}, and C_L fixed

Small-signal domain?

$\{g_{m1}, g_{m3}, g_{m5}, g_{01}, g_{03}, g_{05}\}$

(not independent)

Natural parameter domain?

$\{W_3/L_3, W_1/L_1, W_5/L_5, I_T\}$

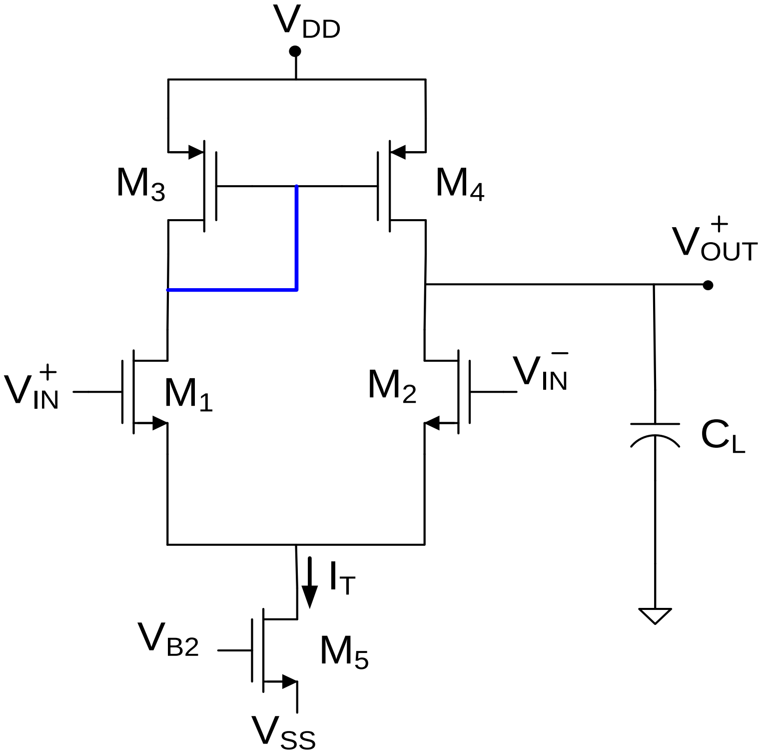
No constraints

A practical parameter domain?

$\{ V_{EB1}\ V_{EB3}\ V_{EB5}\ \ P\}$

No constraints

Design space for single-stage CM 5T op amp



Performance Parameters in Practical Parameter Domain $\{V_{EB1}\ V_{EB3}\ V_{EB5}\ P\}$:

$$A_0 = \left[\frac{1}{\lambda_1 + \lambda_3}\right]\left(\frac{2}{V_{EB1}}\right)$$

$$GB = \left(\frac{P}{V_{DD} C_L}\right)\left[\frac{1}{V_{EB1}}\right]$$

$$SR = \frac{P}{(V_{DD} - V_{SS}) C_L}$$

$$V_{OUT} < V_{DD} - |V_{EB3}|$$

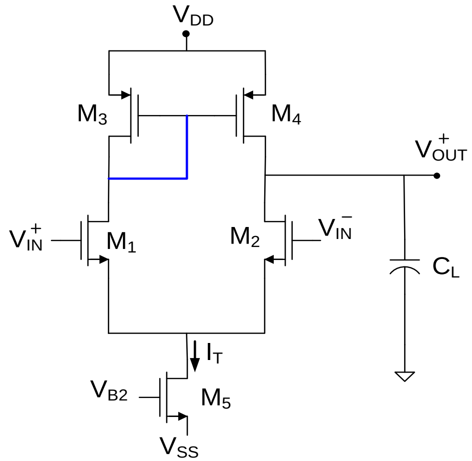
$$V_{OUT} > V_{ic} - V_{T2}$$

$$V_{iC} < V_{DD} + V_{T1} - |V_{T3}| - |V_{EB3}|$$

$$V_{ic} > V_{T1} + V_{EB1} + V_{EB5} + V_{SS}$$

Simple Expressions (7) in Practical Parameter Domain

Design example for single-stage CM 5T op amp



Performance Parameters in Practical Parameter Domain $\{V_{EB1}\ V_{EB3}\ V_{EB5}\ \ P\}$:

$$A_0 = \left[\frac{1}{\lambda_1+\lambda_3}\right]\left(\frac{2}{V_{EB1}}\right)$$

$$GB = \left(\frac{P}{V_{DD}C_L}\right)\left[\frac{1}{V_{EB1}}\right]$$

$$SR = \frac{P}{(V_{DD}-V_{SS})C_L}$$

$$V_{OUT} < V_{DD} - |V_{EB3}|$$

$$V_{OUT} > V_{ic} - V_{T2}$$

$$V_{iC} < V_{DD} + V_{T1} - |V_{T3}| - |V_{EB3}|$$

$$V_{ic} > V_{T1} + V_{EB1} + V_{EB5} + V_{SS}$$

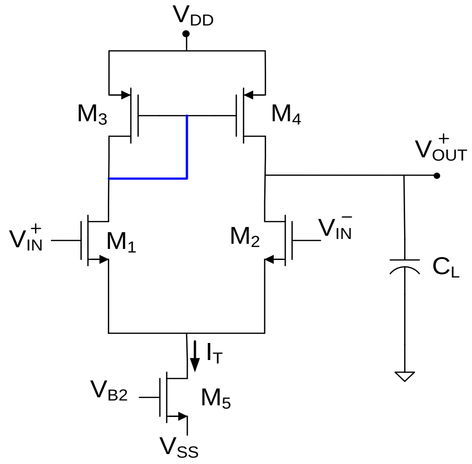
Assume design to meet A_0, GB and signal swing specs.

1. Select Parameter Domain (will use practical parameter domain)
   $\{V_{EB1}\ V_{EB3}\ V_{EB5}\ \ P\}$
2. Pick V_{EB1} to meet gain requirement) $\{$ ~~V_{EB1}~~ $V_{EB3}\ V_{EB5}\ \ P\}$

$$V_{EB1} = \left[\frac{1}{\lambda_1+\lambda_3}\right]\left(\frac{2}{A_0}\right)$$

3. Pick P to meet GB requirement $\{$ ~~V_{EB1}~~ $V_{EB3}\ V_{EB5}$ ~~P~~ $\}$
4. Pick V_{EB3} and V_{EB5} to meet signal swing requirements
5. Map back from the Practical Parameter Domain to the Natural Parameter domain (next page)

Design example for single-stage CM 5T op amp



Performance Parameters in Practical Parameter Domain { V_{EB1} V_{EB3} V_{EB5} P}:

Mapping from Practical Parameter Domain { V_{EB1} V_{EB3} V_{EB5} P} to Natural Parameter Domain { W_1/L_1 W_3/L_3 W_5/L_5 I_T}

From expression $I_{Dk} = \frac{\mu_k C_{ox} W_k}{2L_k} V_{EBk}^2$ it follows that

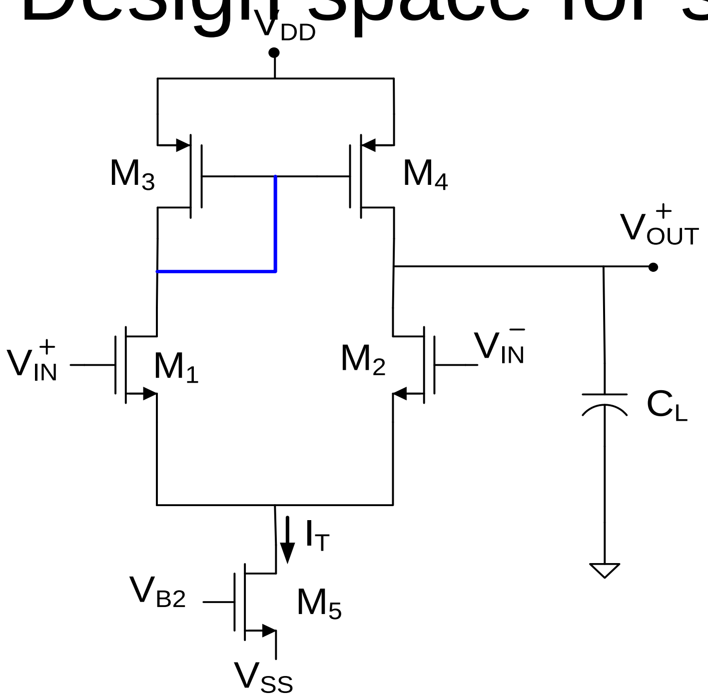
$$\frac{W_1}{L_1} = \frac{1}{\mu_n C_{OX} V_{EB1}^2} \frac{P}{V_{DD} - V_{SS}}$$

$$\frac{W_3}{L_3} = \frac{1}{\mu_p C_{OX} V_{EB3}^2} \frac{P}{V_{DD} - V_{SS}}$$

$$\frac{W_5}{L_5} = \frac{2}{\mu_n C_{OX} V_{EB5}^2} \frac{P}{V_{DD} - V_{SS}}$$

$$I_T = \frac{P}{V_{DD} - V_{SS}} \quad \text{or} \quad V_{B2} = V_{EB5} + V_{ss} + V_{THn}$$

Design space for single-stage CM 5T op amp



Performance Parameters in Natural Parameter Domain $\{ W_1/L_1 \;\; W_3/L_3 \;\; W_5/L_5 \;\; I_T \}$:

$$A_{V0} = \left[\frac{\sqrt{4\mu_n C_{OX}}}{\lambda_1 + \lambda_3} \right] \left(\frac{\sqrt{\frac{W_1}{L_1}}}{\sqrt{I_T}} \right)$$

$$SR = \frac{I_T}{C_L}$$

$$GB = \left[\frac{\sqrt{\mu_n C_{OX}}}{C_L} \right] \sqrt{\frac{W_1}{L_1}} \sqrt{I_T}$$

$$V_{iC} < V_{DD} + V_{T1} - |V_{T3}| - \frac{\sqrt{I_T}}{\sqrt{\mu_p C_{OX}} \sqrt{\frac{W_3}{L_3}}}$$

$$V_{OUT} < V_{DD} - \frac{\sqrt{I_T}}{\sqrt{\mu_p C_{OX}} \sqrt{\frac{W_3}{L_3}}}$$

$$V_{ic} > V_{T1} + \frac{\sqrt{I_T}}{\sqrt{\mu_n C_{OX}} \sqrt{\frac{W_1}{L_1}}} + \frac{\sqrt{I_T}}{\sqrt{\mu_n C_{OX}} \sqrt{\frac{W_5}{L_5}}} + V_{SS}$$

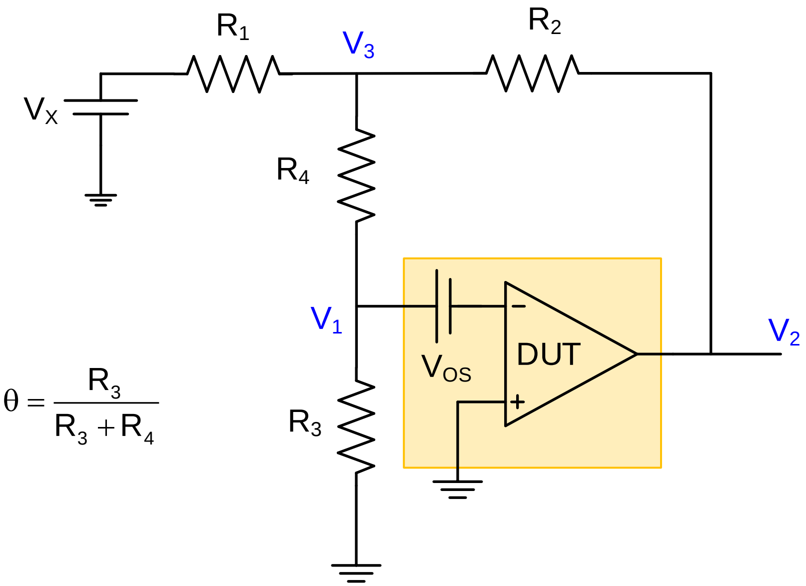
$$V_{OUT} > V_{ic} - V_{T2}$$

Complicated Expressions (7) in Practical Parameter Domain

Measurement and Simulation of Op Amps

- Measurement of A_V is challenging
  - Because it is so large
  - Even harder as A_{V0} becomes larger
  - Offset voltage causes a problem
  - Embed in Feedback Network to Stabilize Operating Point
    - Stability must be managed (for 2 or more gain stages)
    - Use time varying input to distinguish signal information from offset
    - Must be well below first pole frequency to measure A_{v0}
  - Measurement challenges often parallel simulation challenges
- Measurement of GB by indirect closed loop BW measurement is easy
- Measurement of R_0 is challenging
  - Often very small
  - Often challenging to avoid having measurement circuit cause output current to exceed I_{OMAX}

Measurement and Simulation of Op Amps



$$\theta = \frac{R_3}{R_3 + R_4}$$

Consider two inputs, V_{X1} and V_{X2}

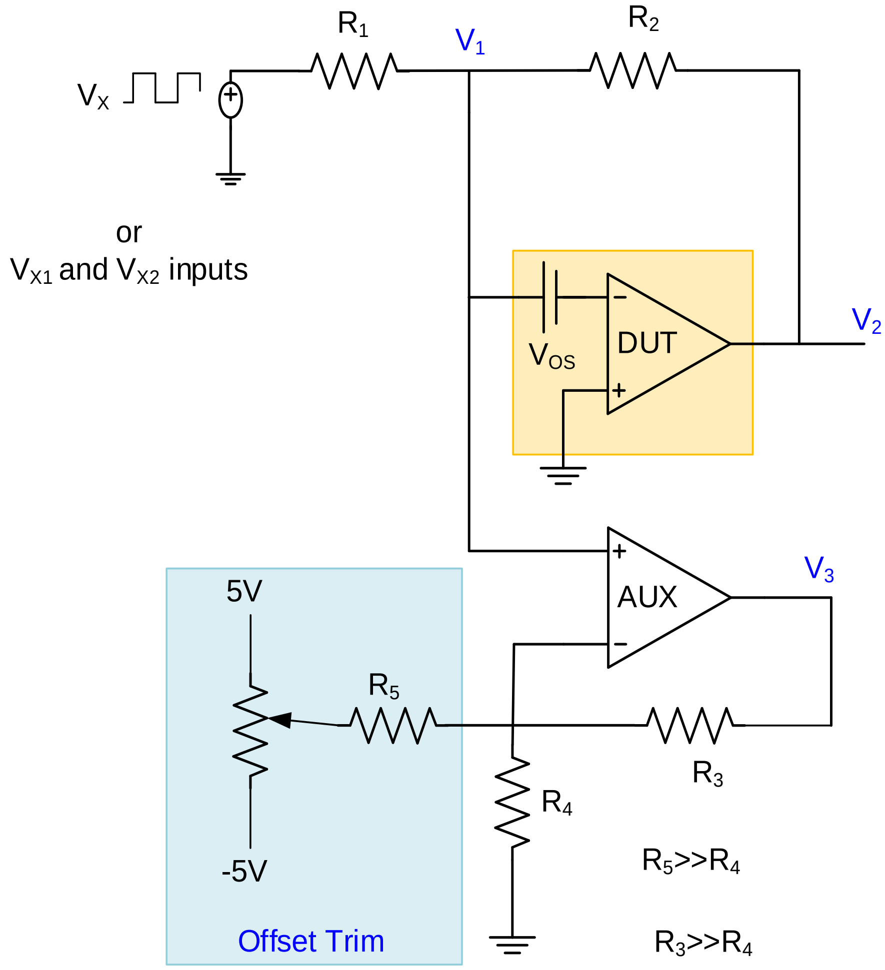
$$V_{21} = -A\left(\theta V_{31} - V_{OS}\right)$$
$$V_{22} = -A\left(\theta V_{32} - V_{OS}\right)$$
$$V_{31}\left(G_1 + G_2 + G_4\right) = G_1 V_{X1} + G_2 V_{21}$$
$$V_{32}\left(G_1 + G_2 + G_4\right) = G_1 V_{X2} + G_2 V_{22}$$

$$A = \frac{1}{\theta}\frac{V_{22} - V_{21}}{V_{31} - V_{32}}$$

$$V_{OS} = \theta \frac{V_{21}V_{32} - V_{31}V_{22}}{V_{21} - V_{22}}$$

Not needed

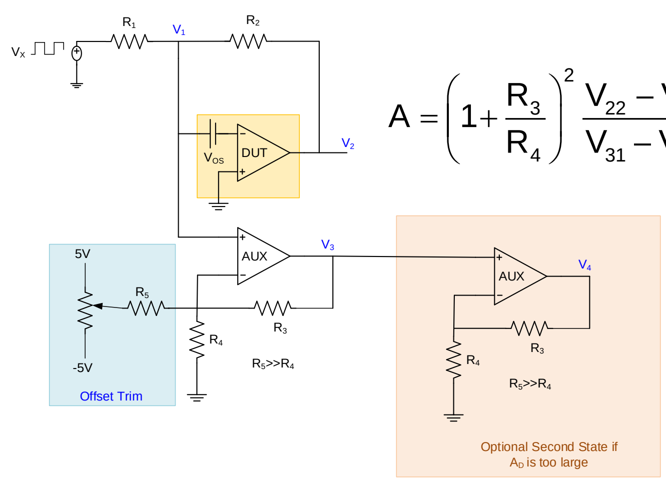
Measurement and Simulation of Op Amps



Consider two inputs, V_{X1} and V_{X2}

$$A = \left(1+\frac{R_3}{R_4}\right)\frac{V_{22}-V_{21}}{V_{31}-V_{32}}$$

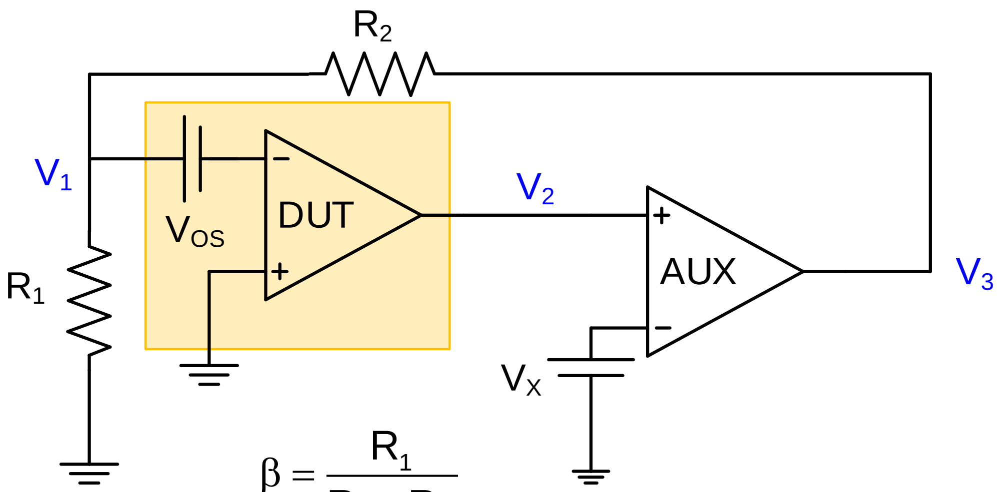
Can also measure V_{OS} with this circuit



$$A = \left(1+\frac{R_3}{R_4}\right)^2\frac{V_{22}-V_{21}}{V_{31}-V_{32}}$$

Can add gain stage if A is very large

Measurement and Simulation of Op Amps



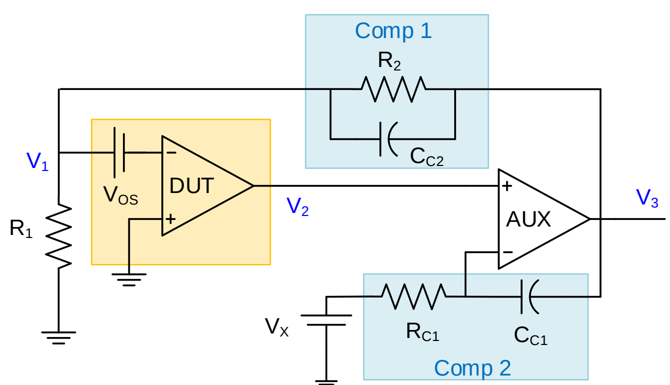
$$\beta = \frac{R_1}{R_1 + R_2}$$

Consider two inputs, V_{X1} and V_{X2}

$$V_{OS} = \frac{\beta\left(V_{32}\frac{V_{X1}}{V_{X2}} - V_{31}\right)}{\left(\frac{V_{X1}}{V_{X2}} - 1\right)}$$

$$A_V = \frac{V_{X2} - V_{X1}}{\beta\left(V_{31} - V_{32}\right)}$$

- Must compensate this circuit and compensation may be a bit complicated
- Compensation beyond scope at this stage in EE 435

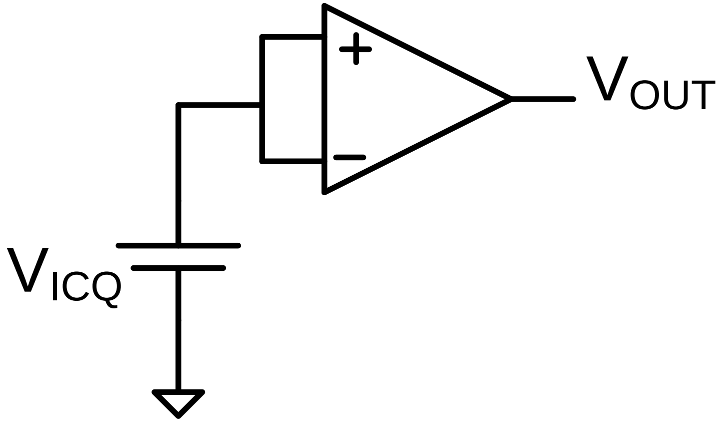


Potential Compensation Structures

Laboratory Support

Offset Voltage

- Systematic Offset Voltage
- Random Offset Voltage



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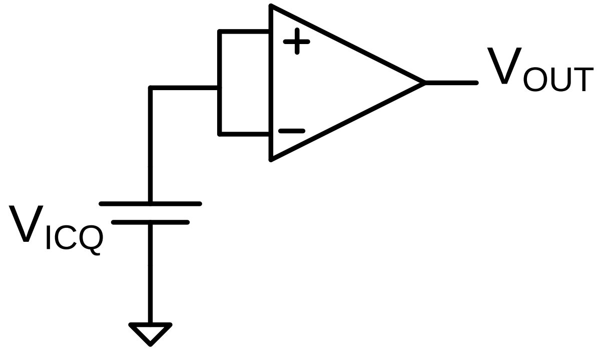
Offset Voltage

- Systematic Offset Voltage
- Random Offset Voltage

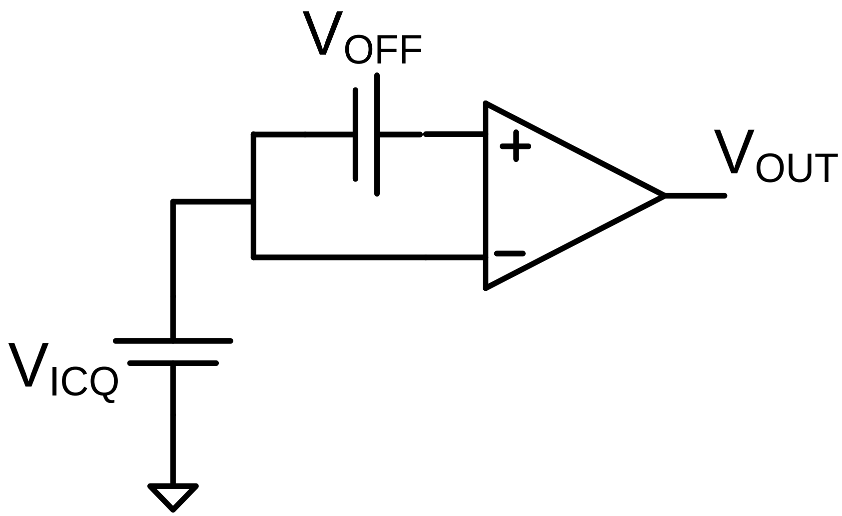


Definition: The output offset voltage is the difference between the desired output and the actual output when V_{id}=0 and V_{ic} is the quiescent common-mode input voltage.

$$V_{OUTOFF} = V_{OUT} - V_{OUTDES}$$

Note: V_{OUTOFF} is dependent upon V_{ICQ} although this dependence is usually quite weak and often not specified

Laboratory Support



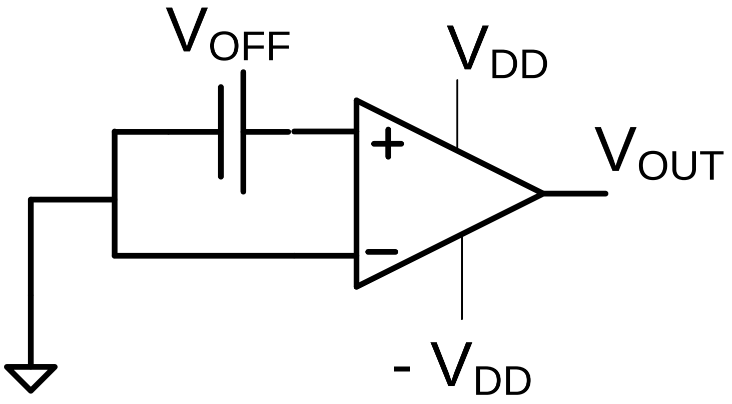
Definition: The input-referred offset voltage is the differential dc input voltage that must be applied to obtain the desired output when V_{ic} is the quiescent common-mode input voltage.

Note: V_{OFF} is usually related to the output offset voltage by the expression

$$V_{OFF} = \frac{V_{OUTOFF}}{A_D}$$

Note: V_{OFF} is dependent upon V_{ICQ} although this dependence is usually quite weak and often not specified

Laboratory Support



When differential input op amps are biased with symmetric supply voltages, it is generally assumed that the desired quiescent input voltage Is 0V and the desired quiescent output voltage is 0V so V_{OFF} is the differential Input voltage needed to make V_{OUT}=0V.

The input offset voltage is comprised of two parts, a systematic component and a random component

$$V_{OFF} = V_{OFFSYS} + V_{OSR}$$

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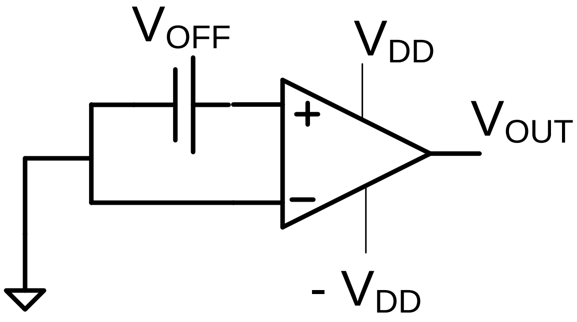

$$V_{OFF} = V_{OFFSYS} + V_{OSR}$$

After fabrication there is no distinction made between V_{OFFSYS} and V_{OSR} and simply V_{OFF} is of concern

V_{OSR} is determined entirely by random variations in component values from their ideal value and will only be seen in a simulation if deviations are intentionally introduced (Monte Carlo Analysis if often used for predicting V_{OSR})

It is expected that V_{OFFSYS} should be small (much smaller than V_{OSR}) and it is the designer’s responsibility to make this small

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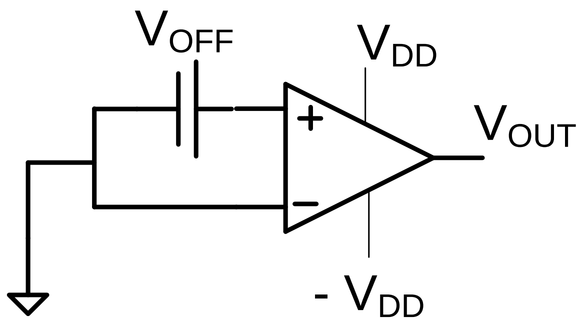
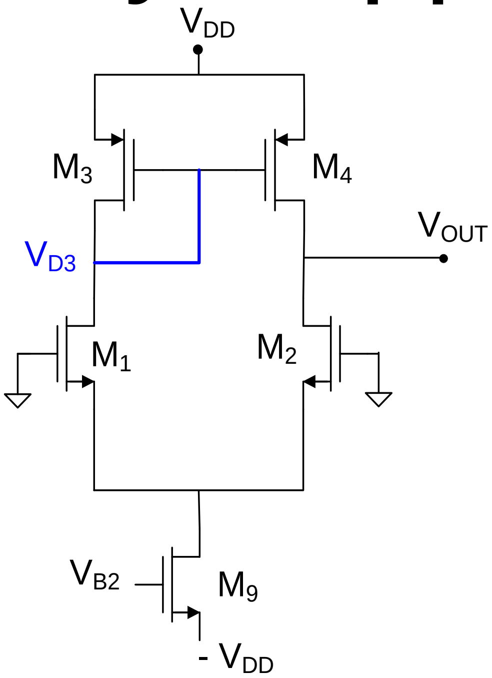


$$V_{OFF} = V_{OFFSYS} + V_{OSR}$$

It is not necessary to make V_{OFFSYS} =0 although this can and is often done by making a minor tweak of matching critical parameters after the design of the op amp is almost complete

V_{OFFSYS} can also be set to 0 by using a degree of freedom of the amplifier design variables but this is generally an unwise use of degrees of freedom (although some textbooks including Martin and Johns in Sec 5.1 do this!)

Laboratory Support

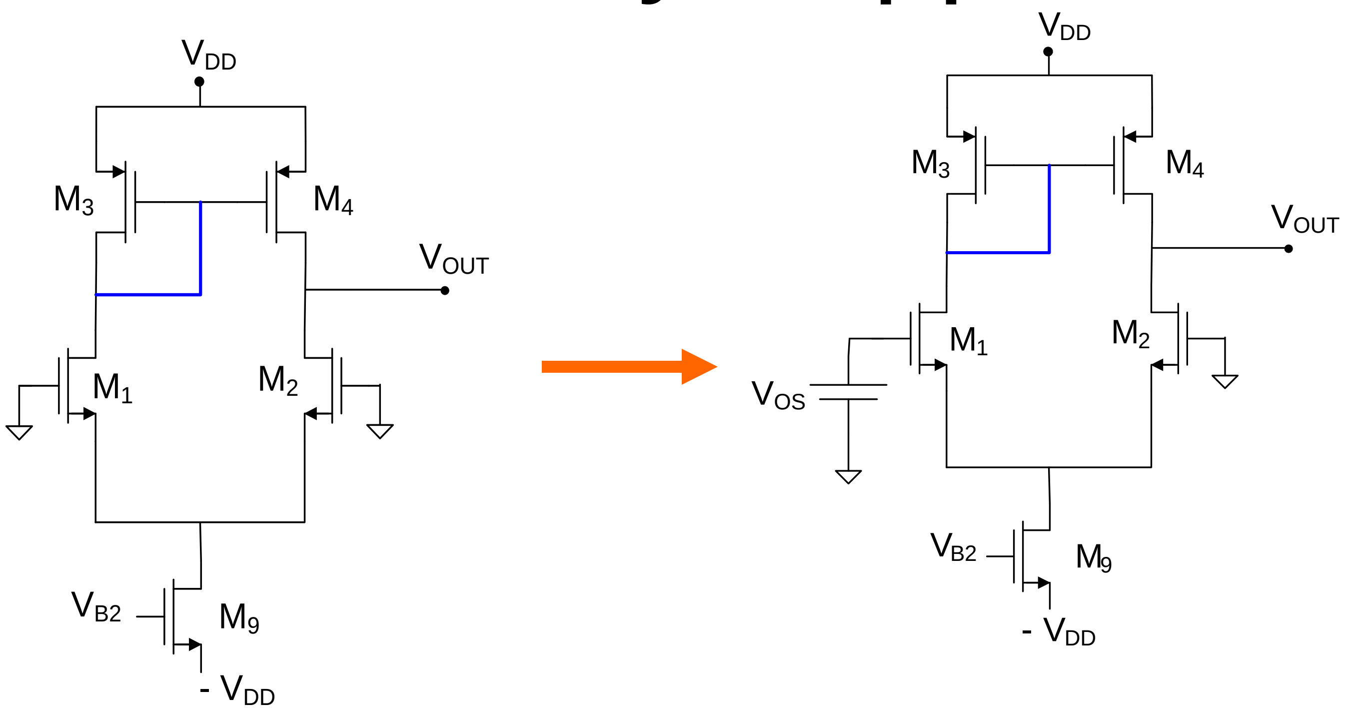


(If no missmatch is introduced, will be seeing only effects of systematic offset)

By symmetry, to force $V_{OUT} = 0$, it is necessary to have $V_{D3}=0$

- Making $V_{D3}=0$ sets $|V_{EB3}| = V_{DD} + V_{Tp}$ and results in the use of one degree of freedom!
- Making V_{EB3} so large will severely limit the voltage swing at V_{OUT}
- This shows why it is not wise to use a degree of freedom to make desired output voltage 0

Laboratory Support

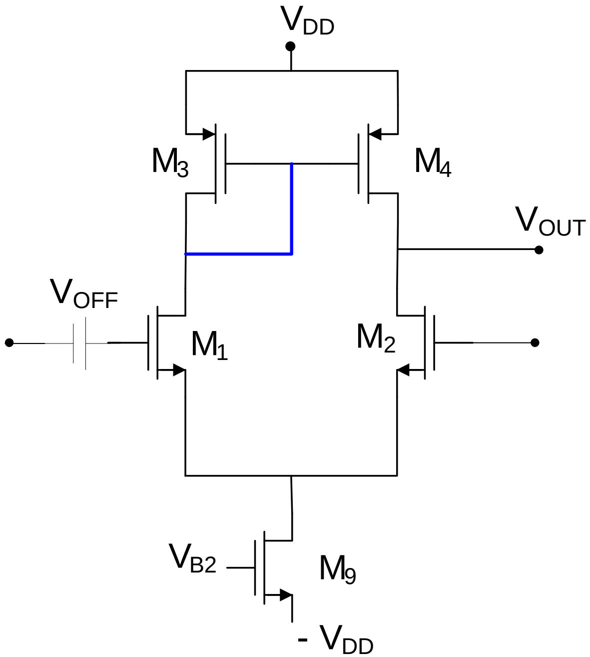


Can sweep a voltage in simulator at gate of M_1 to make $V_{OUT}=V_{OUT\_DESIRED}$

The value of V_{OS} that makes $V_{OUT}=V_{OUT\_DES}$ is the systematic offset voltage

Can simply add the systematic offset voltage to input throughout rest of the design phase and then remove after design is complete or tweak at end of design to eliminate systematic offset.

Laboratory Support



Usually V_{OFF} will change if changes in any design variables are made so re-simulation will be needed to get the correct value of V_{OFF}

If V_{OFF} is not included, ac simulation of open-loop amplifier will usually not give desired results because small-signal models will be developed in simulator at incorrect operating point (often even in incorrect region of operation)

Alternative is to do ac simulations by embedding op amp into a FB configuration that will inherently compensate for offset voltage but issue of compensation must be addressed for amplifiers with two or more poles

Stay Safe and Stay Healthy !

End of Lecture 6