EE 435

Lecture 5

Single-Stage Low-Gain Op Amps

- Slew Rate
- The Reference Op Amp
- 5T Current Mirror Bias Op Amp
- Current Mirrors
- Signal Swing

Review from last lecture:

Where we are at:

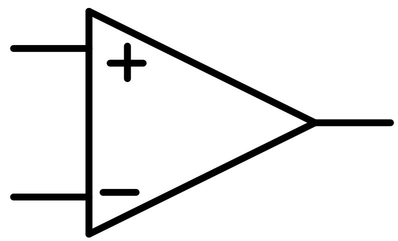
Basic Op Amp Design

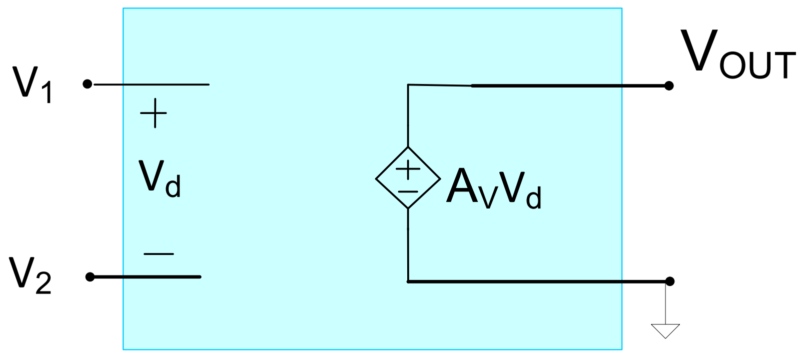
- Fundamental Amplifier Design Issues
- Single-Stage Low Gain Op Amps
- Single-Stage High Gain Op Amps
- Two-Stage Op Amp
- Other Basic Gain Enhancement Approaches

Review from last lecture:

How is Common-Mode Gain Modeled?

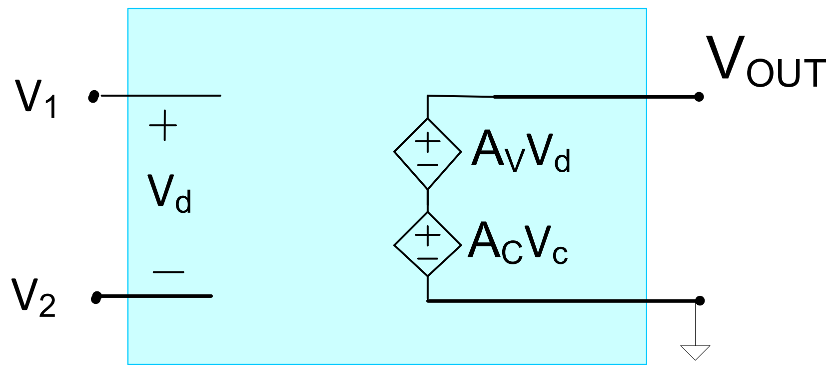
If Op Amp is a Voltage Amplifier with infinite input impedance, zero output impedance, and one terminal of the output is grounded





Ideal Differential Voltage Amplifier

$$V_d = V_1 - V_2$$



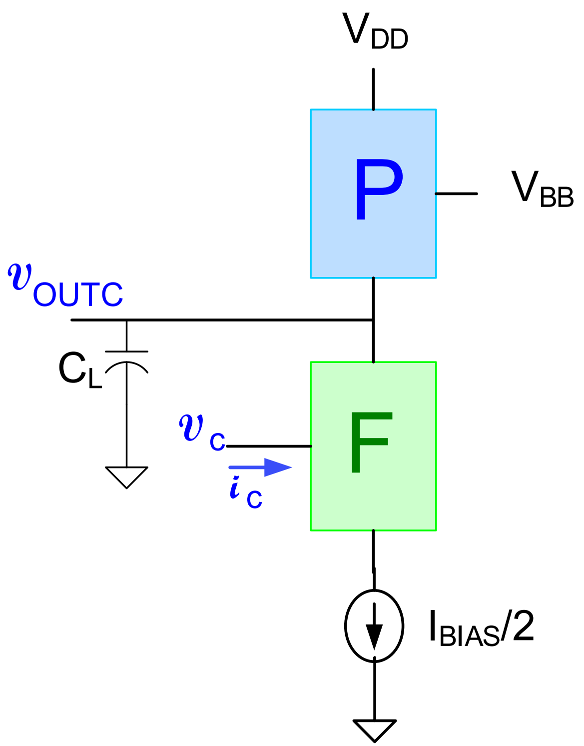
Ideal Voltage Amplifier

$$V_d = V_1 - V_2 \qquad V_c = \frac{V_1 + V_2}{2}$$

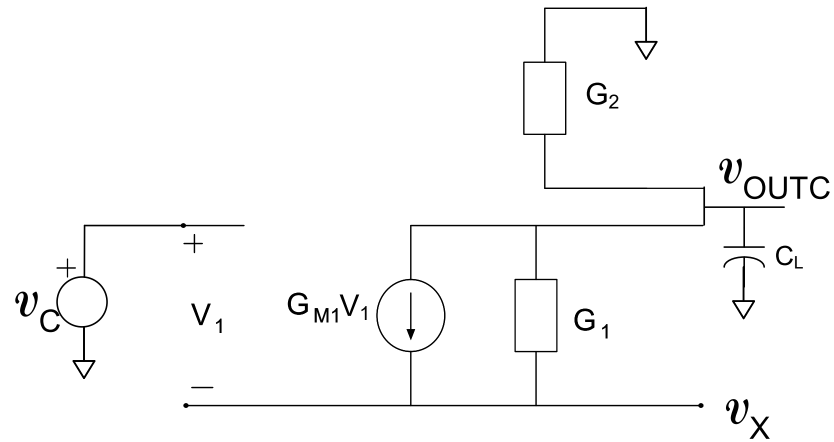
Review from last lecture:

Performance with Common-Mode Input

Consider tail-current bias amplifier with i_c=0



Common-Mode Half-Circuit



$$\left.\begin{aligned} v_{OUTC}(sC+G_1+G_2)+G_{M1}v_1 &= G_1 v_x \\ v_C &= v_1+v_X \\ v_X G_1 - G_{M1}v_1 &= v_{OUTC}\,G_1 \end{aligned}\right\}$$

Solving, we obtain

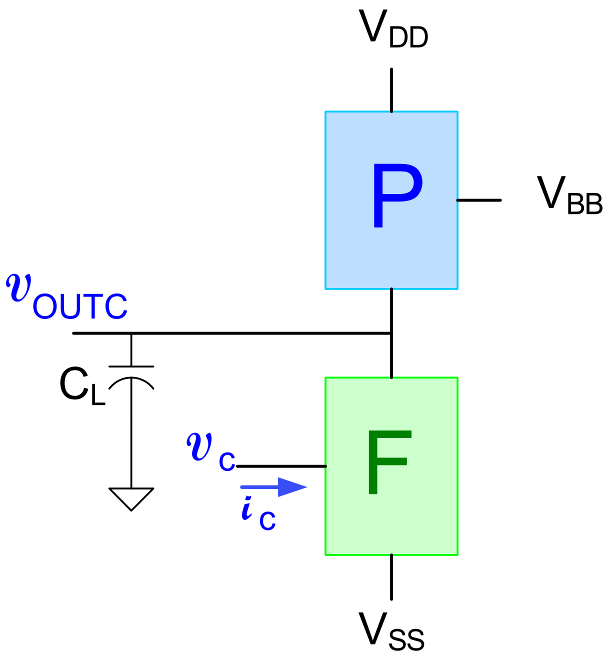
$v_{OUTC}=0$ thus $A_C=0$

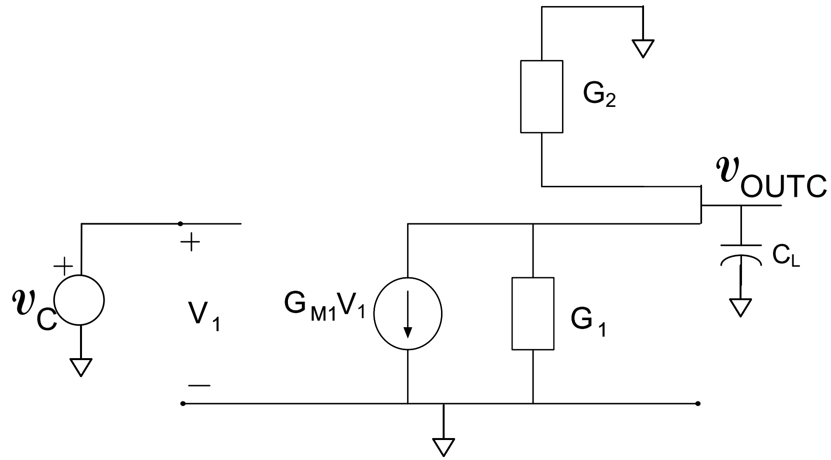
(Note: Have assumed an ideal tail current source in this analysis
A_C will be small but may not vanish if tail current source is not ideal)

Review from last lecture:

Performance with Common-Mode Input

Consider tail-voltage bias amplifier with i_c=0





$$\left.\begin{array}{l} v_{OUTC}\left(sC+G_1+G_2\right)+G_{M1}v_1 = 0 \\ v_C = v_1 \end{array}\right\}$$

Solving, we obtain

$$\frac{v_{OUTC}}{v_C} = A_C = \frac{-G_{M1}}{sC+G_1+G_2}$$

Common-Mode Half-Circuit

This circuit has a rather large common-mode gain and will not reject common-mode signals

- Not a very good differential amplifier
- But of no concern in applications where v_C=0

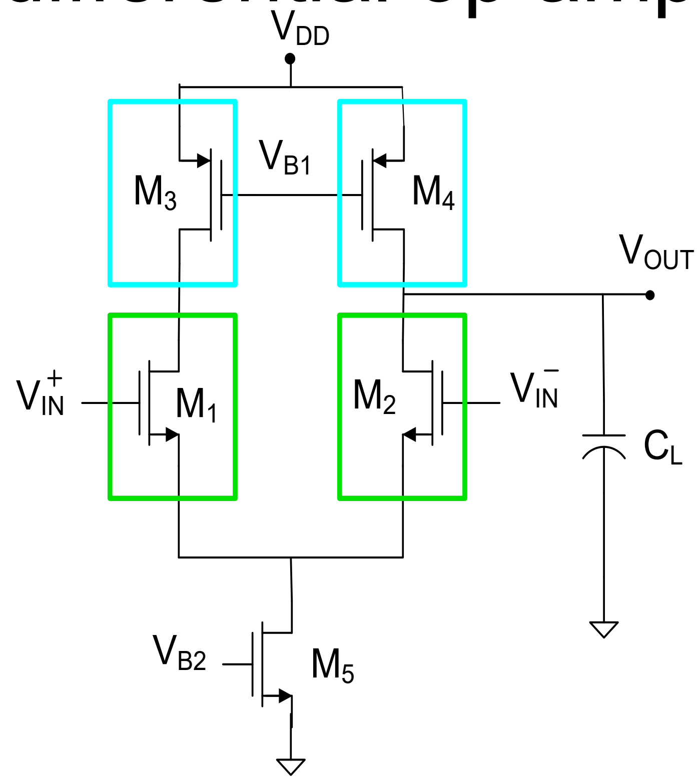
Review from last lecture:

Design of Basic Single-stage low-gain differential op amp

$$A(s)=\frac{-\frac{g_{m1}}{2}}{sC_L+g_{o1}+g_{o3}}$$

$$A_o=\frac{\frac{g_{m1}}{2}}{g_{o1}+g_{o3}}$$

$$GB=\frac{g_{m1}}{2C_L}$$



What are the number of degrees of freedom?
(assume V_{DD}, C_L fixed, Symmetry)

Need a CMFB circuit to establish V_{B1}

Natural Parameters:

$$\left\{\frac{W_1}{L_1},\frac{W_3}{L_3},\frac{W_5}{L_5},V_{B1},V_{B2}\right\}$$

Constraints: $I_{D5}\simeq 2I_{D3}$

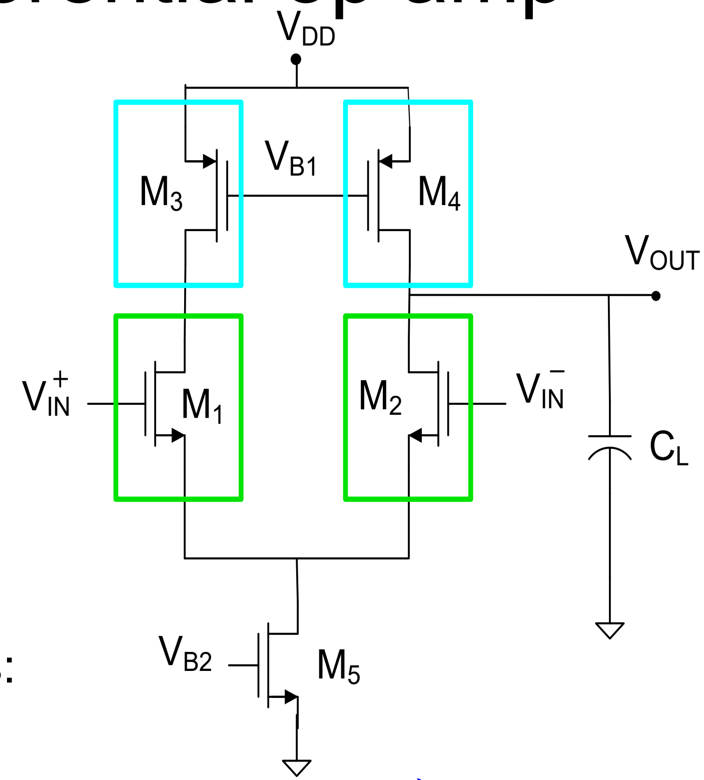
Net Degrees of Freedom: 4

Practical Parameters:

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

Will now express performance characteristics in terms of Practical Parameters

Design of Basic
Single-stage low-gain differential op amp



Single-Ended Output : Differential Input Gain

Practical Parameters: $\{V_{EB1}, V_{EB3}, V_{EB5}, P\}$

$$A_0 = \left[\frac{1}{\lambda_1 + \lambda_3}\right]\left(\frac{1}{V_{EB1}}\right) \qquad GB = \left(\frac{P}{V_{DD} C_L}\right) \bullet \left[\frac{1}{2V_{EB1}}\right]$$

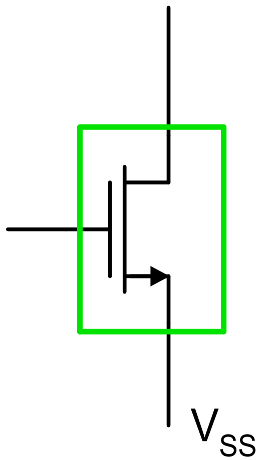
Design Strategy with fixed A_0 and GB requirements:

1. Pick V_{EB1} to meet gain requirements $\{\cancel{V_{EB1}}, V_{EB3}, V_{EB5}, P\}$
2. Pick P to meet GB requirements $\{\cancel{V_{EB1}}, V_{EB3}, V_{EB5}, \cancel{P}\}$
3. Pick V_{EB3} and V_{EB5} to achieve other desirable properties (i.e. explore the remaining part of the design space)

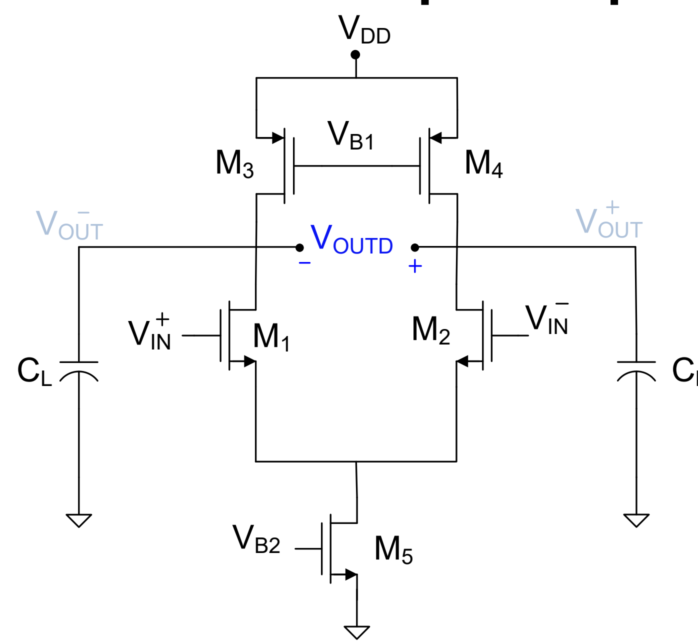
Note: Design strategy may change if A_0 and GB are not firm requirements

Single-stage low-gain differential I/O op amp

Quarter Circuit



$$\mathbf{V_{OD} = V_O^+ - V_O^-}$$



Differential Output : Differential Input Gain

$$A(s) = \frac{g_{m1}}{sC_L + g_{O1} + g_{O3}}$$

$$A_O = \frac{g_{m1}}{g_{O1} + g_{O3}}$$

$$GB = \frac{g_{m1}}{C_L}$$

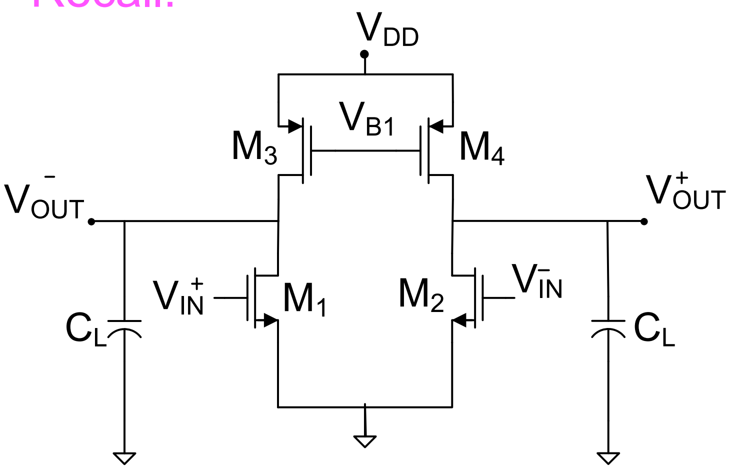
$$A_0 = \left[\frac{1}{\lambda_1 + \lambda_3}\right]\left(\frac{2}{V_{EB1}}\right) \qquad GB = \left(\frac{P}{V_{DD} C_L}\right) \bullet \left[\frac{1}{V_{EB1}}\right]$$

Have 4 degrees of freedom but only two practical variables impact A_0 and GB so still have 2 DOF after meet A_0 and GB requirements that can be used for other purposes

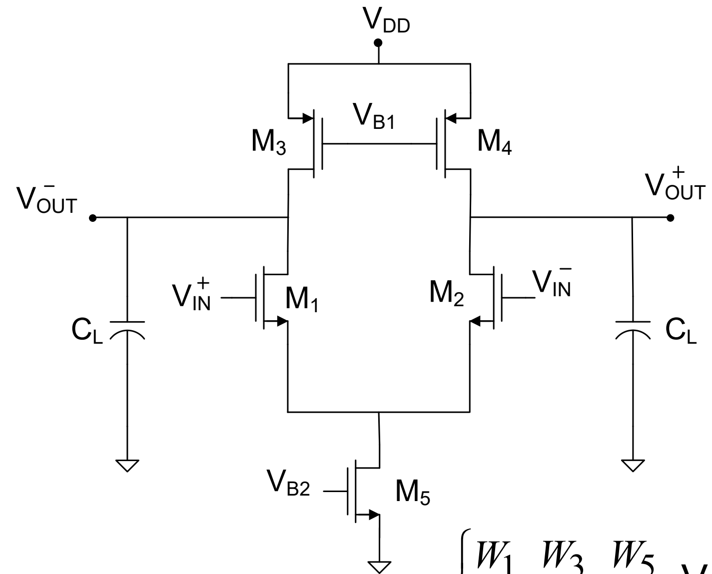
Need a CMFB circuit to establish V_{B1} or V_{B2}

A_D expressions valid for both tail-current and tail-voltage op amp

Recall:



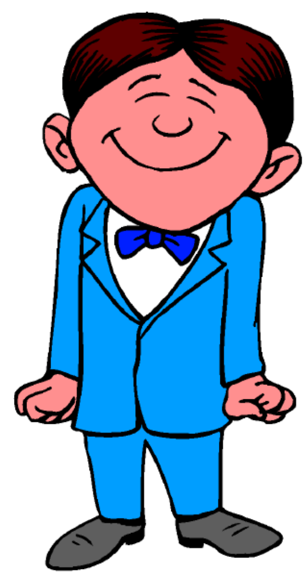
$$\left\{\frac{W_1}{L_1},\frac{W_3}{L_3},V_{B1}\right\}$$



$$\left\{\frac{W_1}{L_1},\frac{W_3}{L_3},\frac{W_5}{L_5},V_{B1},V_{B3}\right\}$$

So which one should be used?

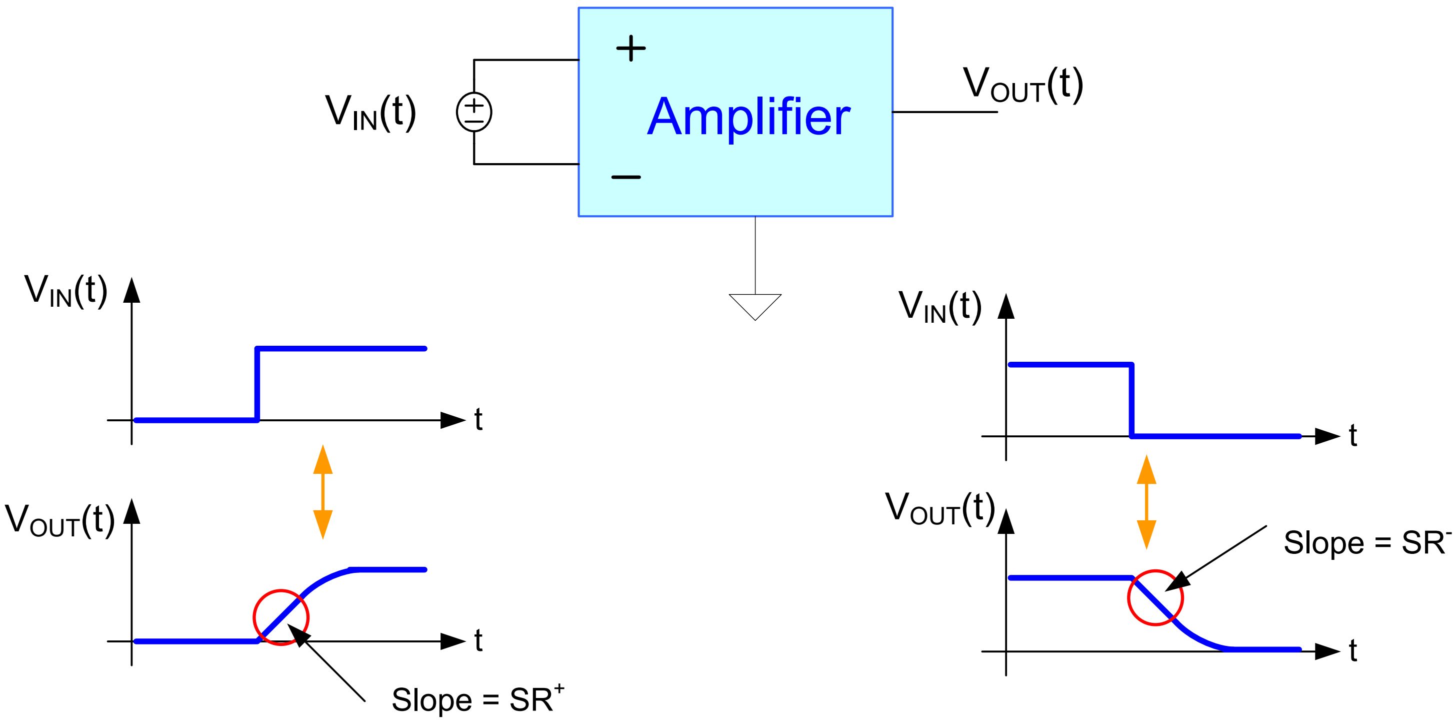
- Common-mode input range large for tail current bias
- Improved rejection of common-mode signals for tail current bias
- Two extra design degree of freedom for tail current bias
- Improved output signal swing for tail voltage bias (will show later)



- Fully Differential Single-Stage Amplifier
  - General Differential Analysis
  - 5T Op Amp from simple quarter circuit
  - Biasing with CMFB circuit
  - Common-mode and differential-mode analysis
  - Common Mode Gain
  - Overall Transfer Characteristics
- Design of 5T Op Amp
- Slew Rate

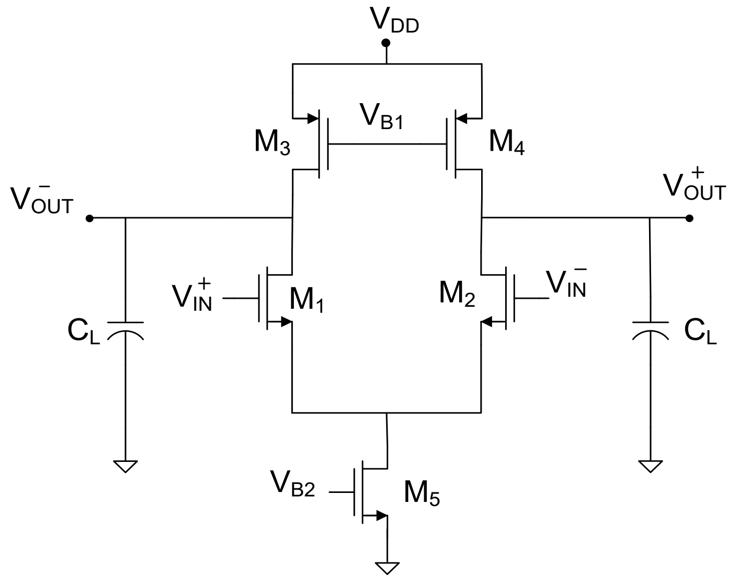
Slew Rate

Definition: The slew rate of an amplifier is the maximum rate of change that can occur at the output node



- SR is a nonlinear large-signal characteristic
- Input is over-driven (some devices in amplifier usually leave normal operating region)
- Hard input overdrive depicted in this figure
- Magnitude of SR^+ and SR^- usually same and called SR (else SR^+ and SR^- must be given)

Slew Rate for 5T Op Amp



With large step input on V_{IN}^+, all tail current (I_T) will go to M_1 thus turning off M_2 thus current through M_4 which is ½ of I_T will go to load capacitor C_L

The I-V characteristics of any capacitor is

$$I = C\frac{dV}{dt}$$

Substituting $I=I_T/2$, $V=V_{OUT}^+$ and $C=C_L$ obtain a voltage ramp at the output thus

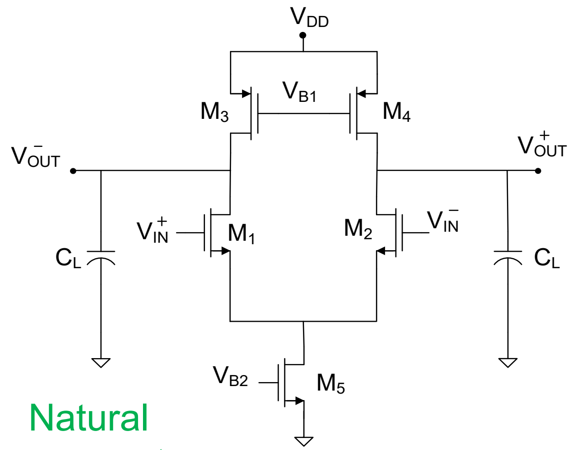
$$SR^+ = \frac{dV_{OUT}^+}{dt} = \frac{I_T}{2C_L}$$

Natural parameter domain

$$SR^+ = \frac{P}{V_{DD}2C_L}$$

Practical parameter domain

Slew Rate for 5T Op Amp



$$SR^{+} = \frac{I_T}{2C_L}$$

Natural parameter domain

$$SR^{+} = \frac{P}{V_{DD} 2C_L}$$

Practical parameter domain

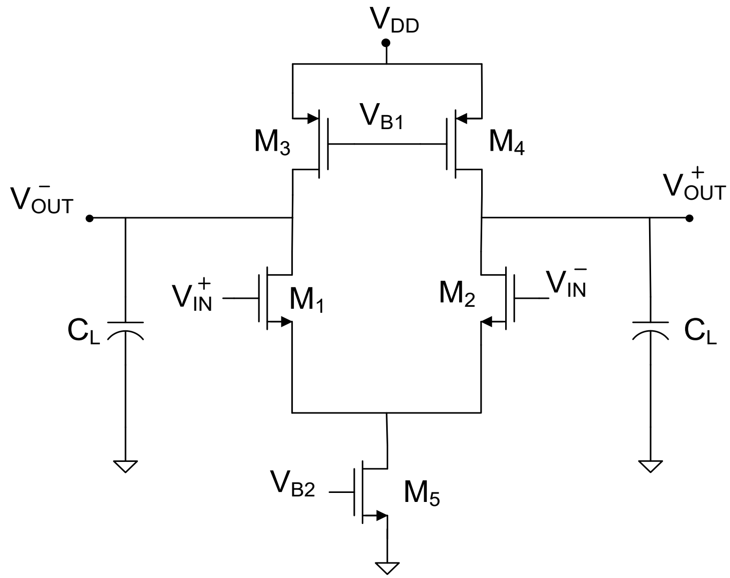
Question: Can SR⁺ be expressed as product of model parameters and architecture dependent term?

$$SR^{+} = \left[\frac{1}{2C_L}\right][I_T] \qquad SR^{+} = \left[\frac{1}{V_{DD} 2C_L}\right][P]$$

Question: Can SR⁺ be expressed in small-signal parameter domain?

$$SR^{+} = \frac{g_{o1}}{\lambda C_L} = \left[\frac{1}{\lambda C_L}\right][g_{o1}]$$

Slew Rate



It can be similarly shown that putting a large negative step on the input steer all current to M_2 thus the current to the capacitor C_L will be I_T minus the current from M_2 which is still $I_T/2$. This will cause a negative ramp voltage on V_{OUT}^+ of value

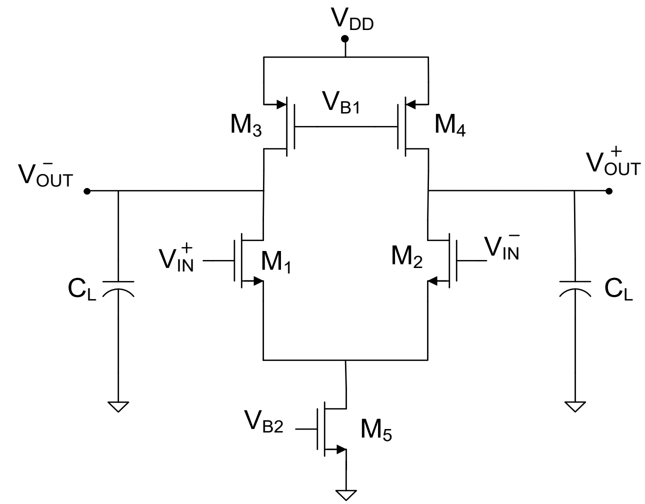
$$SR^- = \frac{dV_{OUT}^+}{dt} = -\frac{I_T}{2C_L} = -\frac{P}{V_{DD}2C_L}$$

Since the magnitude of SR^+ and SR^- are the same, obtain a single SR for the amplifier of value

$$SR = \frac{P}{V_{DD}2C_L}$$

Interdependence of Parameters

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



$$GB = \left(\frac{1}{2V_{DD}C_L}\right) \bullet \left[\frac{P}{V_{EB1}}\right]$$

$$SR = \frac{P}{V_{DD}2C_L}$$

Note: With this structure, the three key performance characteristics $\{A_0$, GB, SR$\}$ can not be independently specified

e.g. If V_{EB1} is picked to set A_0, then $\frac{P}{V_{DD}C_L}$ will determine both GB and SR

Alternately, observe $$SR = \frac{GB}{A_0(\lambda_1 + \lambda_2)}$$

The Reference Op Amp

Would like to have a specific amplifier, termed a Reference Op Amp, that can serve as a base-line so can compare performance of other op amp architectures with respect to that of the Reference Op Amp

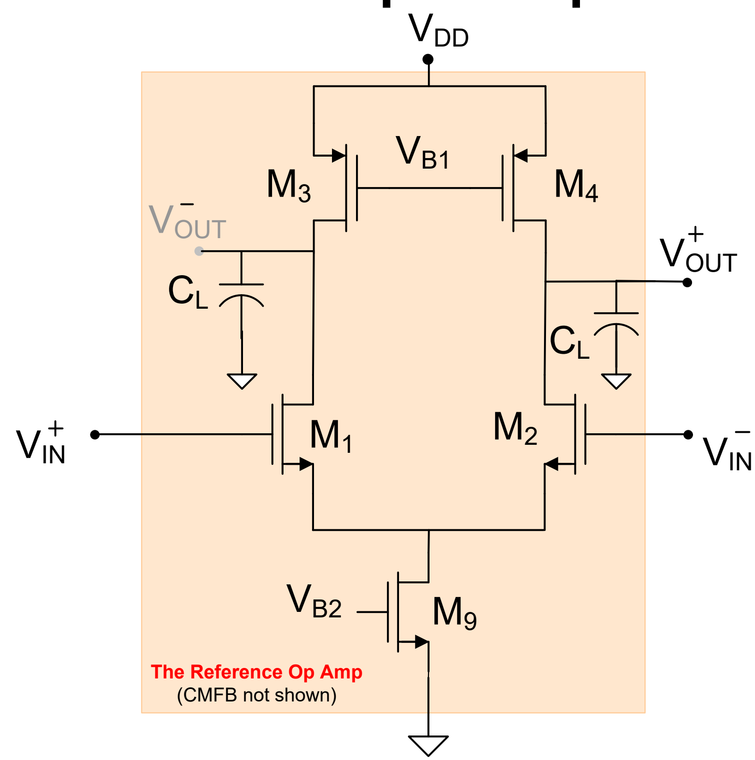
Will use the 5T Op Amp as a Reference Op Amp for comparing single-stage Op Amps

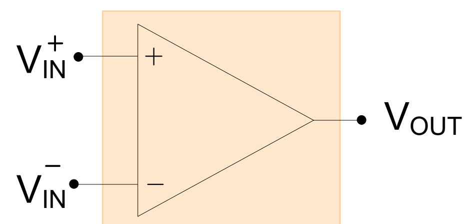
Single-stage low-gain differential op amp

Consider single-ended output performance :

Will term this the **reference op amp**
Will make performance comparisons of other op amps relative to this

$$A(s) = \frac{\frac{g_{m1}}{2}}{sC_L + g_{O1} + g_{O3}}$$





mixed parameters

$$A_{VO} = \frac{1}{2}\frac{g_{m1}}{g_{O1}+g_{O3}}$$

$$GB = \frac{g_{m1}}{2C_L}$$

$$SR = \frac{I_T}{2C_L}$$

practical parameters

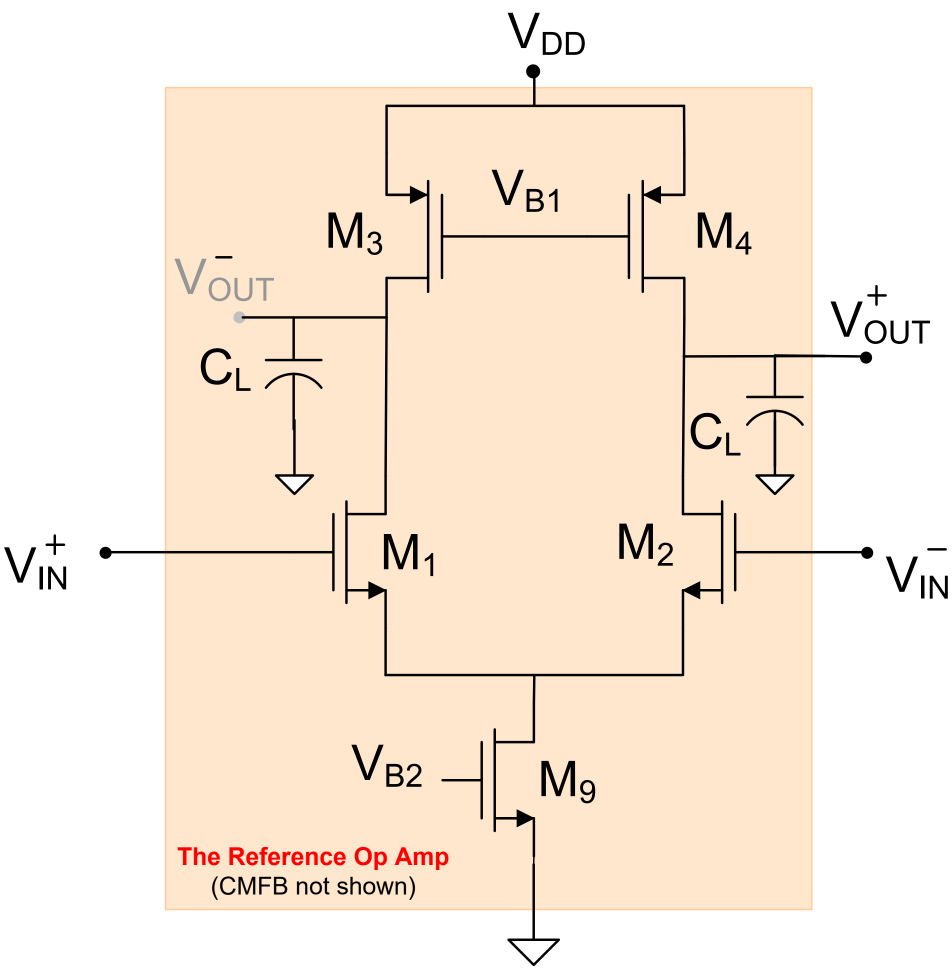
$$A_{V0} = \left[\frac{1}{\lambda_1 + \lambda_3}\right]\left(\frac{1}{V_{EB1}}\right)$$

$$GB = \left(\frac{P}{2V_{DD}C_L}\right) \bullet \left[\frac{1}{V_{EB1}}\right]$$

$$SR = \frac{P}{2V_{DD}C_L}$$

Reference Op Amp

single-ended output



$$A(s)=\frac{\frac{g_{m1}}{2}}{sC_L+g_{O1}+g_{O3}}$$

mixed parameters	practical parameters
$A_{VO}=\frac{1}{2}\frac{g_{m1}}{g_{O1}+g_{O3}}$	$A_{V0}=\left[\frac{1}{\lambda_1+\lambda_3}\right]\left(\frac{1}{V_{EB1}}\right)$
$GB=\frac{g_{m1}}{2C_L}$	$GB=\left(\frac{P}{2V_{DD}C_L}\right)\bullet\left[\frac{1}{V_{EB1}}\right]$
$SR=\frac{I_T}{2C_L}$	$SR=\frac{P}{2V_{DD}C_L}$

- This is probably the simplest differential input op amp and is widely used
- Will go to more complicated structures only if better performance is required

Amplifier Structure Summary

Small Signal Parameter Domain		
Common Source	$A_{VO} = \frac{g_m}{g_O}$	$GB = \frac{g_m}{C_L}$

Practical Parameter Domain		
Common Source	$A_{VO} = \left(\frac{2}{\lambda}\right)\left(\frac{1}{V_{EB}}\right)$	$GB = \left(\frac{2P}{V_{DD}C_L}\right)\left(\frac{1}{V_{EB}}\right)$

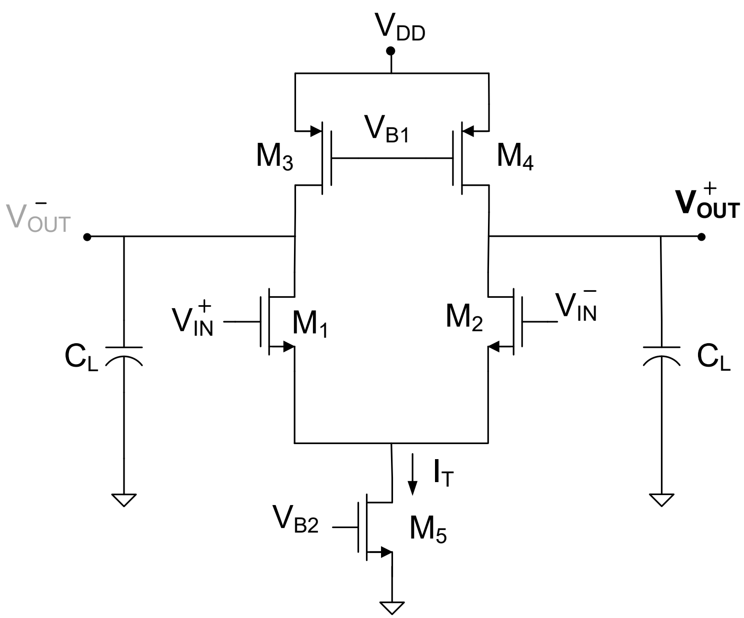
Small Signal Parameter Domain			
Reference Op Amp (single-ended ouput)	$A_{VO} = \frac{1}{2}\frac{g_{m1}}{g_{O1}+g_{O3}}$	$GB = \frac{g_{m1}}{2C_L}$	$SR = \frac{g_{01}}{\lambda C_L}$

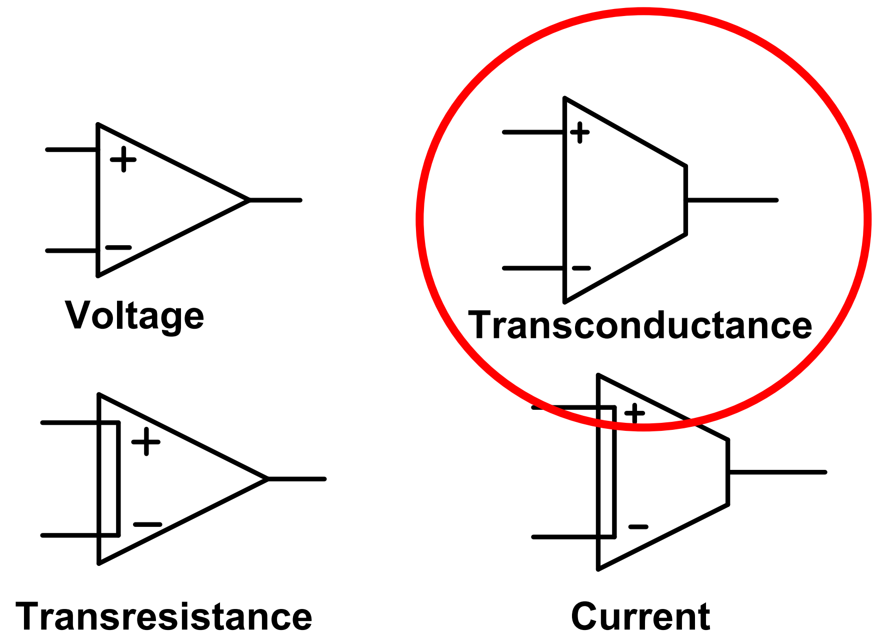
Practical Parameter Domain			
Reference Op Amp(single-ended ouput)	$A_{V0} = \left[\frac{1}{\lambda_1+\lambda_3}\right]\left(\frac{1}{V_{EB1}}\right)$	$GB = \left(\frac{P}{2V_{DD}C_L}\right) \bullet \left[\frac{1}{V_{EB1}}\right]$	$SR = \frac{P}{2V_{DD}C_L}$

Reference Op Amp

single-ended output

What basic type of amplifier is this op amp?





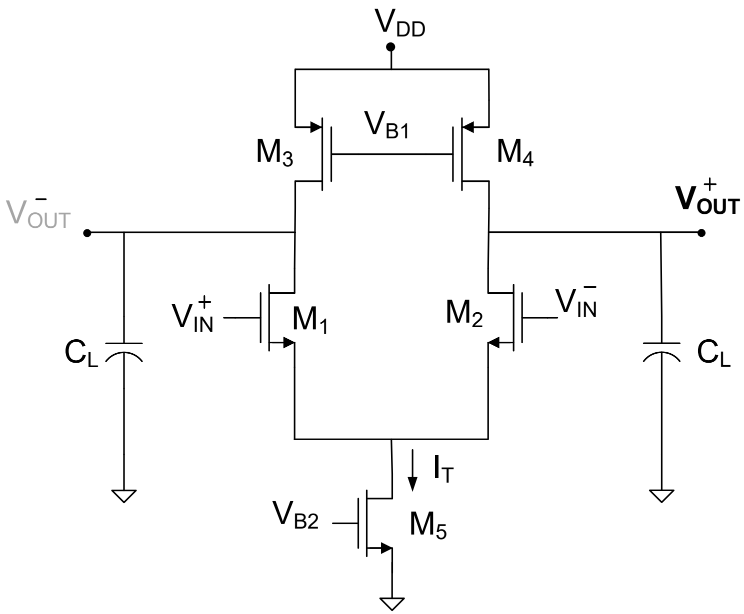
$$A(s) = \frac{\frac{g_{m1}}{2}}{sC_L + g_{O1} + g_{O3}}$$

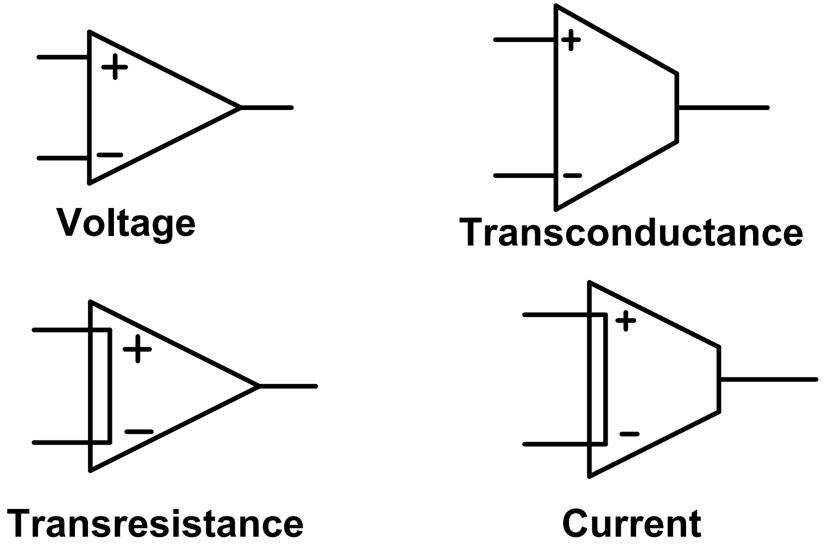
Reference Op Amp

single-ended output

What basic type of amplifier is this op amp? Transconductance

Does it really matter?





$$A(s) = \frac{\frac{g_{m1}}{2}}{sC_L + g_{O1} + g_{O3}}$$

Where we are at:

Basic Op Amp Design

- Fundamental Amplifier Design Issues
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- Other Basic Gain Enhancement Approaches

Where we are at:

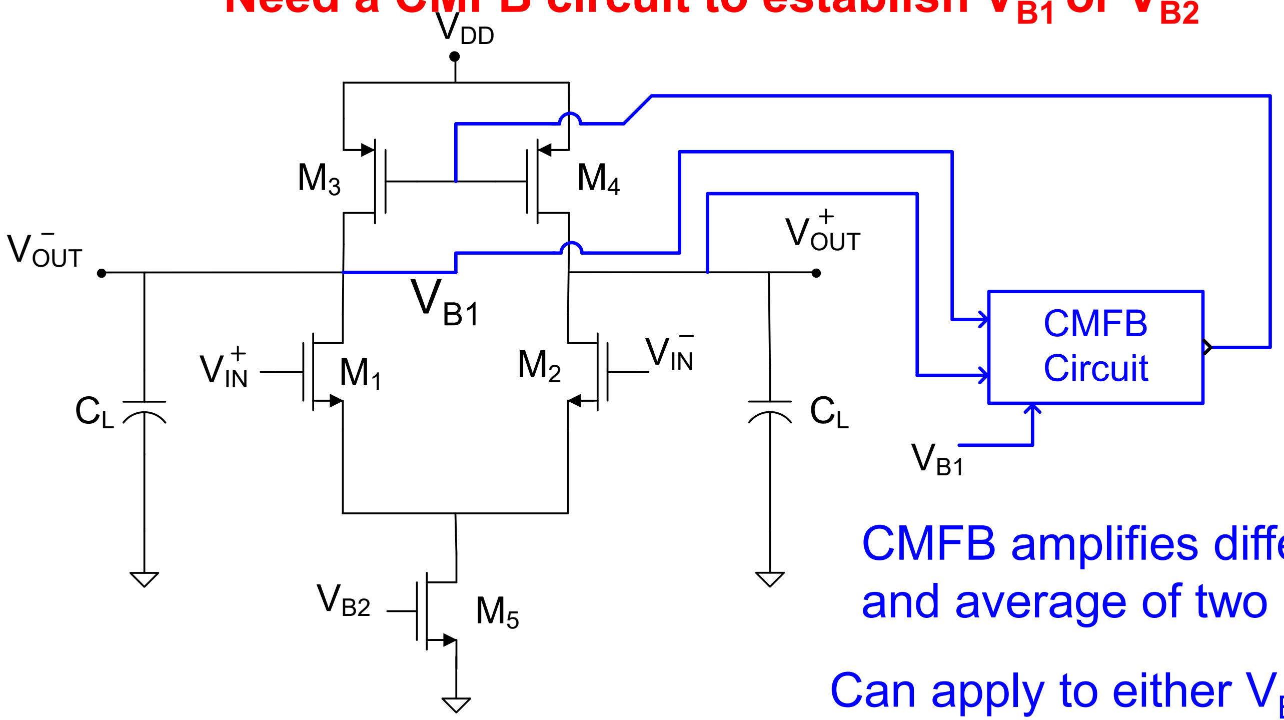
Basic Op Amp Design

Single-Stage Low Gain Op Amps

- 5T Op Amp
- 5T Current-Mirror Bias Op Amp

The 5T Op Amp

Need a CMFB circuit to establish V_{B1} or V_{B2}



CMFB amplifies difference between V_{B1} and average of two signal inputs

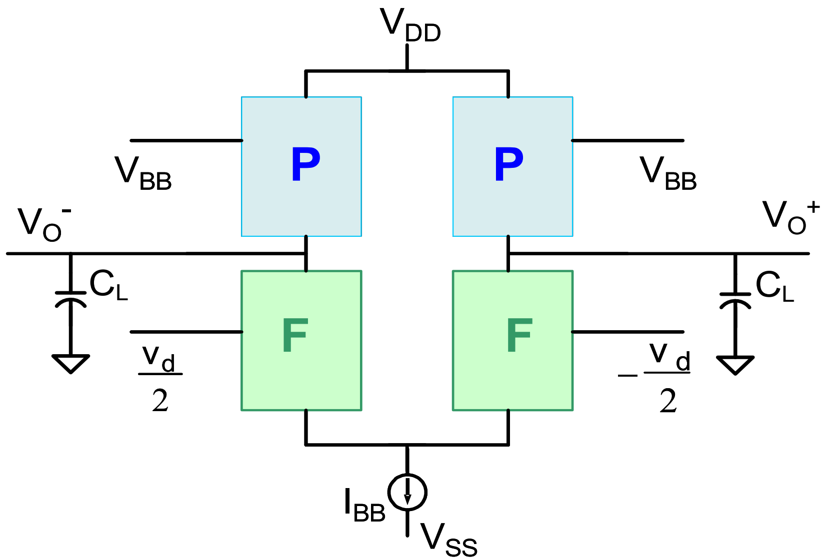
Can apply to either V_{B1} or V_{B2} but not both

Often apply to only fraction of transistor

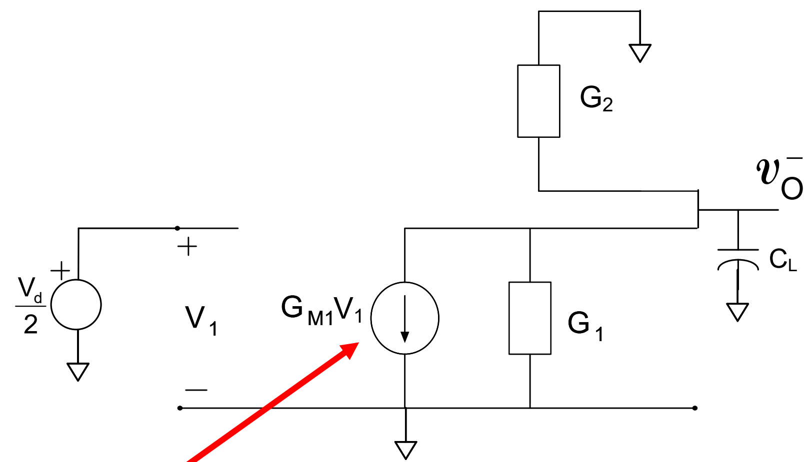
The CMFB circuit is often quite large and requires considerable design effort!

Can the CMFB be removed?

Operation of Op Amp – A conceptual observation



Small signal differential half-circuit



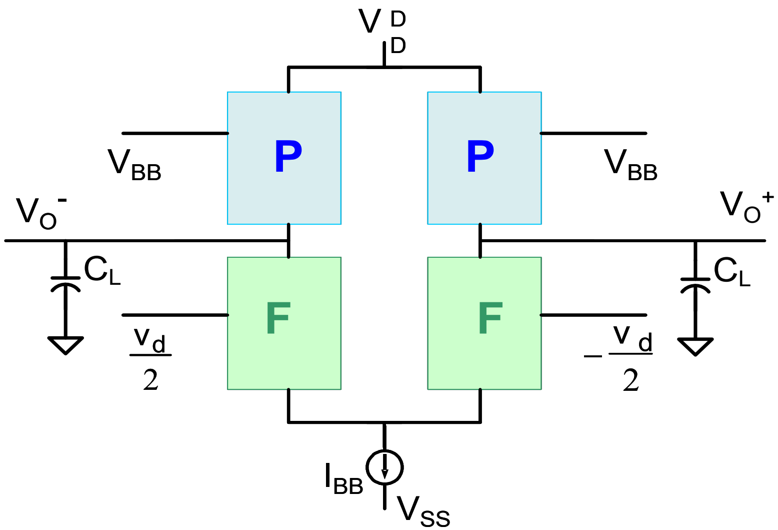
- The signal dependent current in quarter circuit is steered to output node and drives the parallel output conductances of the quarter circuit and counterpart circuit
- If G_1 and G_2 are small, the voltage gain will be large
- If the signal-dependent current could be doubled without changing the output conductances, the gain would be doubled as well !

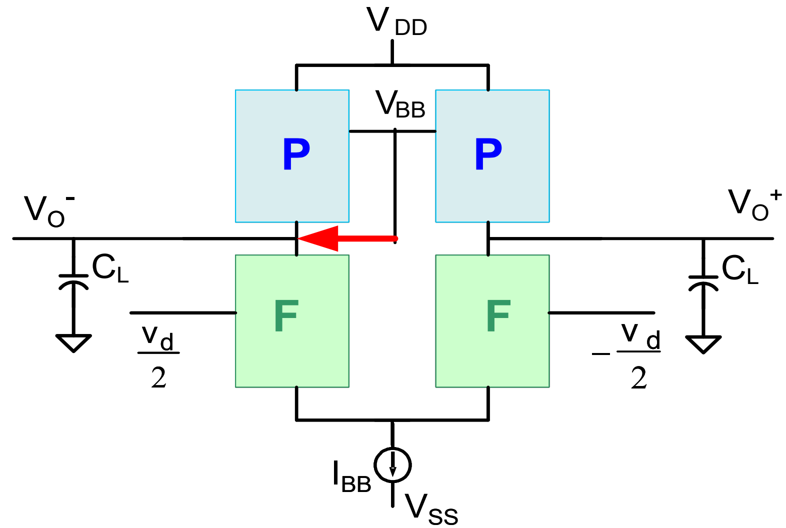
$$A_{VO} = \frac{-G_{M1}}{2(G_1 + G_2)}$$

$$BW = \frac{G_1 + G_2}{C_L}$$

$$GB = \frac{G_{M1}}{2C_L}$$

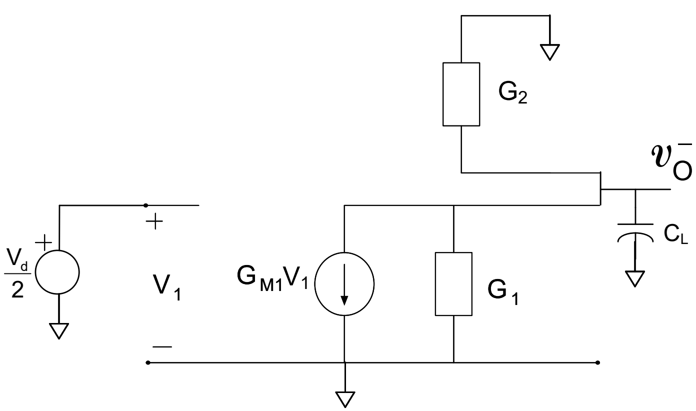
Operation of Op Amp – A conceptual observation





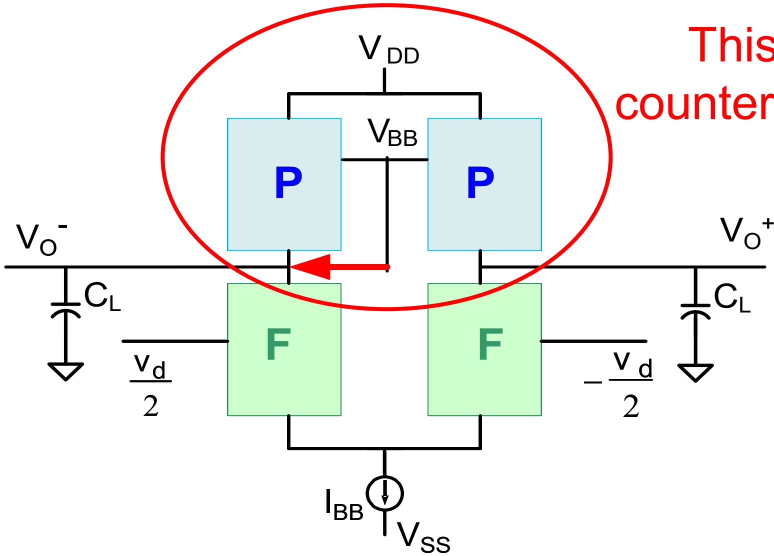
- If the input impedance to the counterpart circuit is infinite and the quiescent values of the left and right drain voltages are the same, connecting the bias port of the counterpart circuit to V_0^- instead of to V_{BB} will cause the signal current in the right counterpart circuit to be equal to that in the left counterpart circuit
- Voltage Gain to V_{OUT}^- not high so this output seldom used
- This will approximately double the signal current steered to V_o^+ and thus doubles the voltage gain ! (formal derivation on following slide)
- This will also eliminate the need for a CMFB circuit !!

Small signal differential half-circuit



No signal current driving counterpart circuit

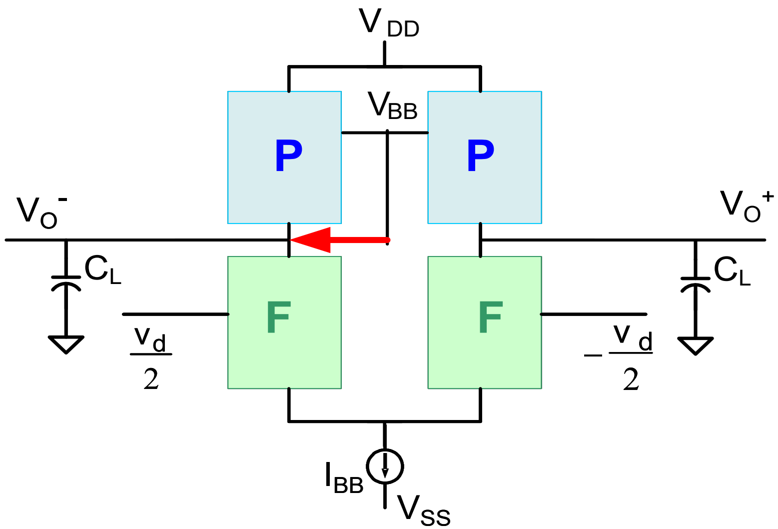
Terminology: "Current Mirror" connection

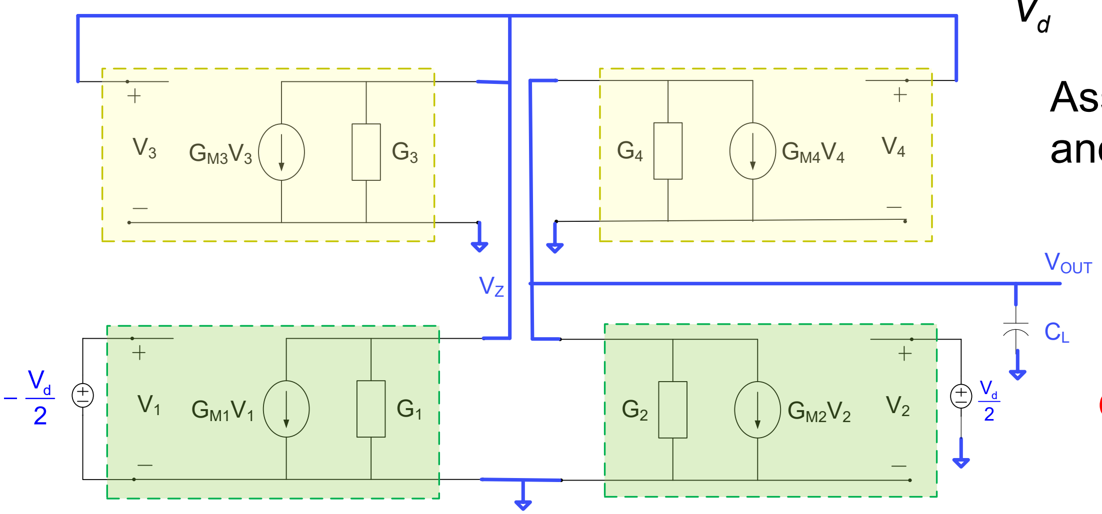


This connection of the counterpart circuits is termed "Current Mirror"

- Will now analyze this circuit to show the gain is doubled !
- Will follow this by a more detailed discussion of the Current Mirror

Doubling of Gain with “Current Mirror” connection





From KCL at two drain nodes ($V_{OUT}=V_O^+$, $V_Z=V_O^-$)

$$\left.\begin{aligned} &V_{OUT}\left(sC_L+G_2+G_4\right)+G_{M2}\frac{V_d}{2}+G_{M4}V_Z=0 \\ &V_Z\left(G_1+G_3\right)+G_{M3}V_Z-G_{M1}\frac{V_d}{2}=0 \end{aligned}\right\}$$

Eliminating V_Z we obtain

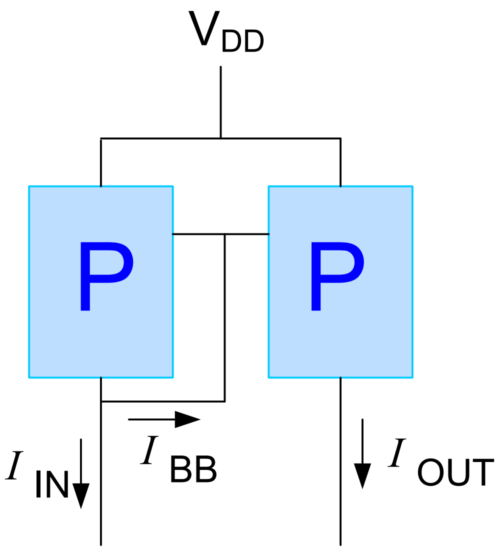
$$\frac{V_{OUT}}{V_d}=A_{VD}=-\frac{G_{M4}G_{M1}+G_{M2}G_{M3}+G_{M2}\left(G_1+G_3\right)}{2\left(sC_L+G_2+G_4\right)\left(G_1+G_3+G_{M3}\right)}$$

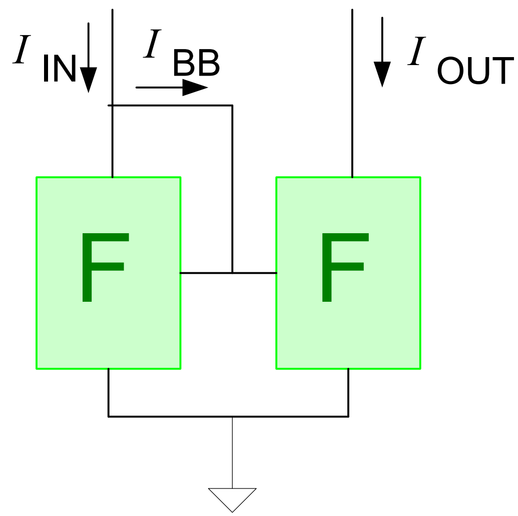
Assuming G_M’s large compared to G’s and left-right symmetry, it follows that

$$A_{VD}=-\frac{G_{M1}}{sC_L+G_2+G_4}$$

dc Voltage Gain to V_{OUT} doubled !

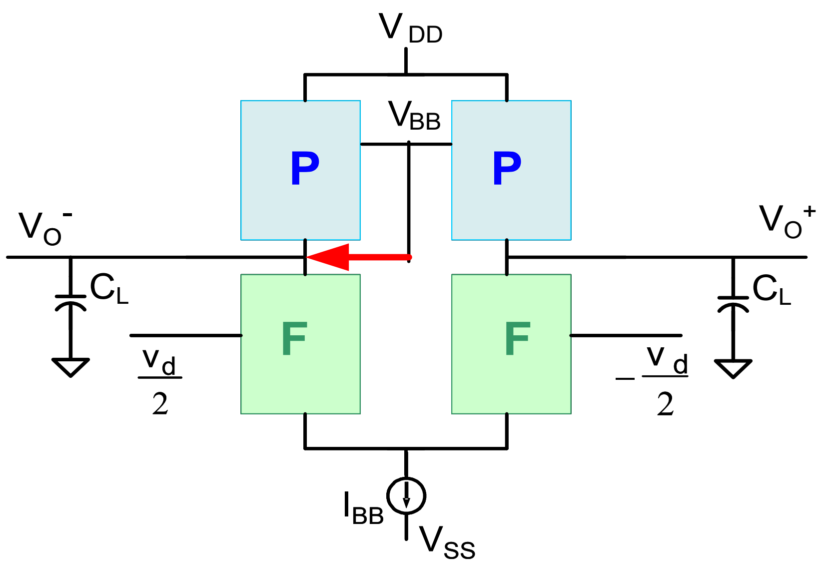
Current Mirrors



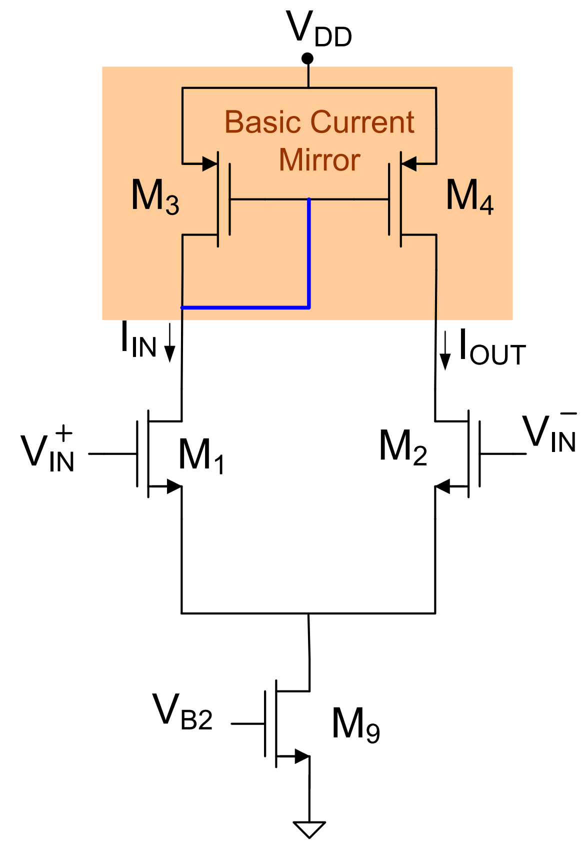


- If the current I_{BB} is small compared to I_{IN}, and the current I_{IN} is nearly independent of the voltage across P, then $I_{OUT} \approx I_{IN}$
- Circuits with this property are called Current Mirrors
- If multiple copies of the right circuit are placed in parallel, the current will be scaled by the number of copies
- These scaled circuits are also called Current Mirrors
- As long as $I_{BB} << I_{IN}$, this scaling in currents occurs even if the circuits are highly nonlinear provided the voltages across the circuits are the same!

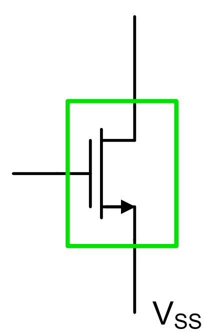
Operation of Op Amp – A different perspective



5T Current-Mirror Bias Op Amp



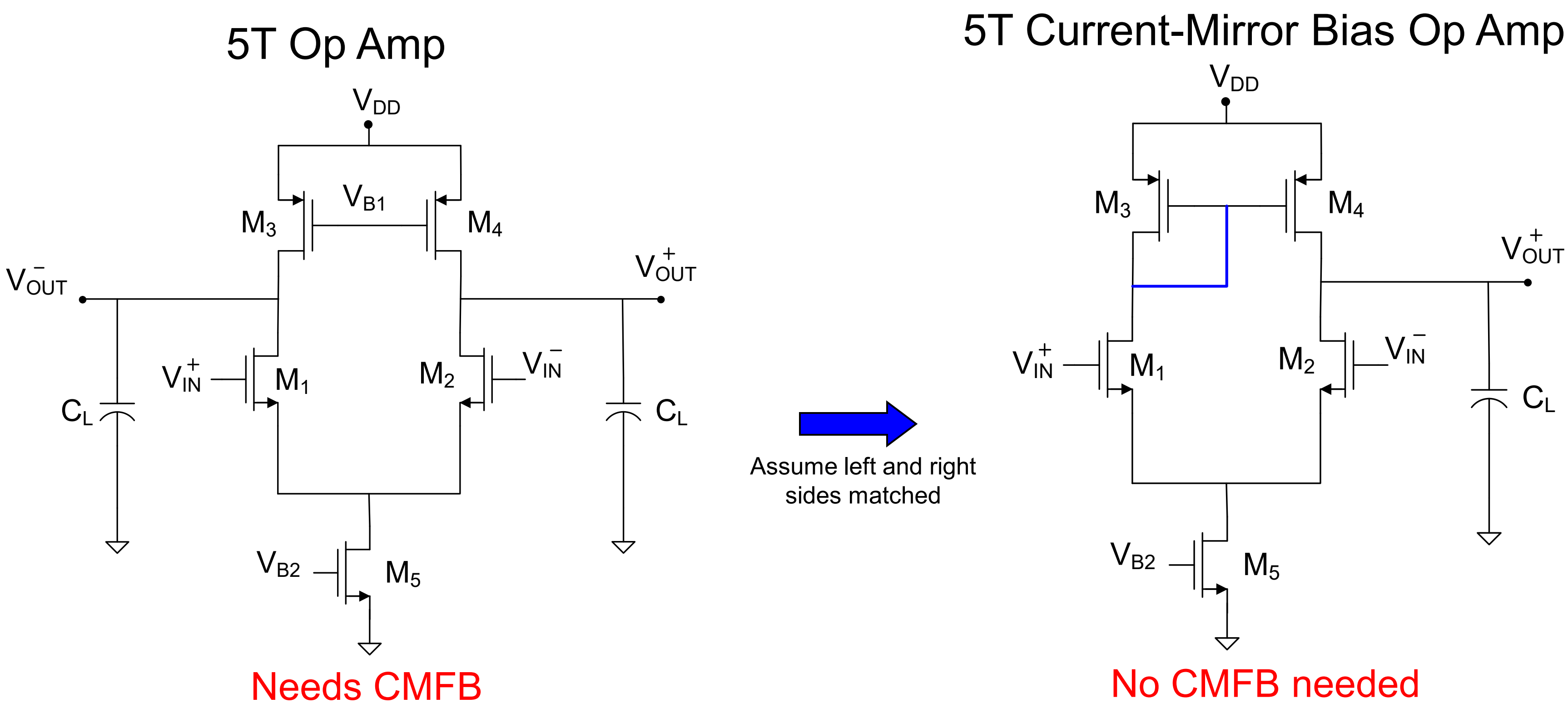
Consider using single n-mos transistor as quarter circuit



- Note counterpart circuits can be recognized as the basic current mirror
- But other current mirrors that may differ from the counterpart circuit could also be used (but then G_4 and G_2 may differ)

Single-stage low-gain differential op amp

(with M_1 as quarter circuit)



- **Can eliminate CMFB circuit <u>if only single-ended output is needed</u> by connecting counterpart circuits as a current mirror**
- **This will double the voltage gain and the GB as well**
- **Still uses counterpart circuits but terminated in different ways**
- **Although not symmetric, previous analysis results with specified modifications still nearly apply**

Single-stage low-gain differential op amp

Current-Mirror Connected Counterpart Circuit

Assume left and right sides matched

No CMFB Circuit Needed

Slew Rate?

When Vd large and negative,

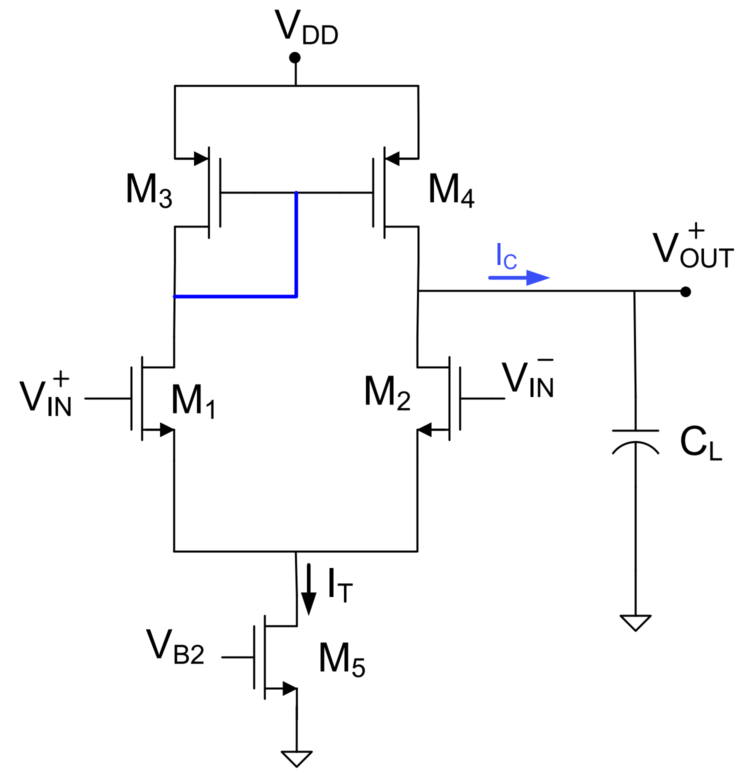
$$I_C = -I_T \qquad SR = -\frac{I_T}{C_L}$$

When Vd large and positive,

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

In terms of practical parameter set

$$SR = \frac{P}{V_{DD} C_L}$$



$$V_d = V_{IN}^{+} - V_{IN}^{-}$$

SR is double that of the 5T op amp !

Single-stage low-gain differential op amp

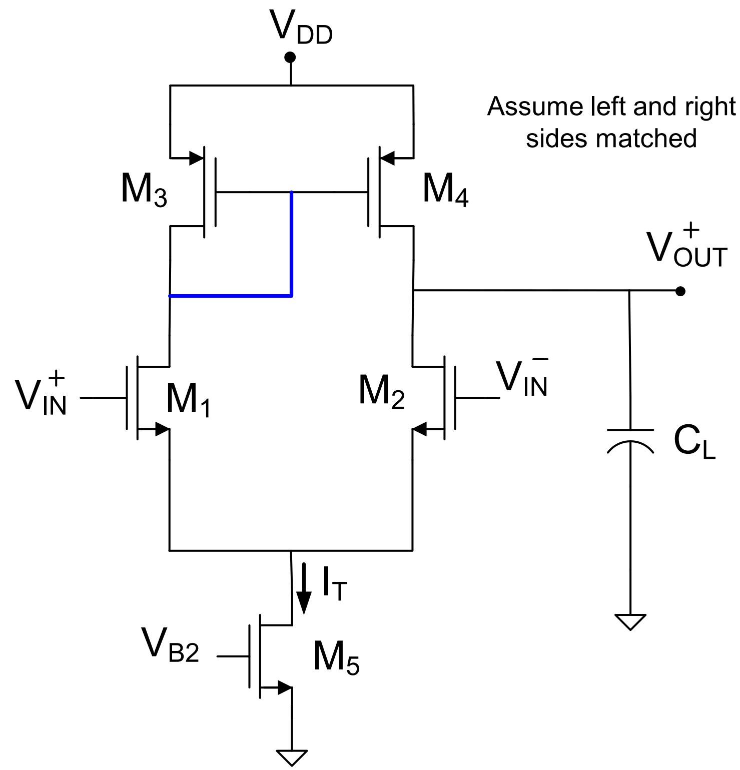
Current-Mirror Connected Counterpart Circuit

No CMFB Circuit Needed

$$A(s) = \frac{g_{m1}}{sC_L + g_{O1} + g_{O3}}$$

$$A_O = \frac{g_{m1}}{g_{O1} + g_{O3}}$$

$$GB = \frac{g_{m1}}{C_L} \qquad SR = \frac{I_T}{C_L}$$



In terms of practical design space parameters

$$A_0 = \left[\frac{1}{\lambda_1 + \lambda_3}\right]\left(\frac{2}{V_{EB1}}\right) \qquad GB = \left(\frac{P}{V_{DD}C_L}\right) \bullet \left[\frac{1}{V_{EB1}}\right] \qquad SR = \frac{P}{V_{DD}C_L}$$

Is a factor of 2 improvement in A_0, GB, and SR significant?

Amplifier Comparison

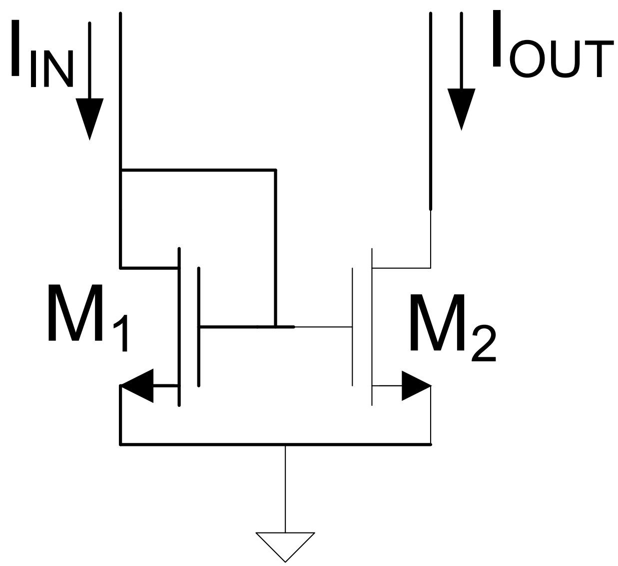
Small Signal Parameter Domain			
Reference Op Amp (single-ended ouput) (5T Op Amp)	$A_{VO} = \frac{1}{2}\frac{g_{m1}}{g_{O1}+g_{O3}}$	$GB = \frac{g_{m1}}{2C_L}$	$SR = \frac{g_{01}}{\lambda C_L}$
Practical Parameter Domain			
Reference Op Amp (single-ended ouput) (5T Op Amp)	$A_{V0} = \left[\frac{1}{\lambda_1+\lambda_3}\right]\left(\frac{1}{V_{EB1}}\right)$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

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)	$A_{V0} = \left[\frac{2}{\lambda_1+\lambda_3}\right]\left(\frac{1}{V_{EB1}}\right)$	$GB = \left(\frac{P}{V_{DD}C_L}\right)\bullet\left[\frac{1}{V_{EB1}}\right]$	$SR = \frac{P}{V_{DD}C_L}$

Current Mirrors

- Current mirrors are really just current amplifiers
- Current mirror (from counterpart circuit) can be used to eliminate CMFB and double gain in basic op amp
- Many different current mirrors exist with varying levels of performance (performance with some better than counterpart current mirror)
- Current mirror not necessarily from counterpart of quarter circuit but often is

Basic Current Mirror



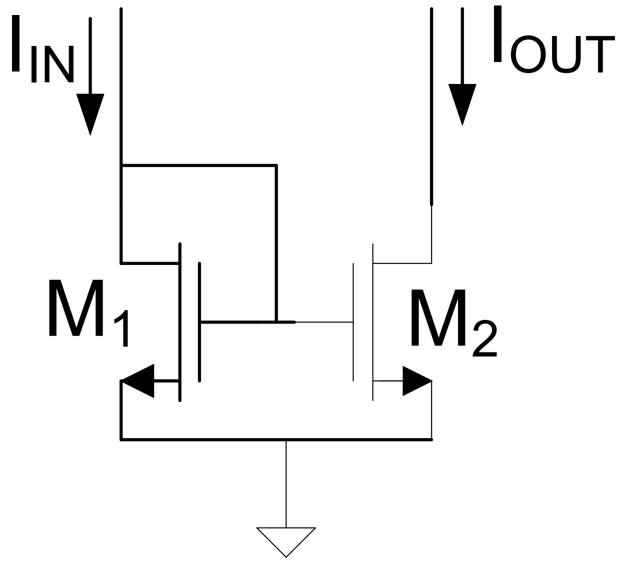
$$I_{IN} = \frac{\mu C_{OX} W_1}{2L_1}\left(V_{GS1} - V_T\right)^2$$

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

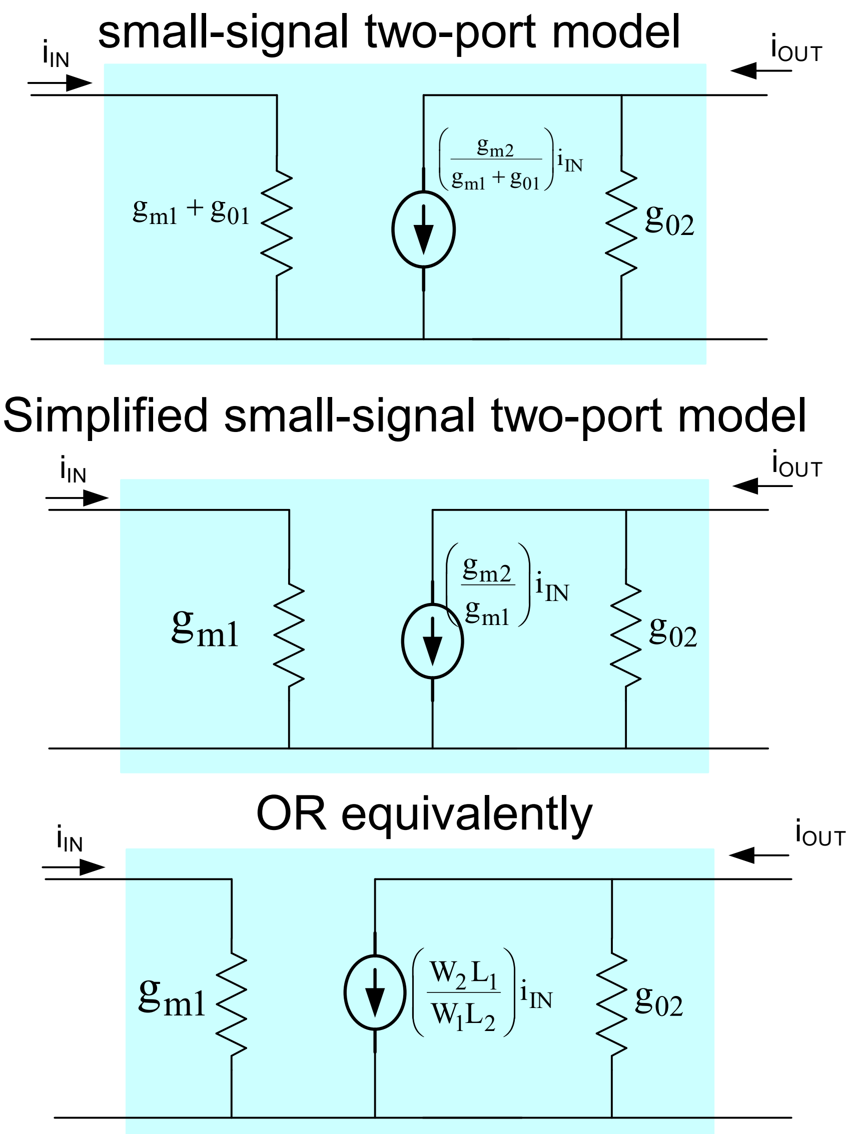
$$\frac{I_{OUT}}{I_{IN}} = \frac{W_2}{W_1}\frac{L_1}{L_2}$$

n-channel

Basic Current Mirror

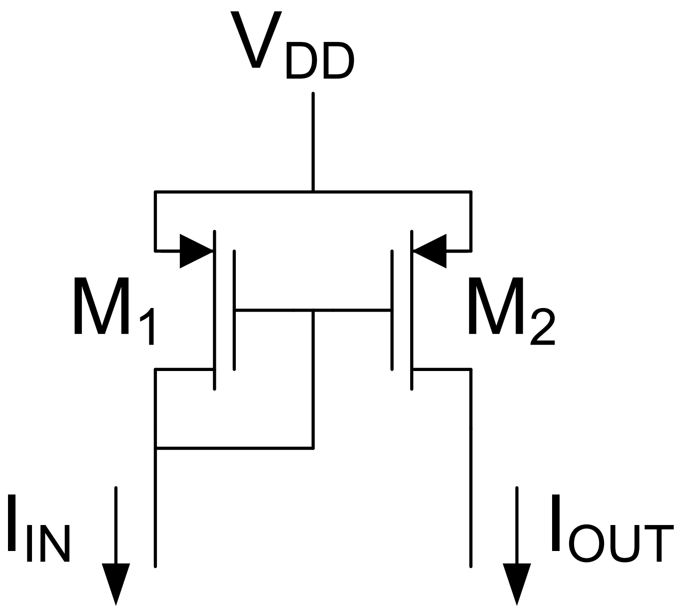


n-channel



If g_{02} is neglected $i_{OUT}=\left(\frac{W_2L_1}{W_1L_2}\right)i_{IN}$

Basic Current Mirror



p-channel

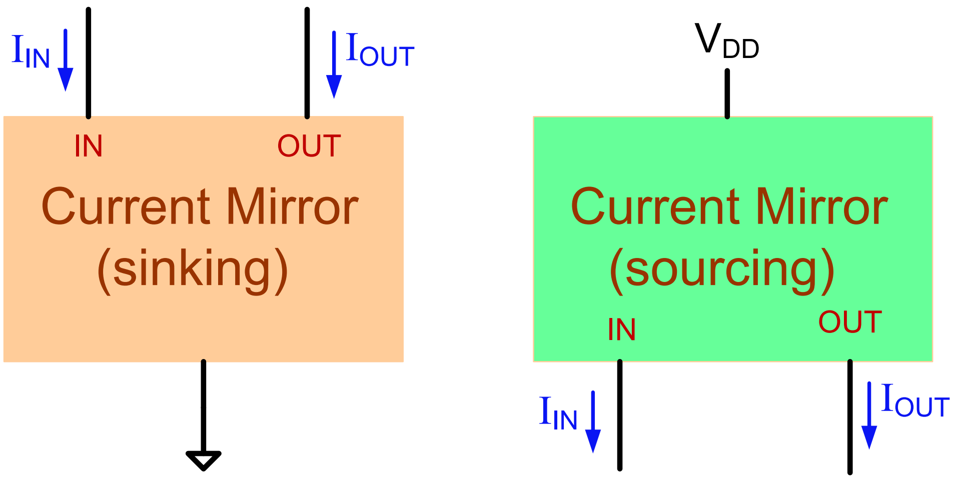
$$I_{IN} = \frac{\mu C_{OX} W_1}{2L_1}\left(V_{GS1}-V_T\right)^2$$

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

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

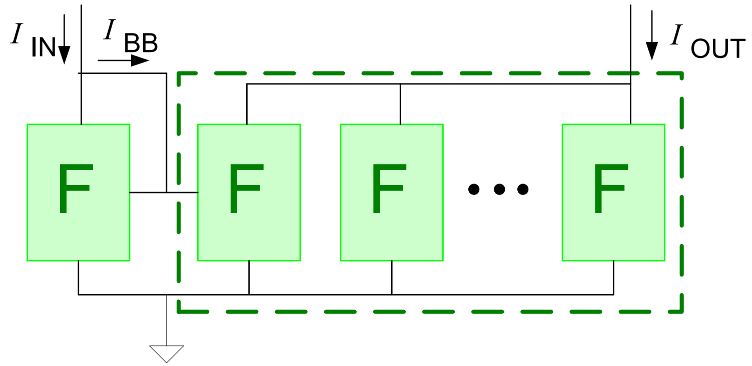
Since counterpart of n-channel current mirror, small signal models identical

Current Mirrors



- More advanced current mirrors exist
- Several of these are discussed in the text

Current Mirrors



K copies of F on right

$$I_{OUT} = KI_{IN}$$

- Quarter circuits with high output impedance are useful for building current mirrors

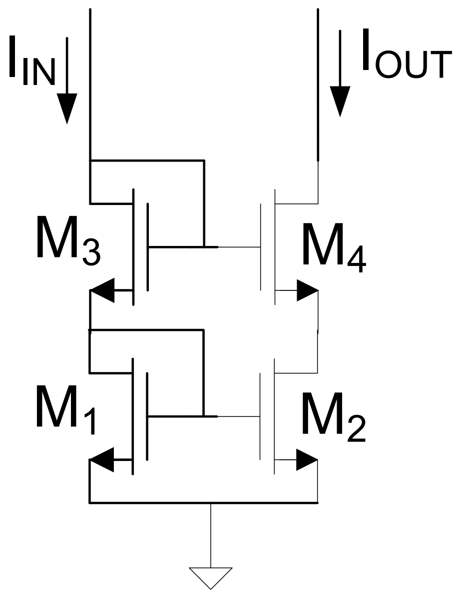
- Replication of K copies is often simply denoted as a device sizing or scaling factor

Properties of Current Mirrors of Interest:

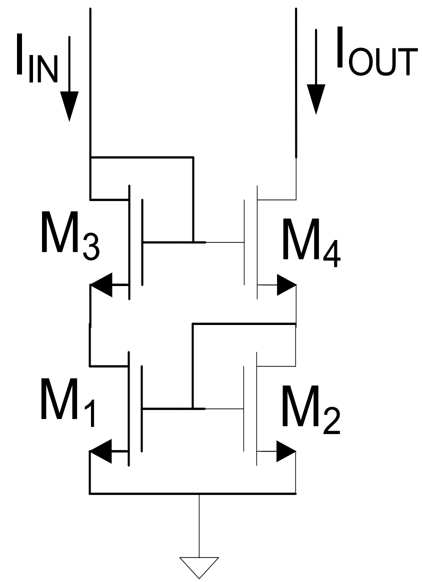
- Mirror Gain Accuracy
- Signal Swing at Output
- Output Impedance (ideally infinite)

More advanced current mirrors usually offer improvements in one or more of these properties but at the expense of another of these properties.

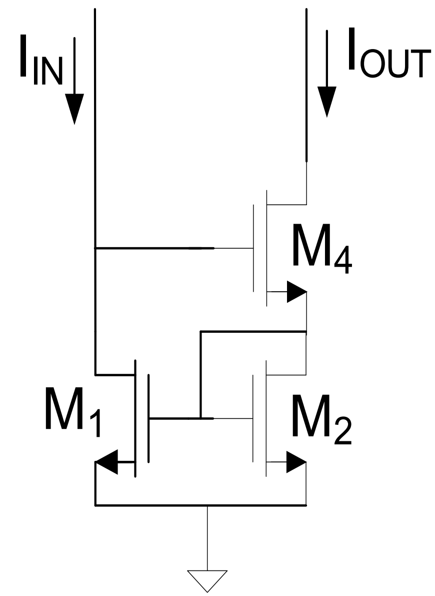
More Advanced Current Mirrors



Cascode Current Mirror

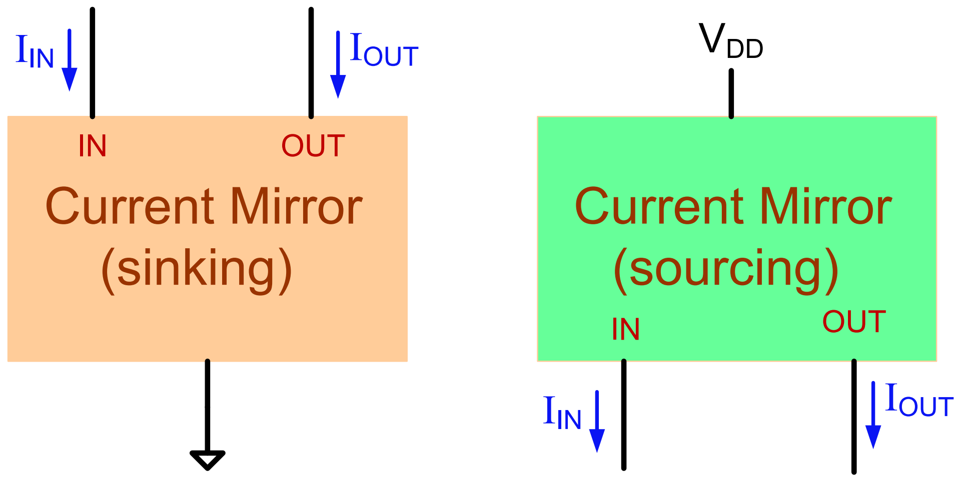


Modified Wilson Current Mirror



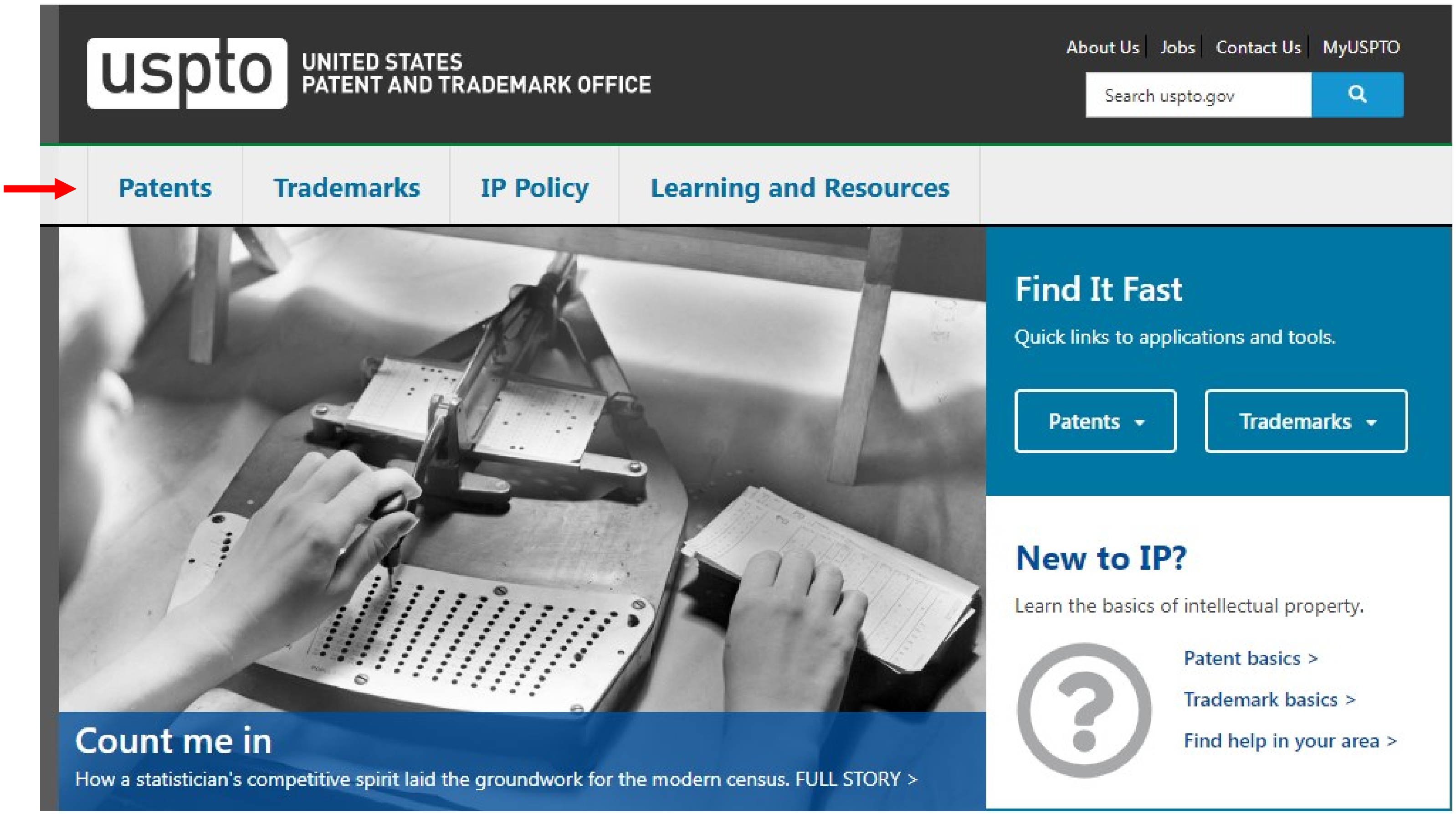
Wilson Current Mirror

Current Mirrors



- The concept of the current mirror was first introduced in about 1969 (not certain who introduced it but probably Wheatley and Wittlinger)
- Many of the basic current mirror circuits were introduced within a few years after the concept first appeared
- How many current mirror circuits are there?
- Have any current mirrors been introduced recently?
- Is there still an opportunity to contribute to the current mirror field?

Consider only US patents



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How to Conduct a Preliminary U.S. Patent Search: A Step by Step Strategy - Web Based Tutorial (38 minutes)

- The Seven Step Strategy - Outlines a suggested procedure for patent searching
- A detailed handout of the Seven Step Strategy with examples and screen shots.

Patents may be searched using the following resources:

- USPTO Patent Full-Text and Image Database (PatFT)
- USPTO Patent Application Full-Text and Image Database (AppFT)
- Global Dossier
- Patent Application Information Retrieval (PAIR)
- Public Search Facility
- Patent and Trademark Resource Centers (PTRCs)
- Patent Official Gazette
- Common Citation Document (CCD)
- Search International Patent Offices
- Search Published Sequences
- Patent Assignment Search
- Patent Examination Data System (PEDS)

USPTO search on Jan 27, 2022

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

	PAT. NO.	Title
1	11,188,112	T Current mirror arrangements with adjustable offset buffers
2	11,152,944	T Termination calibration scheme using a current mirror
3	11,106,233	T Current mirror arrangements with reduced input impedance
4	11,068,010	T Current mirror circuit
5	11,050,424	T Current-mirror based level shifter circuit and methods for implementing the same
6	10,964,743	T Imaging device comprising current mirror circuit
7	10,943,656	T Methods and apparatuses having a voltage generator with an adjustable voltage drop for representing a voltage drop of a memory c
8	10,895,887	T Current mirror arrangements with reduced sensitivity to buffer offsets
9	10,877,503	T Attenuating common mode noise current in current mirror circuits
10	10,845,839	T Current mirror arrangements with double-base current circulators
11	10,839,879	T Read techniques for a magnetic tunnel junction (MTJ) memory device with a current mirror
12	10,756,509	T Accurate current mirror circuit in low voltage headroom applied to laser drivers
13	10,698,435	T Electronic current equalization module, current mirror circuit and method of assembling a current mirror circuit
14	10,671,911	T Current mirror scheme for an integrating neuron circuit
15	10,620,656	T Operating voltage switching device with current mirror
16	10,593,499	T Relay drive circuit with a current mirror circuit
17	10,574,141	T Current mirror calibration circuit and current mirror calibration method
18	10,509,431	T Reversible current mirror and its use in bidirectional communication
19	10,496,121	T Current mirror circuit and driving method of the current mirror circuit
20	10,444,364	T Pinned photodiode pixels including current mirror-based background light suppression, and imaging devices including the same

USPTO search on Feb 2, 2021

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

	PAT. NO.	Title
1	10,895,887 T	Current mirror arrangements with reduced sensitivity to buffer offsets
2	10,877,503 T	Attenuating common mode noise current in current mirror circuits
3	10,845,839 T	Current mirror arrangements with double-base current circulators
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12	10,496,121 T	Current mirror circuit and driving method of the current mirror circuit
13	10,444,364 T	Pinned photodiode pixels including current mirror-based background light suppression, and imaging devices including the same
14	10,439,562 T	Current mirror bias compensation circuit
15	10,419,057 T	Modified current mirror circuit for reduction of switching time
16	10,386,880 T	Circuit arrangement for compensating current variations in current mirror circuit
17	10,373,681 T	Methods and apparatuses having a voltage generator with an adjustable voltage drop for representing a voltage drop of a memo
18	10,353,421 T	Current mirror device and related amplifier circuit
19	10,340,004 T	Write voltage generating circuit comprising a current mirror
20	10,332,590 T	Static random access memory (SRAM) bit cells employing current mirror-gated read ports for reduced power consumption
21	10,331,844 T	Methods of tuning current ratio in a current mirror for transistors formed with the same FEOL layout and a modified BEOL lay
22	10,317,925 T	Attenuating common mode noise current in current mirror circuits
23	10,228,713 T	Large range current mirror
24	10,133,293 T	Low supply active current mirror
25	10,133,292 T	Low supply current mirror

USPTO search on Jan 24, 2020

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

	PAT. NO.	Title
1	10,509,431	Reversible current mirror and its use in bidirectional communication
2	10,496,121	Current mirror circuit and driving method of the current mirror circuit
3	10,444,364	Pinned photodiode pixels including current mirror-based background light suppression, and imaging devices including the same
4	10,439,562	Current mirror bias compensation circuit
5	10,419,057	Modified current mirror circuit for reduction of switching time
6	10,386,880	Circuit arrangement for compensating current variations in current mirror circuit
7	10,373,681	Methods and apparatuses having a voltage generator with an adjustable voltage drop for representing a voltage drop of a memory ce
8	10,353,421	Current mirror device and related amplifier circuit
9	10,340,004	Write voltage generating circuit comprising a current mirror
10	10,332,590	Static random access memory (SRAM) bit cells employing current mirror-gated read ports for reduced power consumption
11	10,331,844	Methods of tuning current ratio in a current mirror for transistors formed with the same FEOL layout and a modified BEOL layout
12	10,317,925	Attenuating common mode noise current in current mirror circuits
13	10,228,713	Large range current mirror
14	10,133,293	Low supply active current mirror
15	10,133,292	Low supply current mirror
16	10,095,259	Circuit arrangement for compensating current variations in current mirror circuit
17	10,089,929	Pixel driver circuit with load-balance in current mirror circuit
18	10,076,326	Surgical stapler having current mirror-based motor control
19	10,054,974	Current mirror devices using cascode with back-gate bias
20	10,038,431	Current mirror array for high-frequency clock generator

USPTO search on Jan 21, 2018

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

	PAT. NO.		Title
1	9,864,395	T	Base current compensation for a BJT current mirror
2	9,857,824	T	Calibration of a resistor in a current mirror circuit
3	9,829,906	T	Current mirror circuit and receiver using the same
4	9,787,178	T	Current mirror circuit and charge pump circuit
5	9,746,871	T	Noise canceling current mirror circuit for improved PSR
6	9,740,232	T	Current mirror with tunable mirror ratio
7	9,728,256	T	Methods and apparatuses having a voltage generator with an adjustable voltage drop for representing a voltage drop
8	9,713,212	T	Current mirror circuit and method
9	9,693,417	T	LED mains voltage measurement using a current mirror
10	9,680,483	T	Current mirror circuit and charge pump circuit
11	9,671,228	T	Floating current mirror for RLG discharge control
12	9,641,167	T	Current mirror circuits with narrow bandwidth bias noise reduction
13	9,638,584	T	Differential temperature sensor with sensitivity set by current-mirror and resistor ratios without limiting DC bias
14	9,632,522	T	Current mirror bias circuit with voltage adjustment
15	9,622,303	T	Current mirror and constant-current LED driver system for constant-current LED driver IC device
16	9,595,310	T	Circuits for control of time for read operation, using a current mirror circuit to mirror a reference current into the du
17	9,563,223	T	Low-voltage current mirror circuit and method
18	9,559,641	T	Current mirror, control method, and image sensor
19	9,548,022	T	Pixel and organic light emitting display device including current mirror
20	9,497,402	T	Image lag mitigation for buffered direct injection readout with current mirror

USPTO search on Jan 26, 2014

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

Results of Search in US Patent Collection db for:
TTL/(current AND mirror): 509 patents.
*Hits **1** through **50** out of **509***

Next 50 Hits

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Refine Search TTL/(current AND mirror)

	PAT. NO.	
1	8,618,787	Current mirror and high-compliance single-stage amplifier
2	8,598,953	System and method for pre-charging a current mirror
3	8,598,914	Comparator circuit with current mirror
4	8,587,287	High-bandwidth linear current mirror
5	8,575,971	Current mirror and current cancellation circuit
6	8,569,674	Multiplexed photocurrent monitoring circuit comprising current mirror circuits
7	8,537,868	Laser diode write driver feedback, current mirror, and differential-pair circuitry
8	8,531,236	Current mirror arrangement and method for switching on a current
9	8,519,794	Current mirror with low headroom and linear response
10	8,511,842	Eddy current based mirror wavefront control
11	8,502,751	Pixel driver circuit with load-balance in current mirror circuit
12	8,471,631	Bias circuit, power amplifier, and current mirror circuit
13	8,456,227	Current mirror circuit
14	8,450,992	Wide-swing cascode current mirror
15	8,441,381	Gate leakage compensation in a current mirror

USPTO search on Jan 22, 2012

475 patents with “current and mirror” in title ~~since~~ 1976

Searching US Patent Collection...

Results of Search in US Patent Collection db for:
TTL/(current AND mirror): 475 patents.
*Hits **1** through **50** out of **475***

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Refine Search ttl/(current and mirror)

	PAT. NO.	Title
1	8,026,757 T	Current mirror circuit, in particular for a non-volatile memory device
2	7,994,861 T	System and method for pre-charging a current mirror
3	7,973,488 T	Constant current driver circuit with voltage compensated current sense mirror
4	7,933,138 T	F-RAM device with current mirror sense amp
5	7,932,712 T	Current-mirror circuit
6	7,923,942 T	Constant current source mirror tank dimmable ballast for high impedance lamps
7	7,915,948 T	Current mirror circuit
8	7,911,870 T	Fuse data read circuit having control circuit between fuse and current mirror circuit
9	7,907,012 T	Current mirror with low headroom and linear response
10	7,894,235 T	F-RAM device with current mirror sense amp
11	7,889,106 T	Current mirror circuit and digital-to-analog conversion circuit
12	7,868,808 T	Phase-locked loop circuitry using charge pumps with current mirror circuitry
13	7,859,135 T	Internal power supply circuit having a cascode current mirror circuit
14	7,858,966 T	Protected qubit based on superconducting current mirror
15	7,851,834 T	Cascode current mirror and method
16	7,839,670 T	F-RAM device with current mirror sense amp
17	7,834,694 T	Differential current mirror circuit

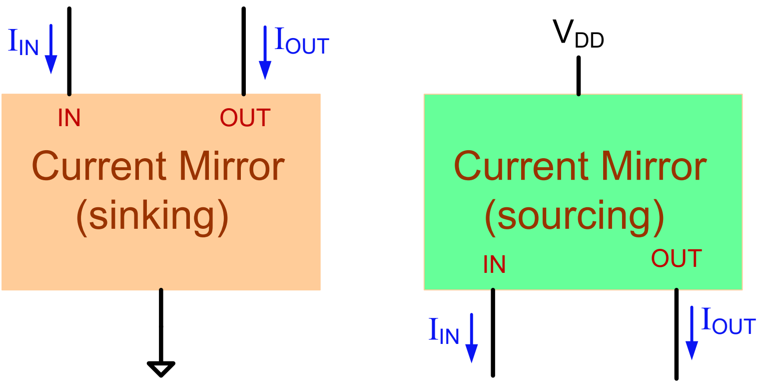
USPTO search on Jan 27, 2022

612 patents with “current and mirror” in title between 1976 and 2021

7 patents with “current and mirror” in title in 2021

- Averaged 12.4 patents/year from 1976 to 2006
- Averaged 17 patents/year in 2012 and 2013
- Averaged 13 patents/year in 2016 and 2017
- Averaged 13 patents/year in 2018 and 2020
- 7 patents from Feb 2, 2021 to Jan 27, 2022

USPTO search on Jan 21, 2018



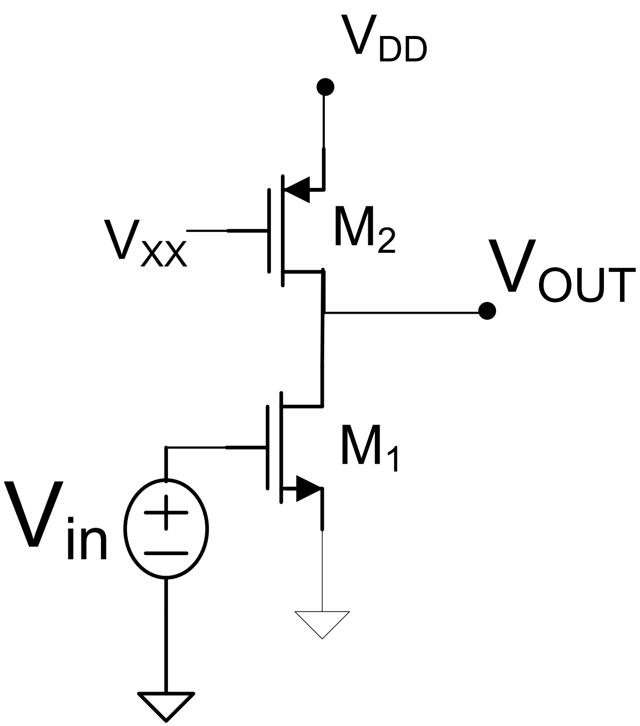
612 patents with “current and mirror” in title since 1976

Number of patents/year in past decade is still close to 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

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

To keep M_1 out of Cutoff

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

To keep M_2 out of Triode Region

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

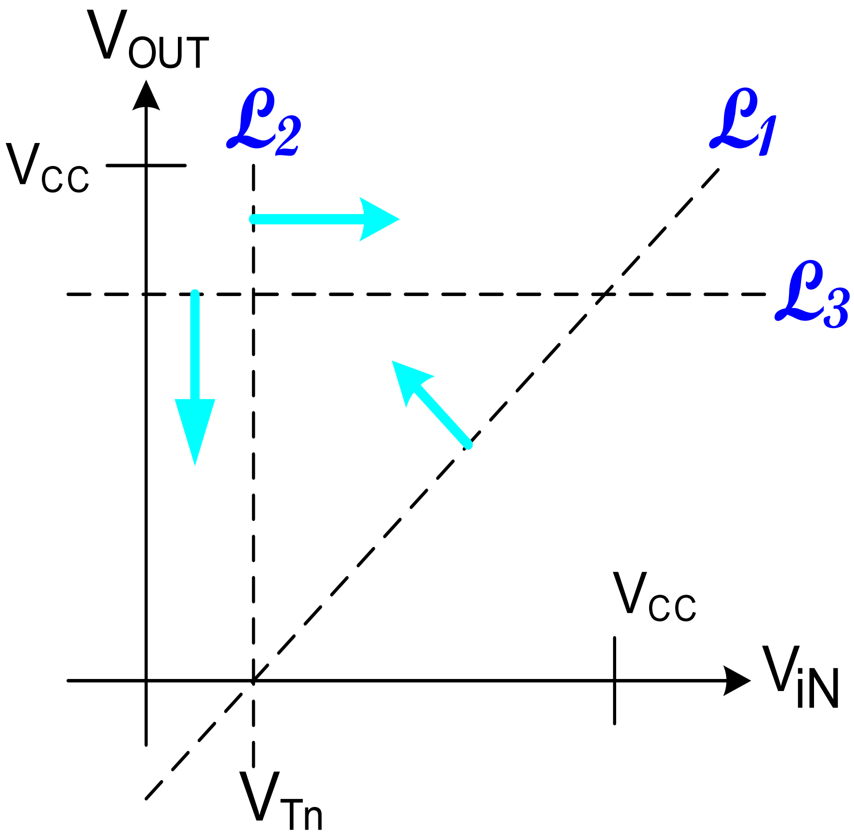
$$V_{XX} - V_{Tp} > V_{OUT}$$

Signal Swing

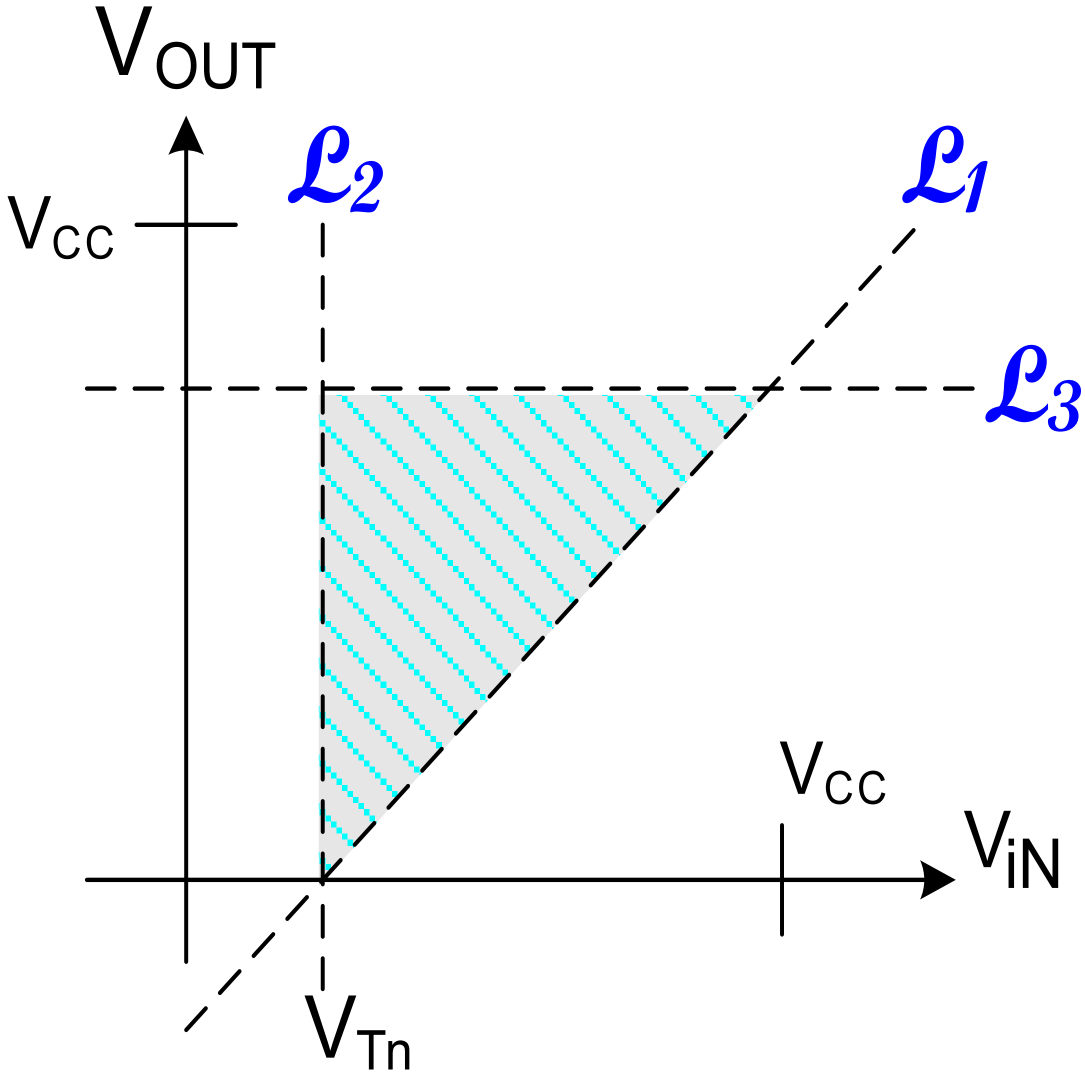
$\mathcal{L}_1$: $V_{OUT} > V_{iN} - V_{Tn}$

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

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



Signal Swing

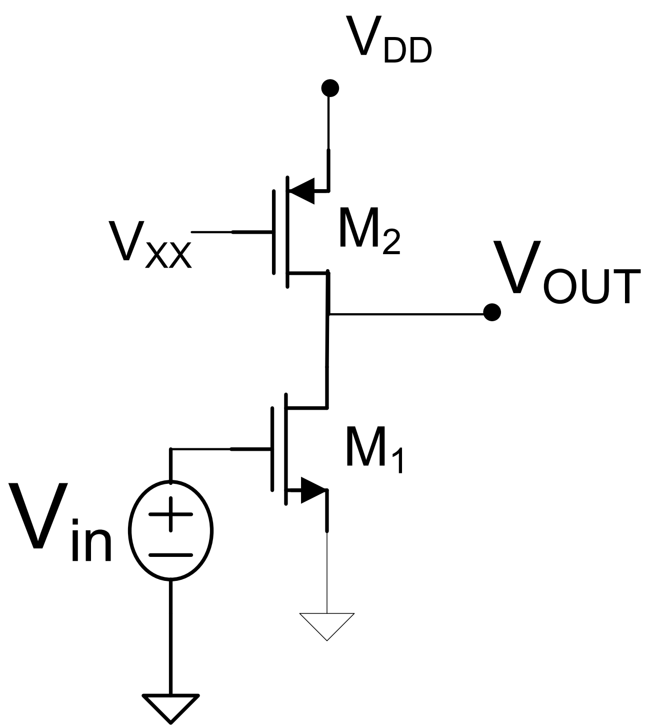


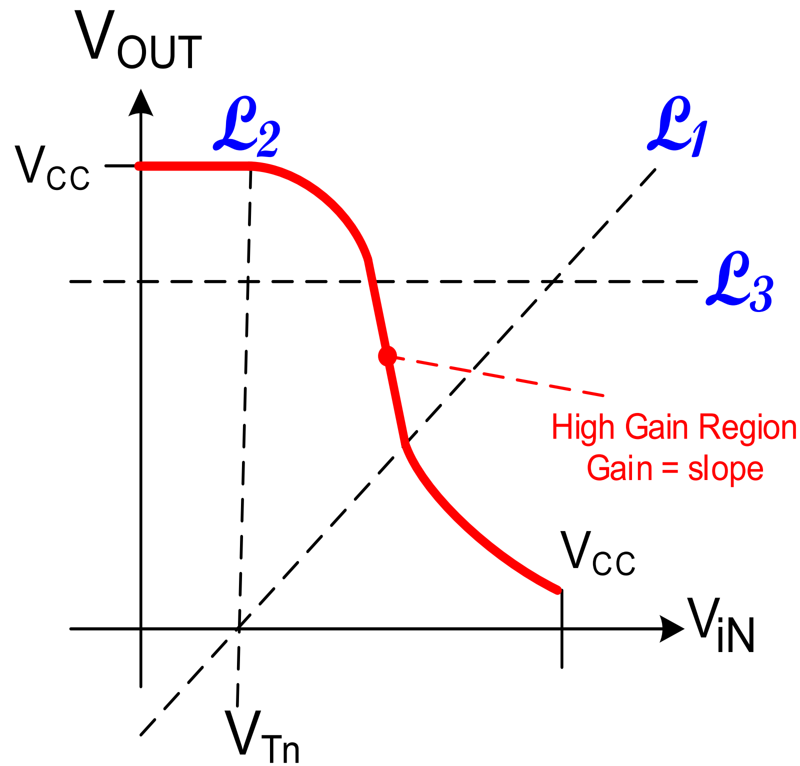
$\mathcal{L}_1$: $V_{OUT} > V_{iN} - V_{Tn}$

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

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

Signal Swing



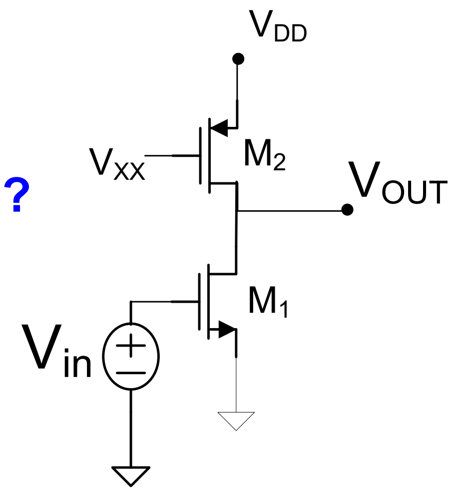


Transfer Characteristics of amplifier

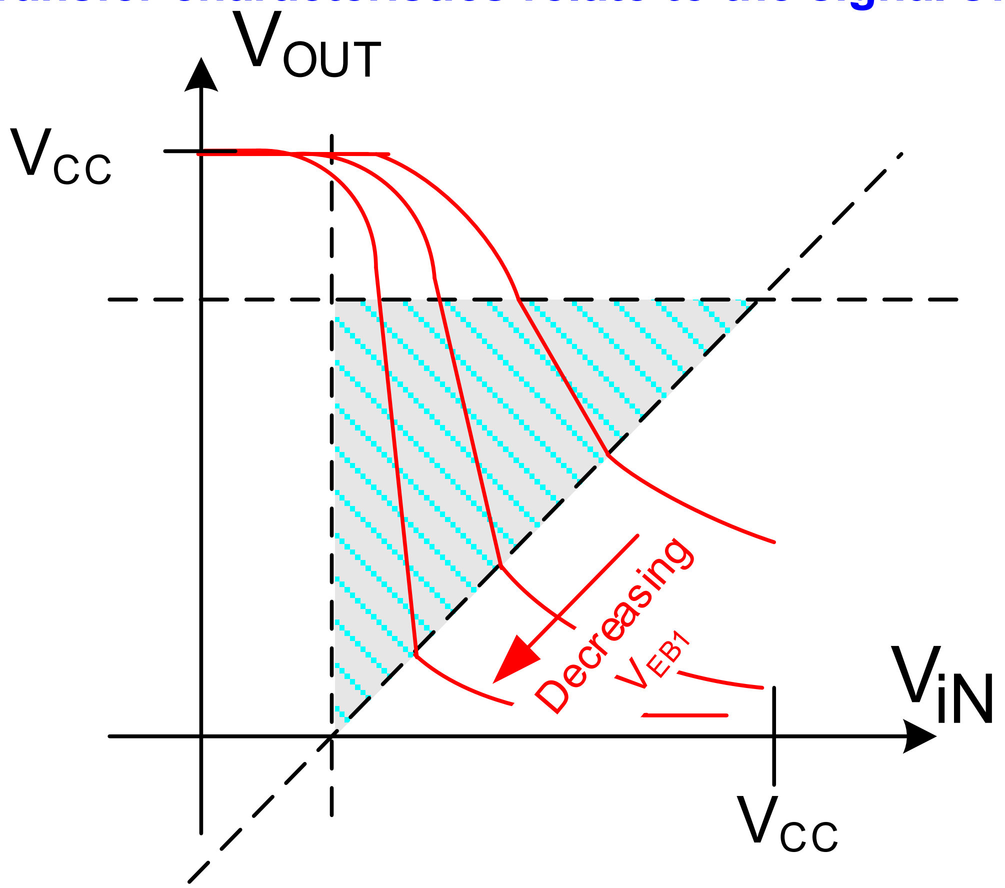
How do the transfer characteristics relate to the signal swing ?

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}

Stay Safe and Stay Healthy !

End of Lecture 5