

# EE 435


## Lecture 5

### Single-Stage Low-Gain Op Amps

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

Review from last lecture:  
Where we are at:

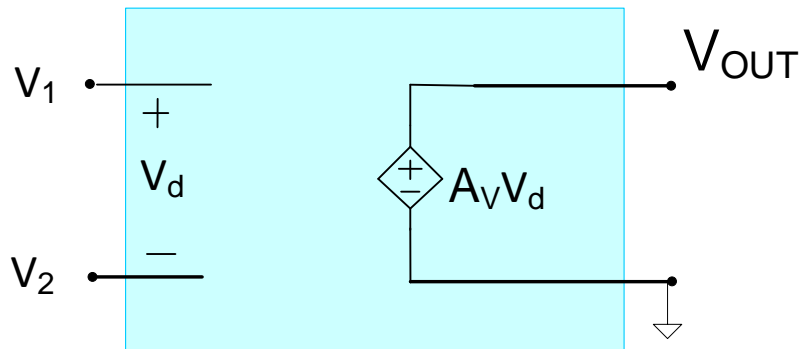
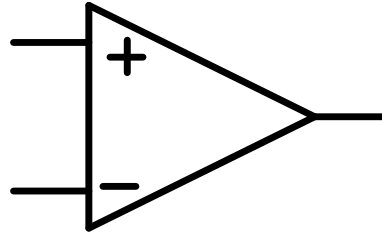
# Basic Op Amp Design

- 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:

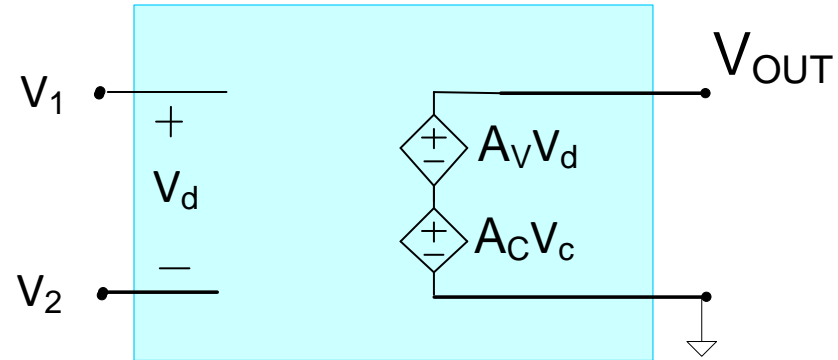
# How is Common-Mode Gain Modeled?

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

$$V_d = V_1 - V_2$$



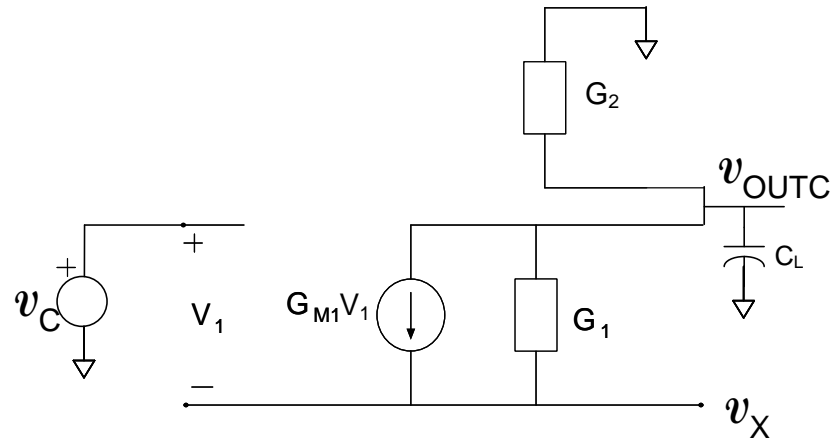
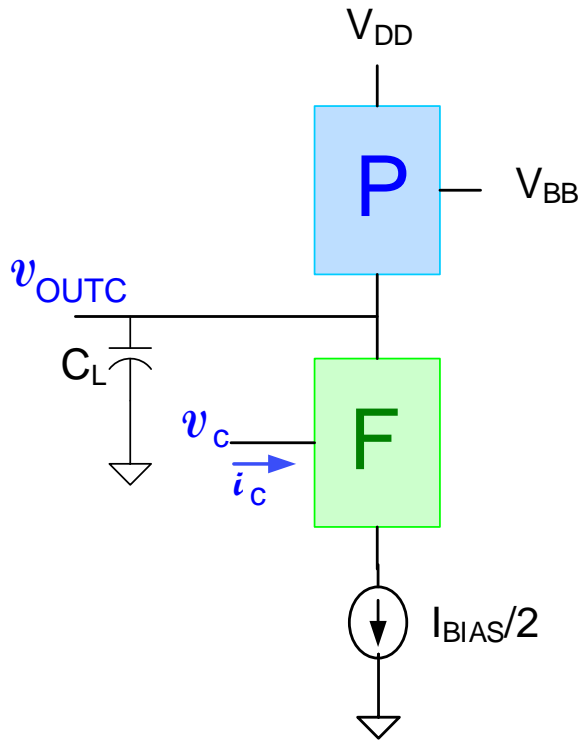
Ideal Voltage Amplifier

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

## Review from last lecture:

# Performance with Common-Mode Input

Consider tail-current bias amplifier with  $i_c=0$



$$\left. \begin{aligned} v_{OUTC}(sC+G_1+G_2)+G_{M1}v_1 &= G_1v_x \\ v_c &= v_1+v_x \\ v_xG_1 - G_{M1}v_1 &= v_{OUTC}G_1 \end{aligned} \right\}$$

Solving, we obtain

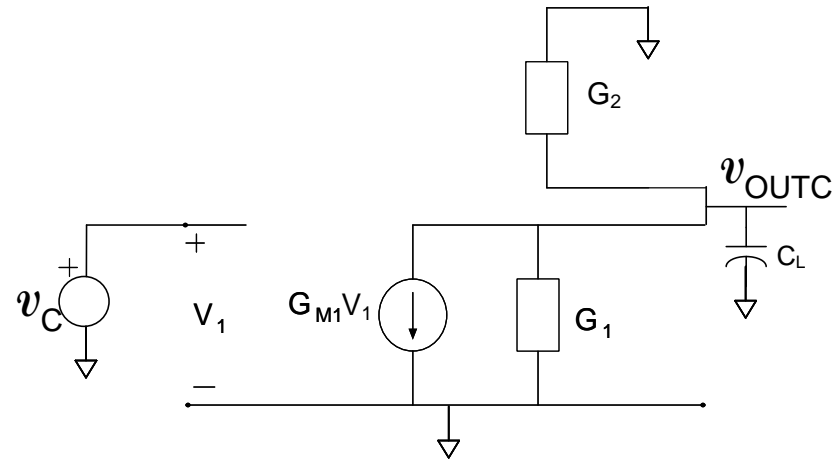
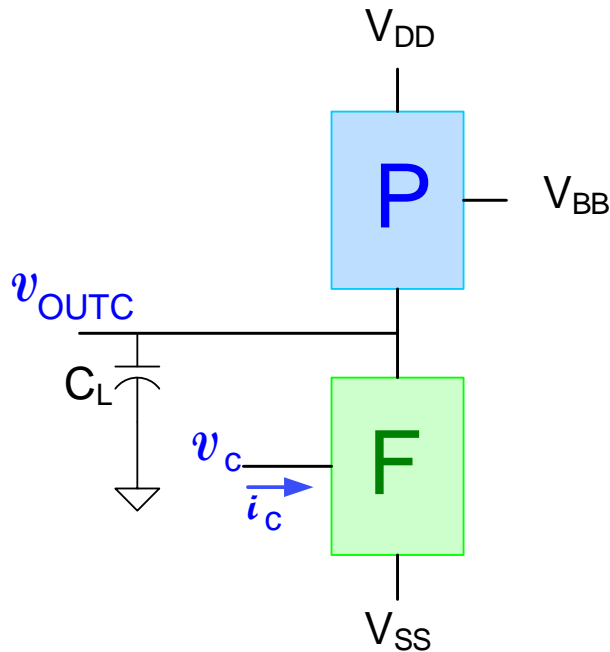
$$v_{OUTC}=0 \quad \text{thus } A_C=0$$

Common-Mode Half-Circuit

(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  $i_c=0$



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

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

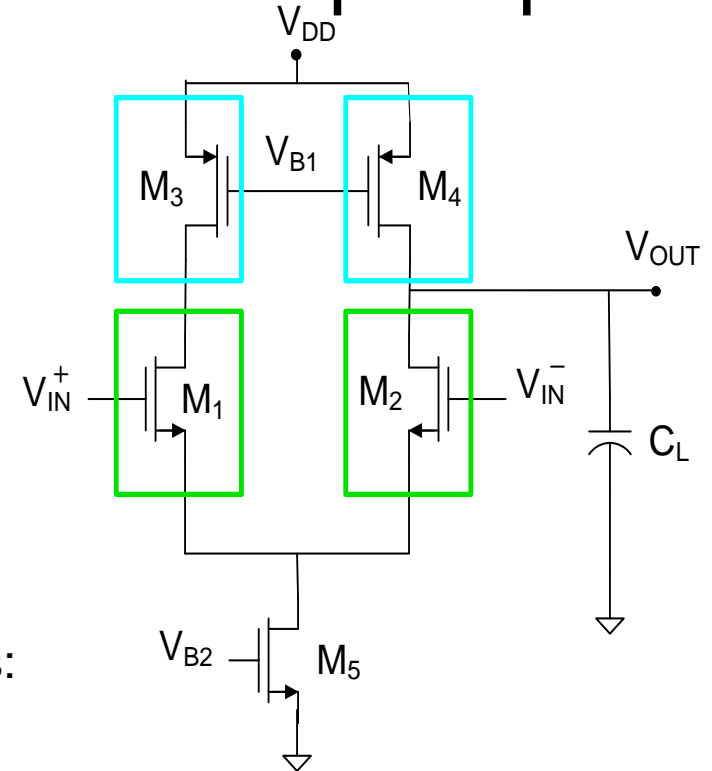
- Not a very good differential amplifier
- But of no concern in applications where  $v_c=0$

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

Single-Ended Output : Differential Input Gain

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

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



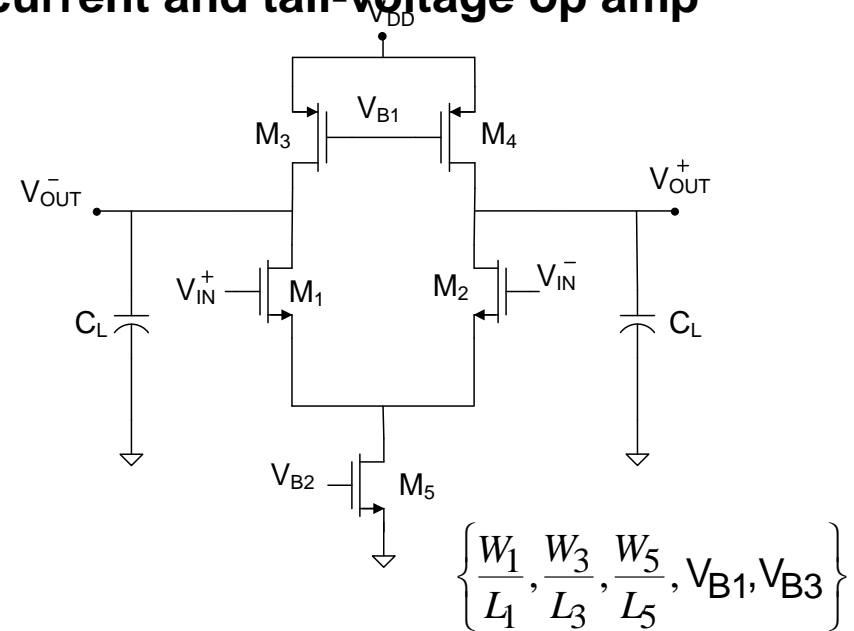
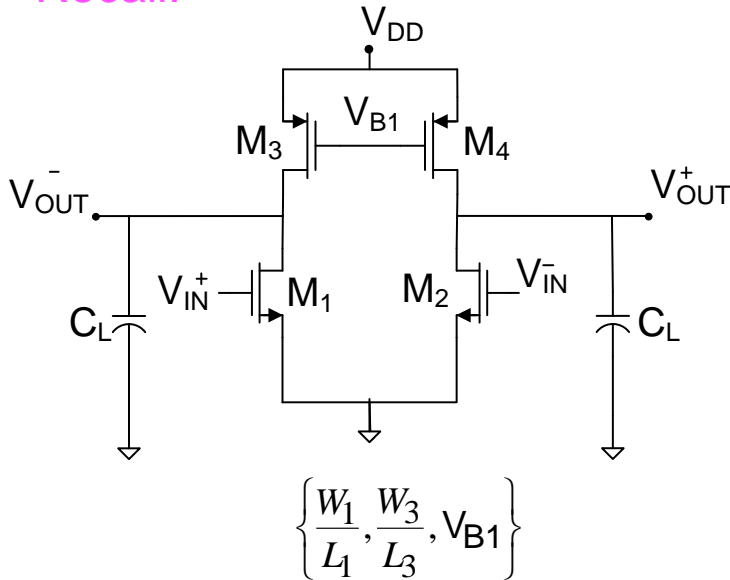
Design Strategy with fixed  $A_0$  and GB requirements:

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

# Review from last lecture:

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



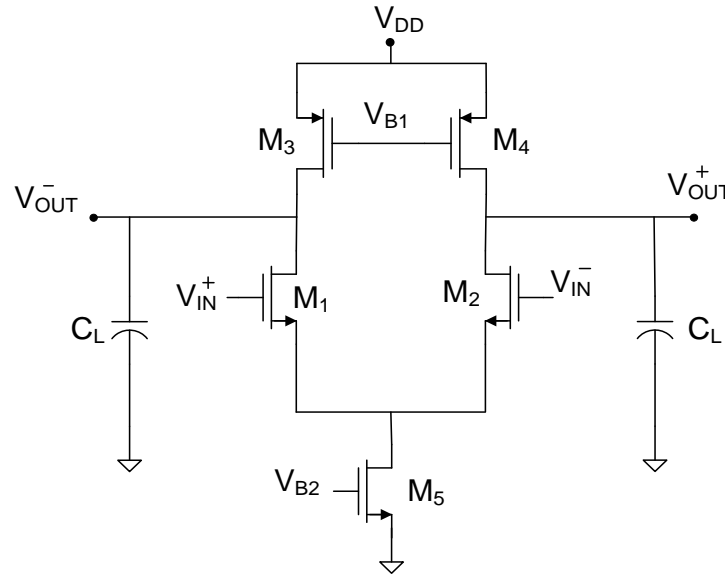
So which one should be used?

- 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)



## Review from last lecture:

# Slew Rate



It can be similarly shown that putting a 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

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



# The Reference Op Amp

Would like to have a specific amplifier, termed a Reference Op Amp, that can serve as a baseline 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

practical parameters

$$A_{VO} = \frac{1}{2} \frac{g_{m1}}{g_{o1} + g_{o3}}$$

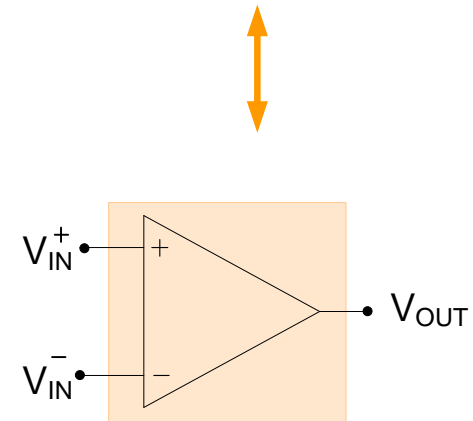
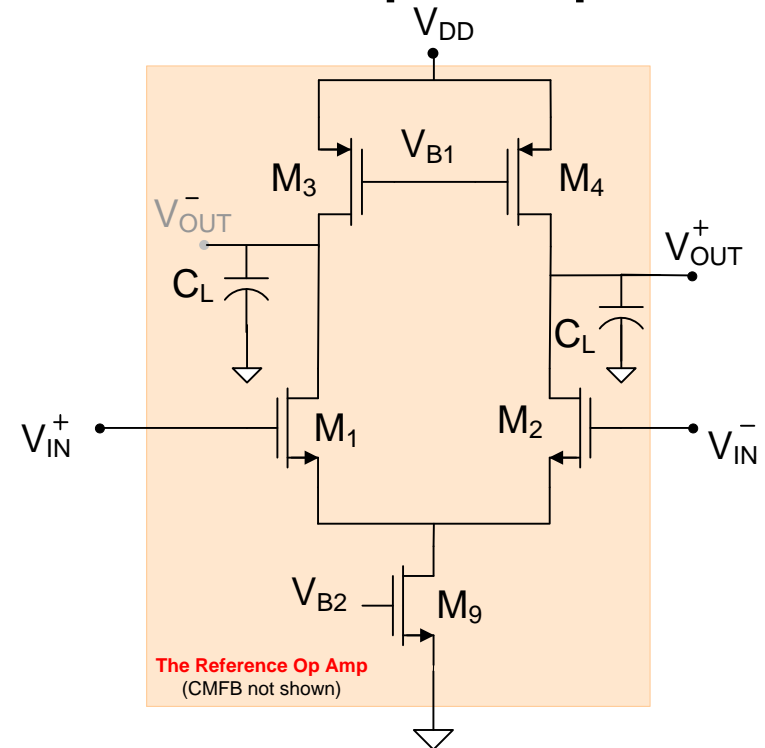
$$A_{V0} = \left[ \frac{1}{\lambda_1 + \lambda_3} \right] \left( \frac{1}{V_{EB1}} \right)$$

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

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

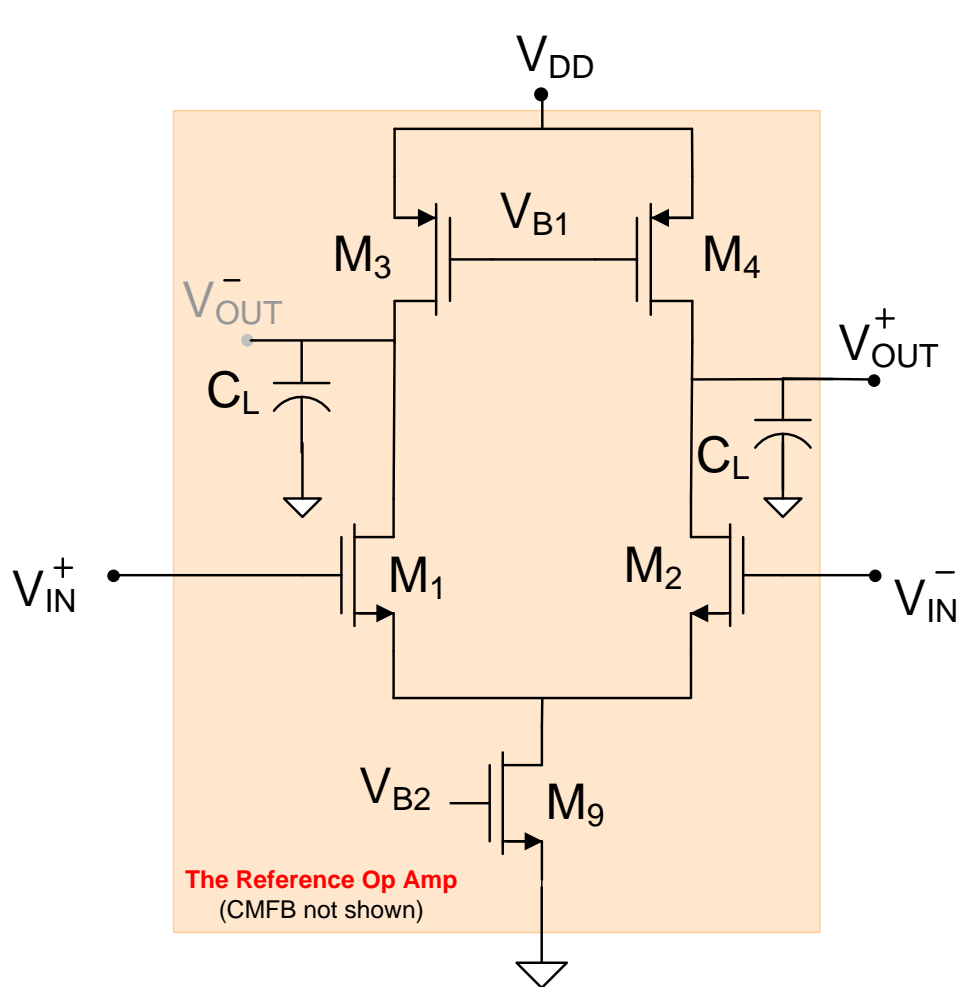
$$SR = \frac{I_T}{2C_L}$$

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



# Reference Op Amp

single-ended output



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

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

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

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

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

- 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	$A_{vo} = \left(\frac{2}{\lambda}\right) \left(\frac{1}{V_{EB}}\right)$	$GB = \left(\frac{2P}{V_{DD} C_L}\right) \left(\frac{1}{V_{EB}}\right)$

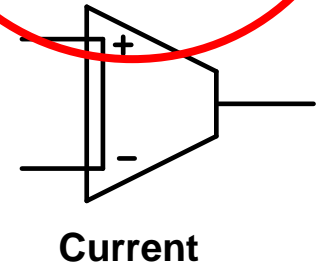
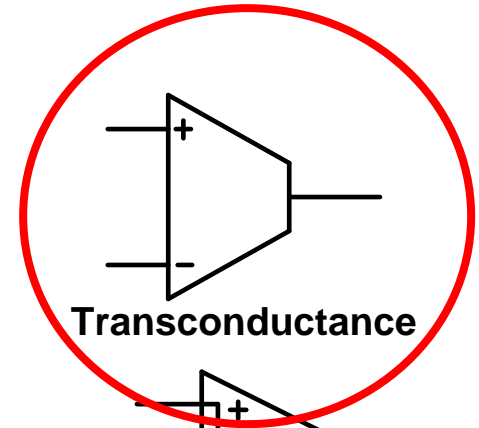
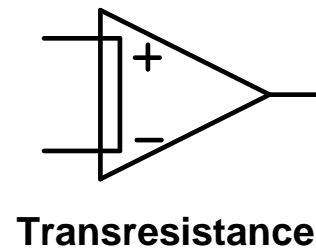
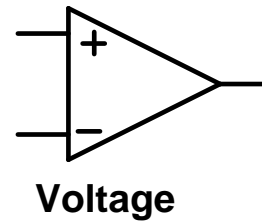
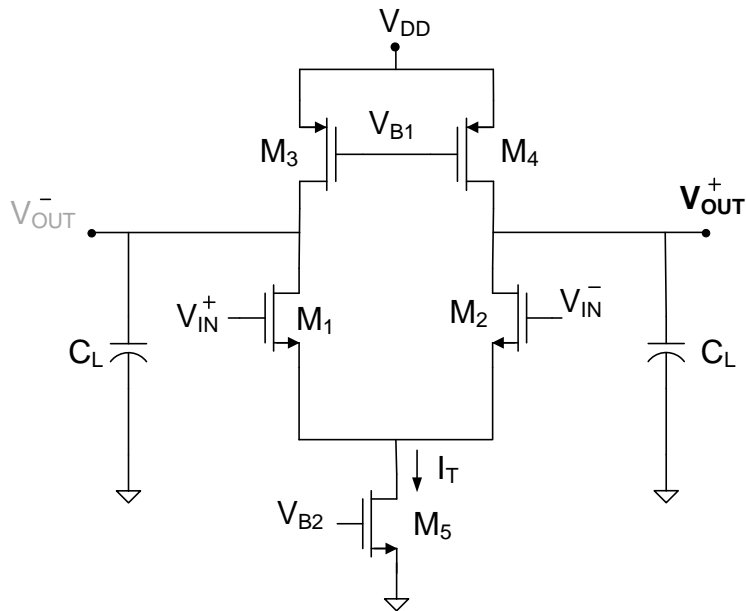
Small Signal Parameter Domain			
Reference Op Amp (single-ended output)	$A_{vo} = \frac{1}{2} \frac{g_{m1}}{g_{o1} + g_{o3}}$	$GB = \frac{g_{m1}}{2C_L}$	$SR = \frac{g_{o1}}{\lambda C_L}$

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

# Reference Op Amp

single-ended output

What basic type of amplifier is this op amp?



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

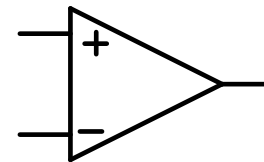
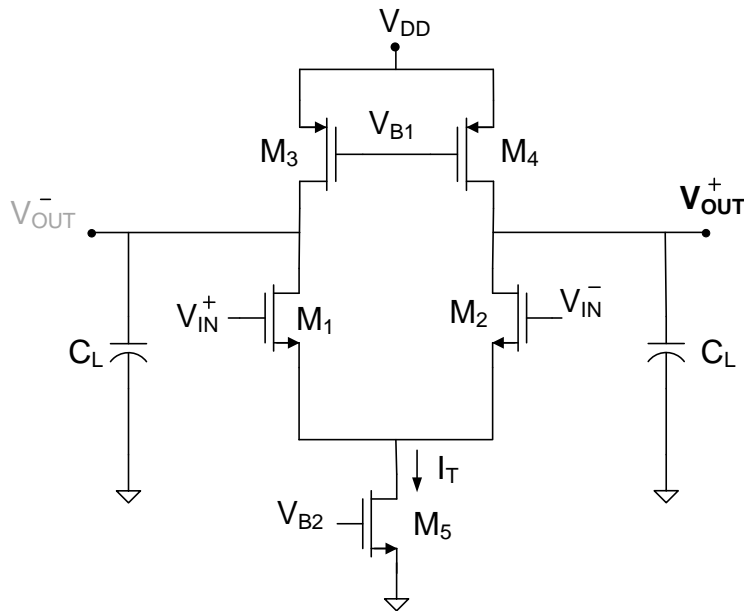
# Reference Op Amp

single-ended output

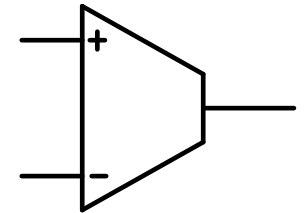
What basic type of amplifier is this op amp?

Does it really matter?

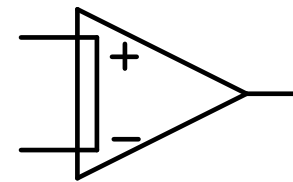
Transconductance



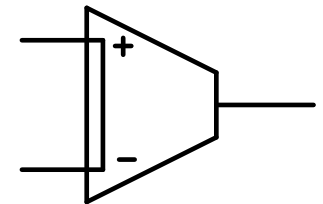
Voltage



Transconductance



Transresistance



Current

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

Where we are at:

# Basic Op Amp Design

- Fundamental Amplifier Design Issues



- Single-Stage Low Gain Op Amps

- Single-Stage High Gain Op Amps

- Two-Stage Op Amp

- Other Basic Gain Enhancement Approaches

Where we are at:

# Basic Op Amp Design

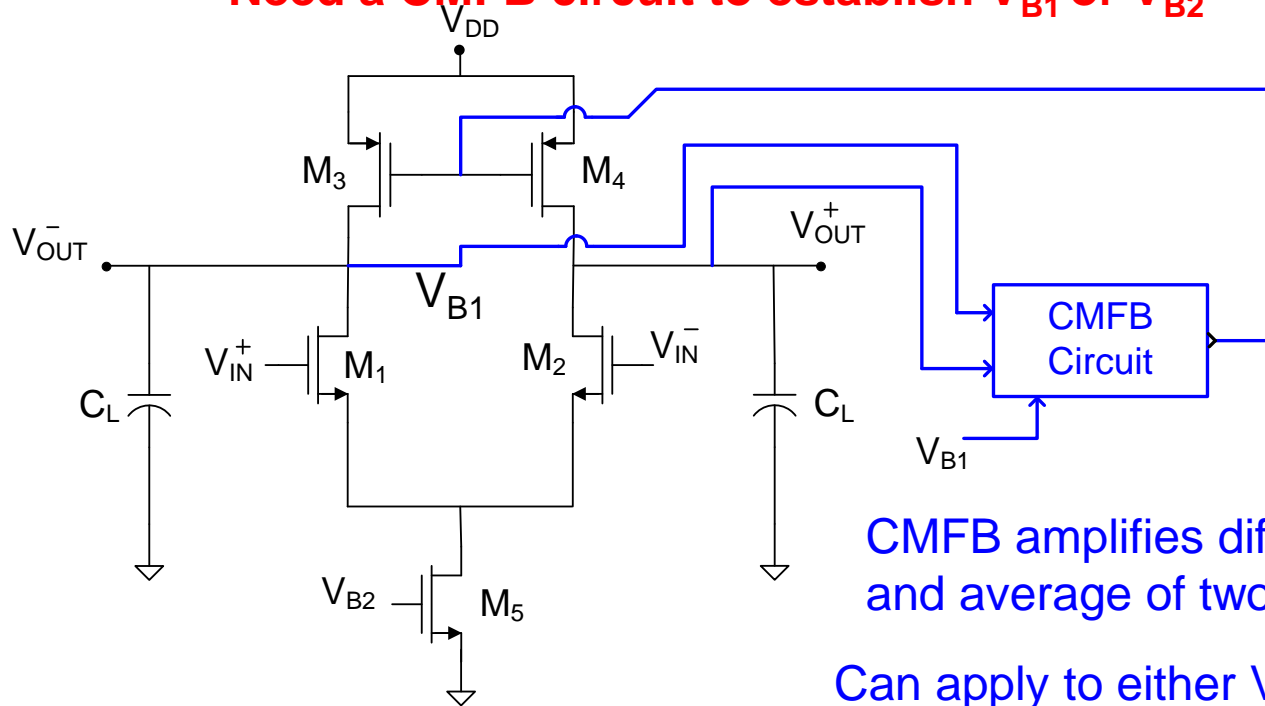
## Single-Stage Low Gain Op Amps

- 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

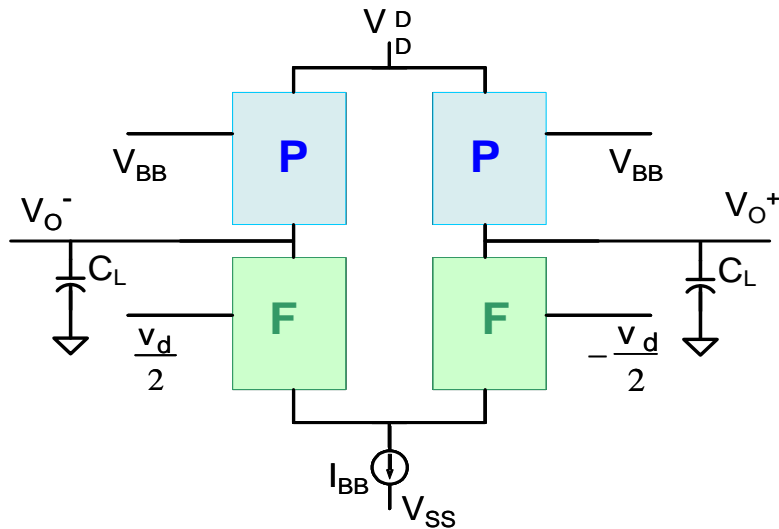
Can apply to either  $V_{B1}$  or  $V_{B2}$  but not both

Often apply to only fraction of transistor

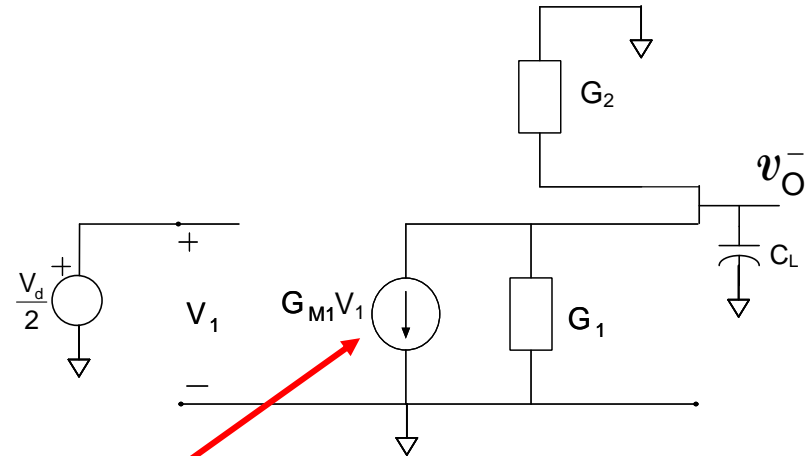
The CMFB circuit is often quite large and requires considerable design effort!

Can the CMFB be removed?

# Operation of Op Amp – A different perspective



Small signal differential half-circuit



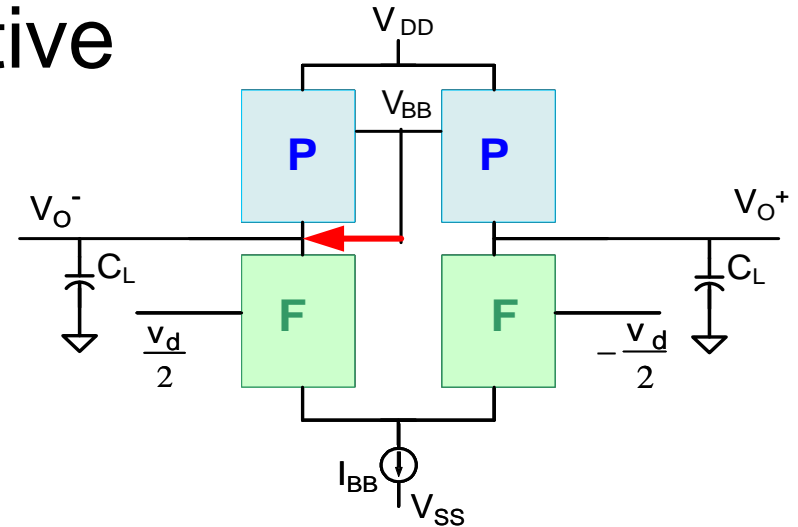
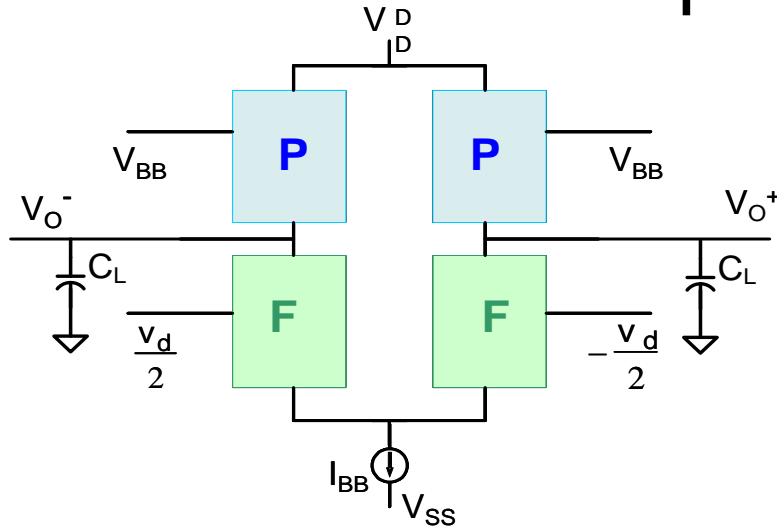
- The signal dependent current in quarter circuit is steered to output node and drives the parallel output conductances of the quarter circuit and counterpart circuit
- If  $G_1$  and  $G_2$  are small, the voltage gain will be large
- If the signal-dependent current could be doubled without changing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

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

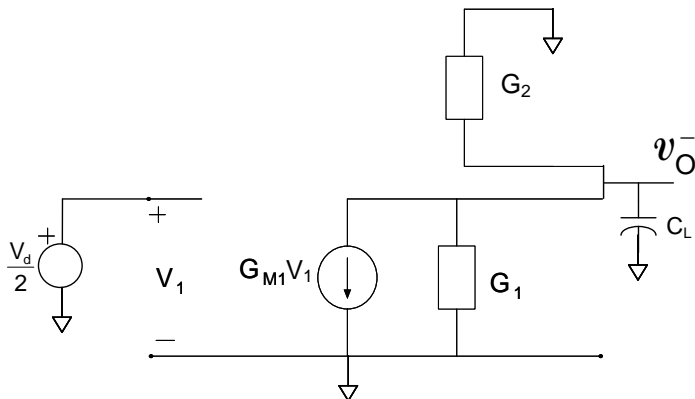
$$BW = \frac{G_1 + G_2}{C_L}$$

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

# Operation of Op Amp – A different perspective



## Small signal differential half-circuit



No signal current driving counterpart circuit

- 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  $V_O^-$  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
- This will approximately double the signal current steered to  $V_O^+$  and thus double the voltage gain ! (formal derivation on following slide)
- Voltage Gain to  $V_{OUT}^-$  not high so this output seldom used
- This will also eliminate the need for a CMFB circuit !

# Doubling of Gain with “Current Mirror” connection

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

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

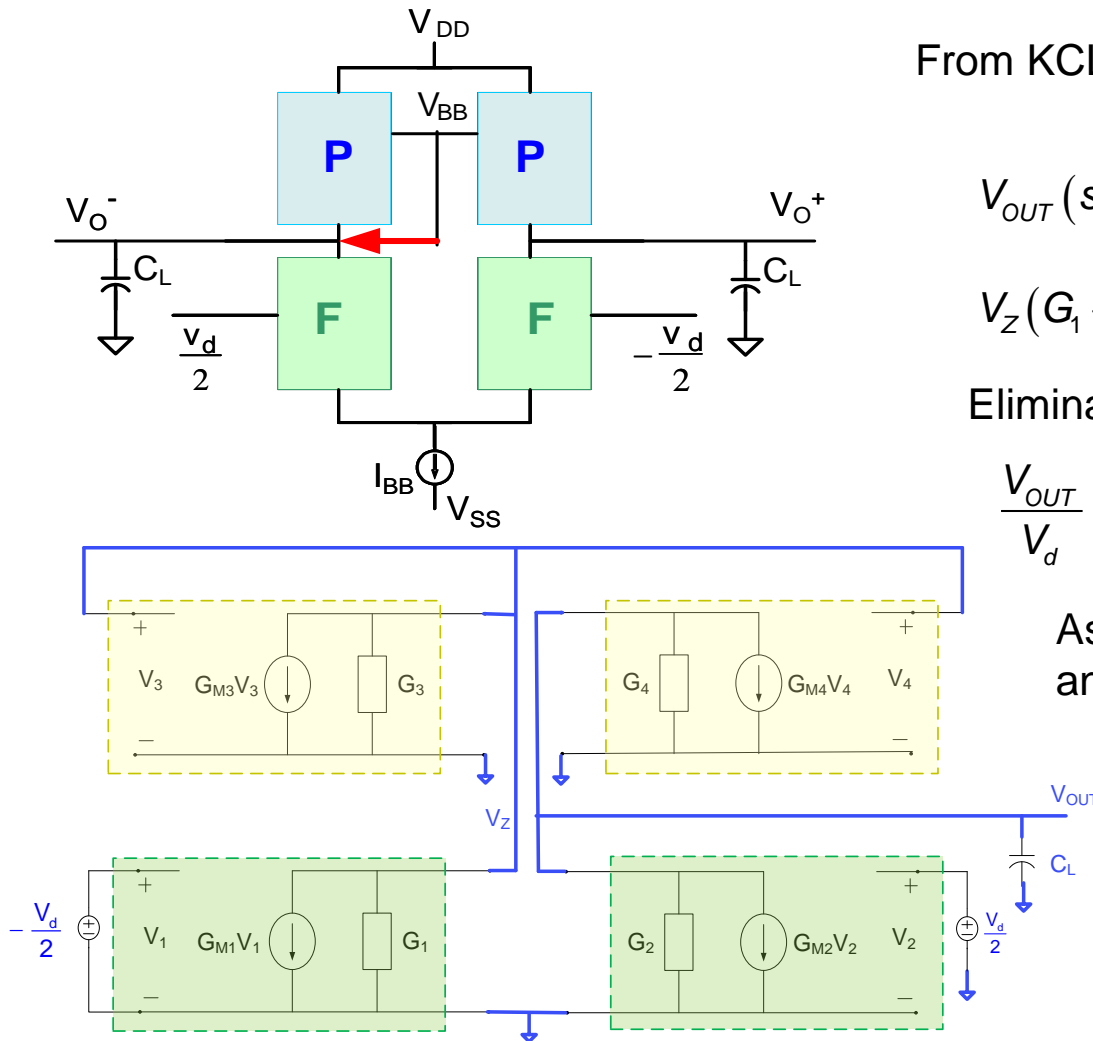
Eliminating  $V_Z$  we obtain

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

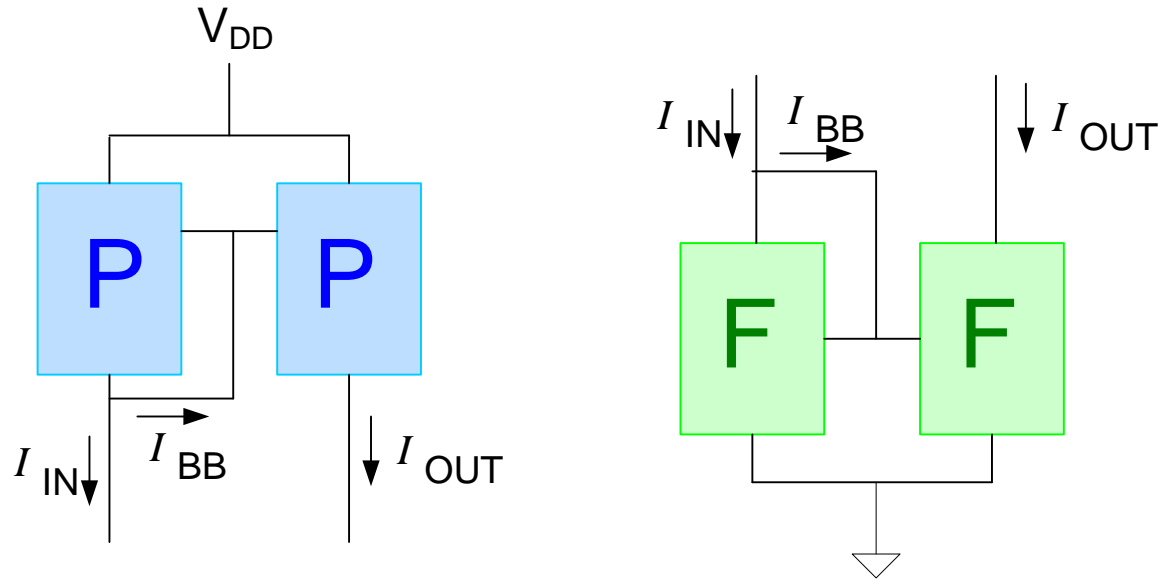
Assuming  $G_M$ 's large compared to  $G$ 's and left-right symmetry, it follows that

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

dc Voltage Gain to  $V_{OUT}$  doubled !

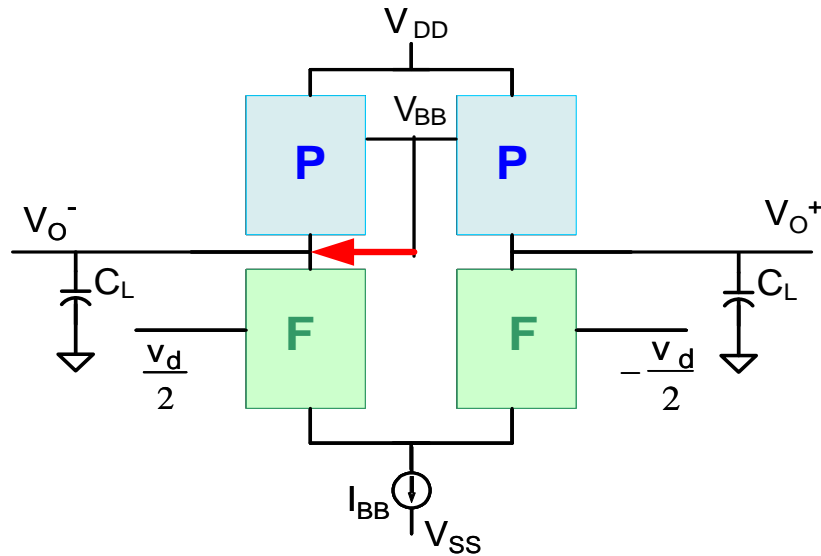


# Current Mirrors

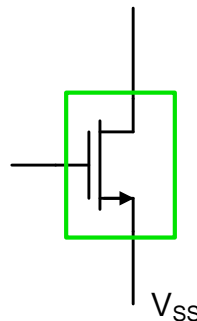


- If the current  $I_{BB}$  is small compared to  $I_{IN}$ , and the current  $I_{IN}$  is nearly independent of the voltage across P, then  $I_{OUT} \approx I_{IN}$
- Circuits with this property are called Current Mirrors
- If multiple copies of the right circuit are placed in parallel, the current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

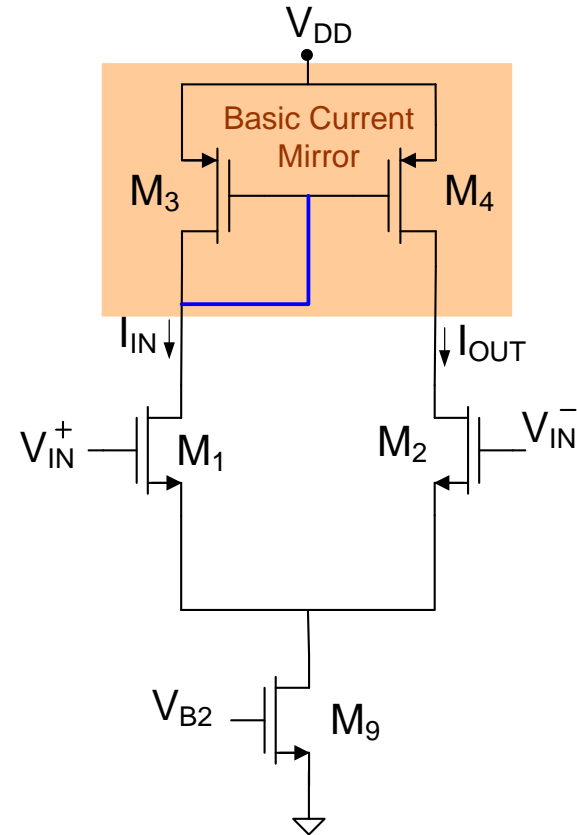
# Operation of Op Amp – A different perspective



Consider using single n-mos transistor as quarter circuit



## 5T Current-Mirror Bias Op Amp

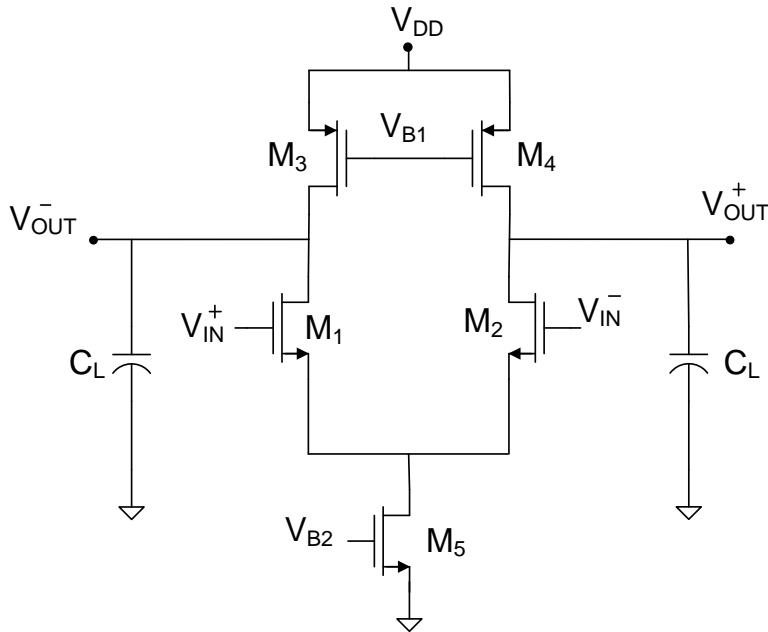


- Note counterpart circuits can be recognized as the basic current mirror
- But other current mirrors that may differ from the counterpart circuit could also be used (but then  $G_4$  and  $G_2$  may differ)

# Single-stage low-gain differential op amp

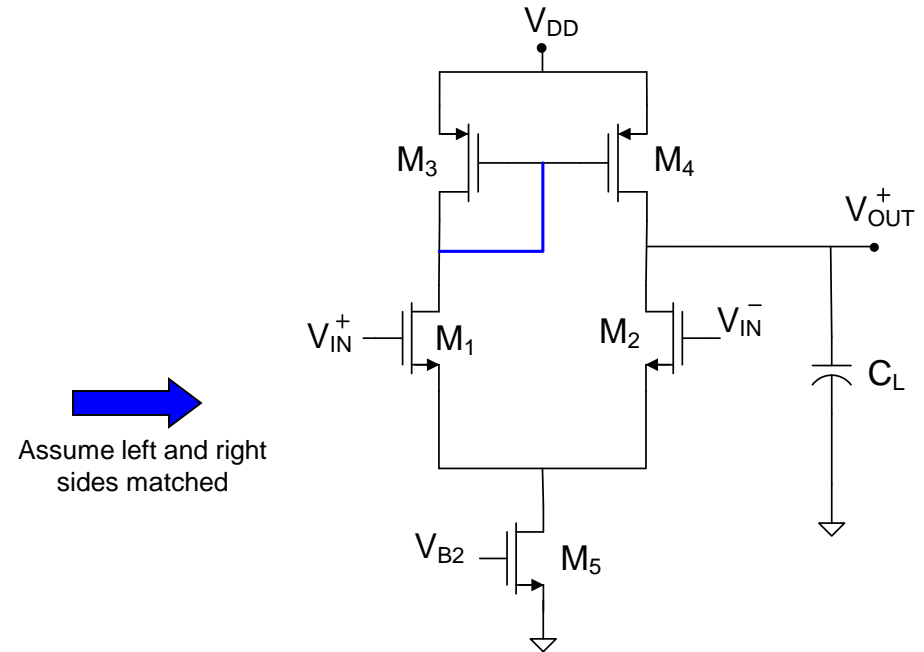
(with  $M_1$  as quarter circuit)

5T Op Amp



Needs CMFB

5T Current-Mirror Bias Op Amp



Assume left and right sides matched

No CMFB needed

- Can eliminate CMFB circuit if only single-ended output is needed 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  $V_d$  large and negative,

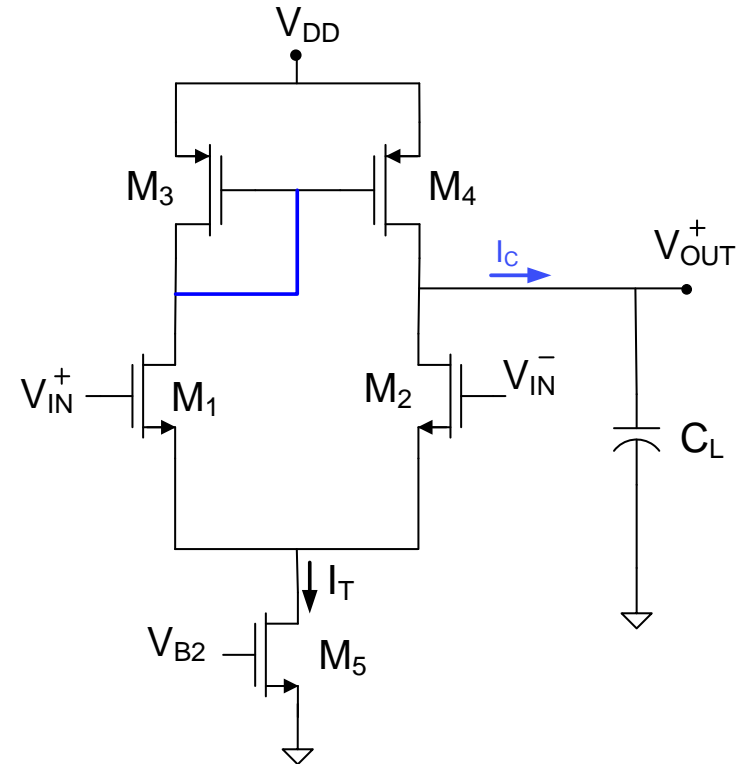
$$I_C = -I_T \quad SR = -\frac{I_T}{C_L}$$

When  $V_d$  large and positive,

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

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

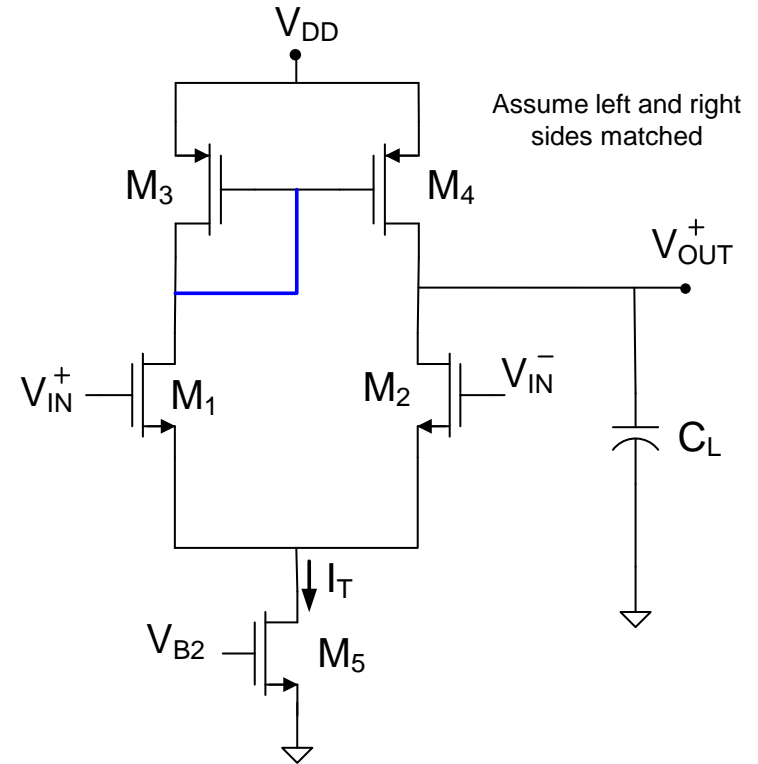
Current-Mirror Connected Counterpart Circuit

**No CMFB Circuit Needed**

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

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

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



In terms of practical design space parameters

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

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

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

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

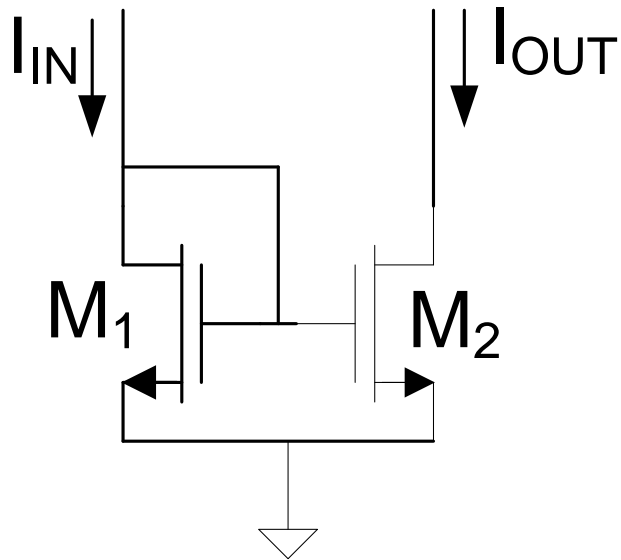
# Amplifier Comparison

Small Signal Parameter Domain			
Reference Op Amp (single-ended output) (5T Op Amp)	$A_{vo} = \frac{1}{2} \frac{g_{m1}}{g_{o1} + g_{o3}}$	$GB = \frac{g_{m1}}{2C_L}$	$SR = \frac{g_{o1}}{\lambda C_L}$
Practical Parameter Domain			
Reference Op Amp (single-ended output) (5T Op Amp)	$A_{vo} = \left[ \frac{1}{\lambda_1 + \lambda_3} \right] \left( \frac{1}{V_{EB1}} \right)$	$GB = \left( \frac{P}{2V_{DD}C_L} \right) \cdot \left[ \frac{1}{V_{EB1}} \right]$	$SR = \frac{P}{2V_{DD}C_L}$
Small Signal Parameter Domain			
Op Amp with CM Load and $M_1$ QC (5T Op Amp wCM)	$A_{VO} = \frac{g_{m1}}{g_{o1} + g_{o3}}$	$GB = \frac{g_{m1}}{C_L}$	$SR = 2 \frac{g_{o1}}{\lambda C_L}$
Practical Parameter Domain			
Op Amp with CM Load and $M_1$ QC (5T Op Amp wCM)	$A_{vo} = \left[ \frac{2}{\lambda_1 + \lambda_3} \right] \left( \frac{1}{V_{EB1}} \right)$	$GB = \left( \frac{P}{V_{DD}C_L} \right) \cdot \left[ \frac{1}{V_{EB1}} \right]$	$SR = \frac{P}{V_{DD}C_L}$

# 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



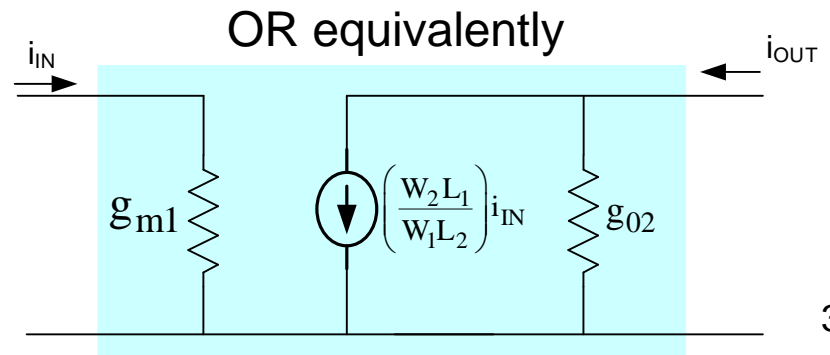
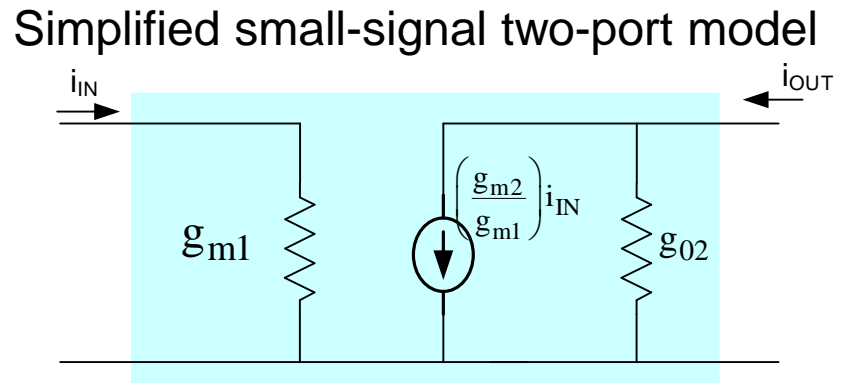
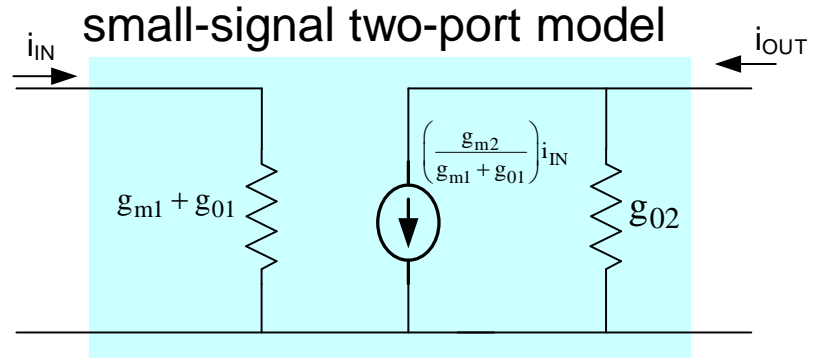
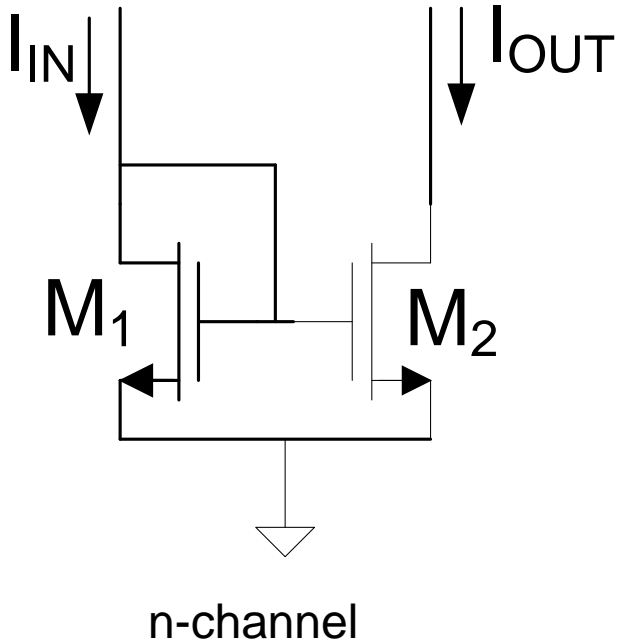
n-channel

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

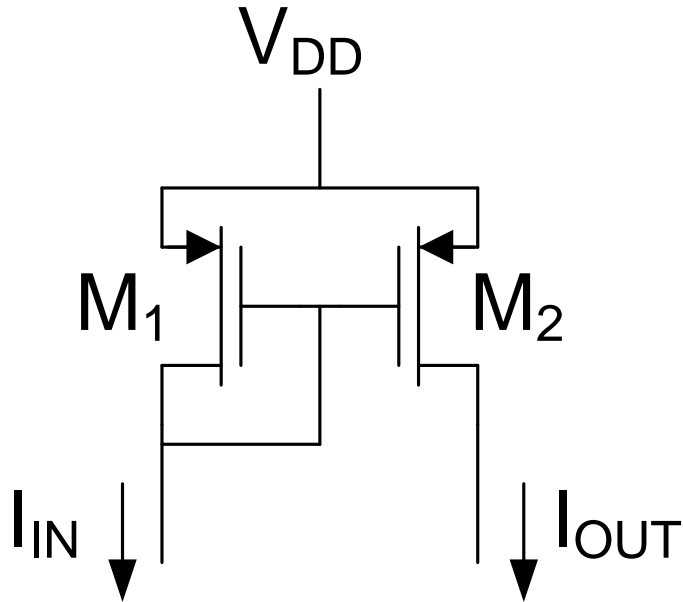
$$I_{OUT} = \frac{\mu C_{OX} W_2}{2L_2} (V_{GS2} - V_T)^2$$

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

# Basic Current Mirror



# Basic Current Mirror



p-channel

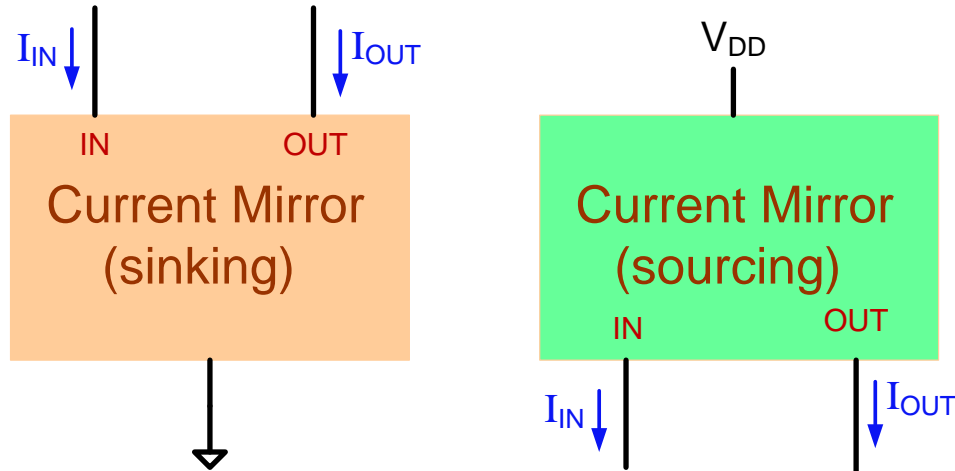
$$I_{IN} = \frac{\mu C_{OX} W_1}{2L_1} (V_{GS1} - V_T)^2$$

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

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

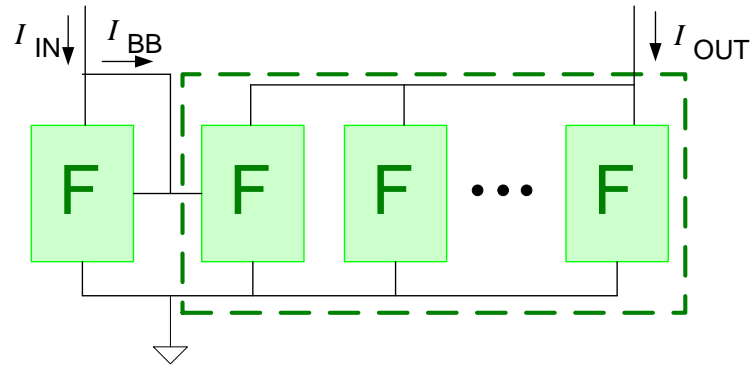
Since counterpart of n-channel current mirror, small signal models identical

# 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

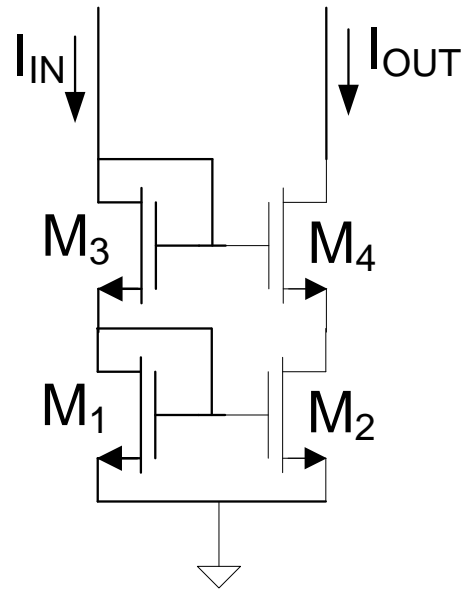
## Properties of Current Mirrors of Interest:

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

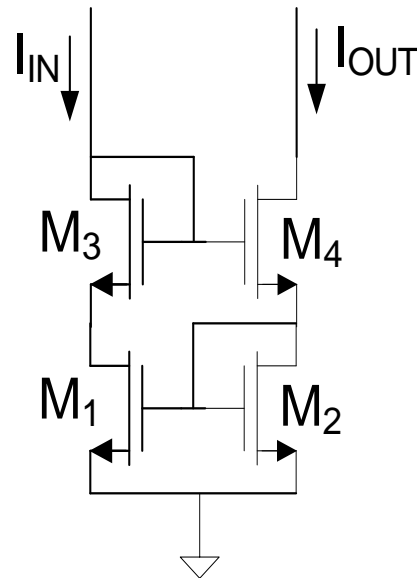
More advanced current mirrors usually offer improvements in one or more of these properties but at the expense of another of these properties.



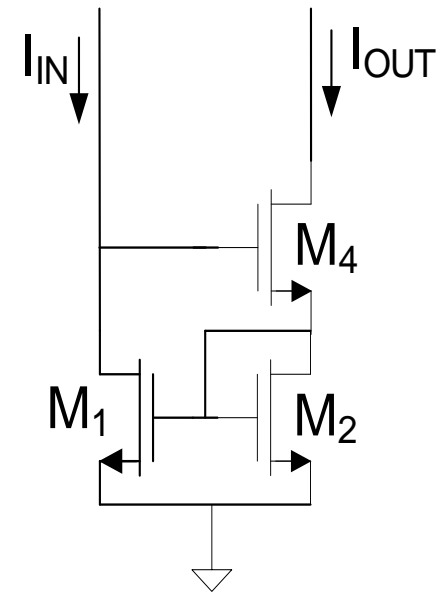
# More Advanced Current Mirrors



Cascode Current Mirror

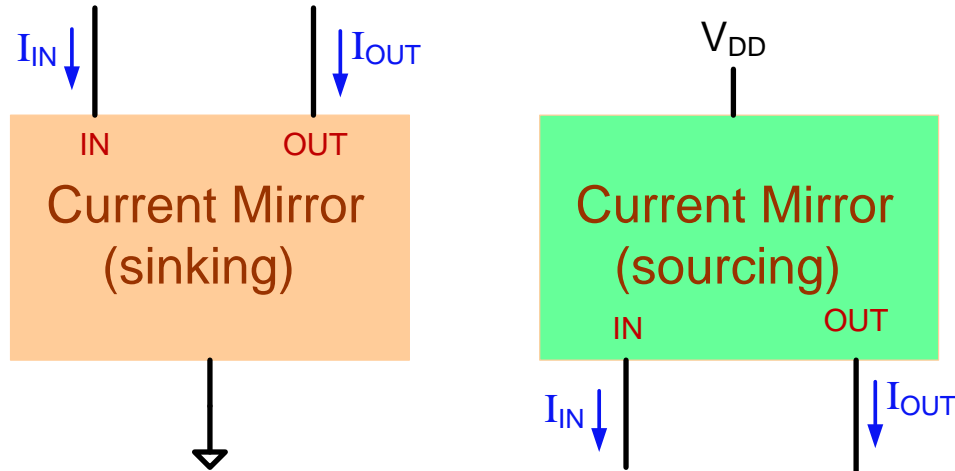


Modified Wilson Current Mirror



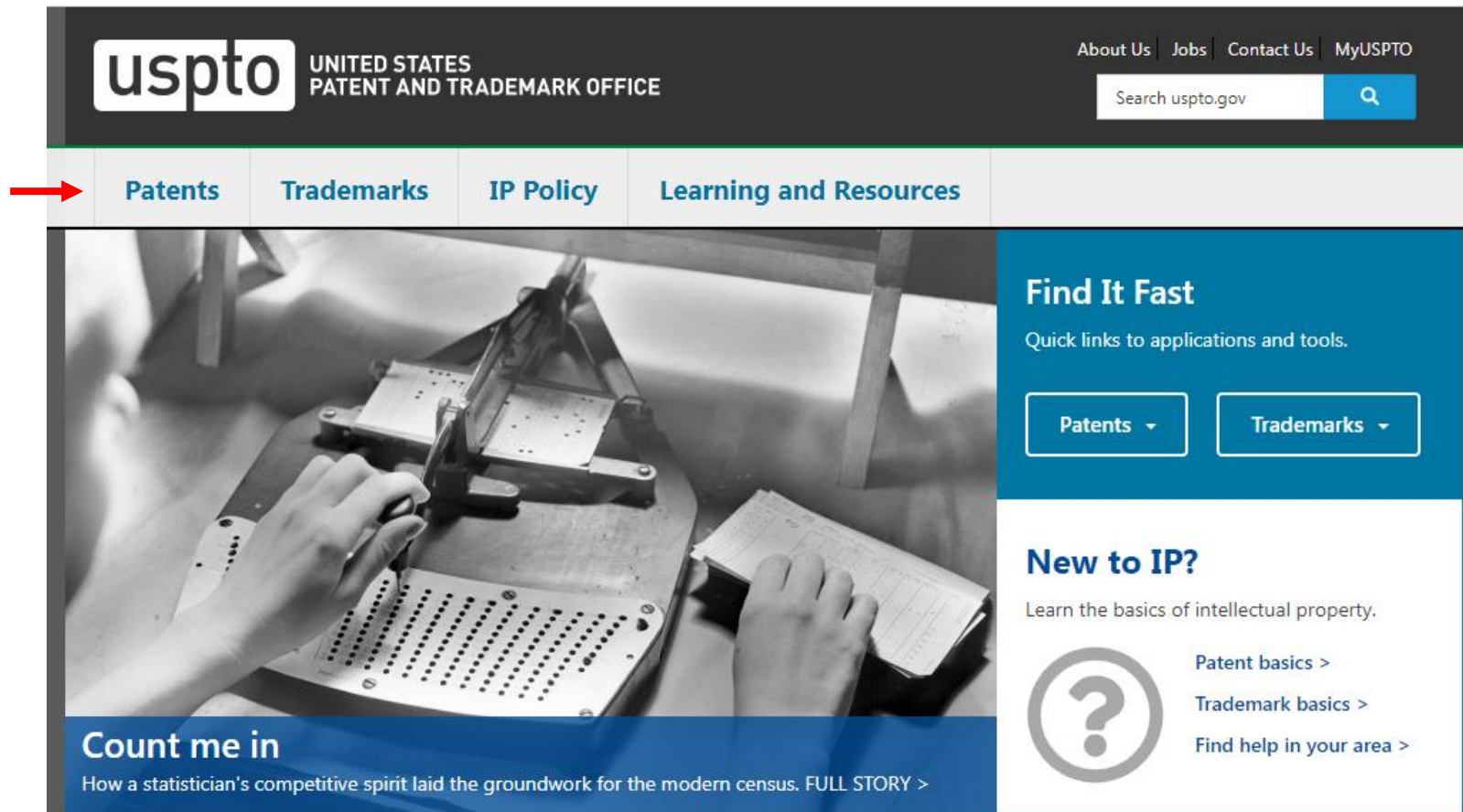
Wilson Current Mirror

# 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



The image shows a screenshot of the United States Patent and Trademark Office (USPTO) website. At the top left is the USPTO logo and the text "UNITED STATES PATENT AND TRADEMARK OFFICE". To the right are links for "About Us", "Jobs", "Contact Us", and "MyUSPTO", along with a search bar labeled "Search uspto.gov". Below the header is a navigation bar with four main categories: "Patents", "Trademarks", "IP Policy", and "Learning and Resources". A red arrow points to the "Patents" link. The main content area features a large image of a person using a mechanical calculator. To the right of the image are two sections: "Find It Fast" with quick links to "Patents" and "Trademarks", and "New to IP?" with links for "Patent basics", "Trademark basics", and "Find help in your area". At the bottom left of the main content area is a section titled "Count me in" with a link to "FULL STORY".

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### Find It Fast

Quick links to applications and tools.

Patents ▾ | Trademarks ▾

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Learn the basics of intellectual property.

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Find help in your area >

### Count me in

How a statistician's competitive spirit laid the groundwork for the modern census. [FULL STORY >](#)



Application process

**Search for patents**

Accessing Published Applications

Authority Files

Filing Year by Application Serial Number

Understanding Patent Classifications

Withdrawn Patent Numbers

Learn about patent classification

Filing online

Checking application status

# Search for patents

**New to Patent Searching?** See this important information about searching for patents:

[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 Feb 2, 2021

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

PAT. NO.	Title
1 <a href="#">10,895,887</a>	<a href="#">Current mirror arrangements with reduced sensitivity to buffer offsets</a>
2 <a href="#">10,877,503</a>	<a href="#">Attenuating common mode noise current in current mirror circuits</a>
3 <a href="#">10,845,839</a>	<a href="#">Current mirror arrangements with double-base current circulators</a>
4 <a href="#">10,839,879</a>	<a href="#">Read techniques for a magnetic tunnel junction (MTJ) memory device with a current mirror</a>
5 <a href="#">10,756,509</a>	<a href="#">Accurate current mirror circuit in low voltage headroom applied to laser drivers</a>
6 <a href="#">10,698,435</a>	<a href="#">Electronic current equalization module, current mirror circuit and method of assembling a current mirror circuit</a>
7 <a href="#">10,671,911</a>	<a href="#">Current mirror scheme for an integrating neuron circuit</a>
8 <a href="#">10,620,656</a>	<a href="#">Operating voltage switching device with current mirror</a>
9 <a href="#">10,593,499</a>	<a href="#">Relay drive circuit with a current mirror circuit</a>
10 <a href="#">10,574,141</a>	<a href="#">Current mirror calibration circuit and current mirror calibration method</a>
11 <a href="#">10,509,431</a>	<a href="#">Reversible current mirror and its use in bidirectional communication</a>
12 <a href="#">10,496,121</a>	<a href="#">Current mirror circuit and driving method of the current mirror circuit</a>
13 <a href="#">10,444,364</a>	<a href="#">Pinned photodiode pixels including current mirror-based background light suppression, and imaging devices including the same</a>
14 <a href="#">10,439,562</a>	<a href="#">Current mirror bias compensation circuit</a>
15 <a href="#">10,419,057</a>	<a href="#">Modified current mirror circuit for reduction of switching time</a>
16 <a href="#">10,386,880</a>	<a href="#">Circuit arrangement for compensating current variations in current mirror circuit</a>
17 <a href="#">10,373,681</a>	<a href="#">Methods and apparatuses having a voltage generator with an adjustable voltage drop for representing a voltage drop of a memor</a>
18 <a href="#">10,353,421</a>	<a href="#">Current mirror device and related amplifier circuit</a>
19 <a href="#">10,340,004</a>	<a href="#">Write voltage generating circuit comprising a current mirror</a>
20 <a href="#">10,332,590</a>	<a href="#">Static random access memory (SRAM) bit cells employing current mirror-gated read ports for reduced power consumption</a>
21 <a href="#">10,331,844</a>	<a href="#">Methods of tuning current ratio in a current mirror for transistors formed with the same FEOL layout and a modified BEOL lay</a>
22 <a href="#">10,317,925</a>	<a href="#">Attenuating common mode noise current in current mirror circuits</a>
23 <a href="#">10,228,713</a>	<a href="#">Large range current mirror</a>
24 <a href="#">10,133,293</a>	<a href="#">Low supply active current mirror</a>
25 <a href="#">10,133,292</a>	<a href="#">Low supply current mirror</a>

# USPTO search on Jan 24, 2020

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

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

# USPTO search on Jan 21, 2018

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

PAT. NO.	Title
1 <a href="#">9.864.395</a>	<a href="#">Base current compensation for a BJT current mirror</a>
2 <a href="#">9.857.824</a>	<a href="#">Calibration of a resistor in a current mirror circuit</a>
3 <a href="#">9.829.906</a>	<a href="#">Current mirror circuit and receiver using the same</a>
4 <a href="#">9.787.178</a>	<a href="#">Current mirror circuit and charge pump circuit</a>
5 <a href="#">9.746.871</a>	<a href="#">Noise canceling current mirror circuit for improved PSR</a>
6 <a href="#">9.740.232</a>	<a href="#">Current mirror with tunable mirror ratio</a>
7 <a href="#">9.728.256</a>	<a href="#">Methods and apparatuses having a voltage generator with an adjustable voltage drop for representing a voltage drop</a>
8 <a href="#">9.713.212</a>	<a href="#">Current mirror circuit and method</a>
9 <a href="#">9.693.417</a>	<a href="#">LED mains voltage measurement using a current mirror</a>
10 <a href="#">9.680.483</a>	<a href="#">Current mirror circuit and charge pump circuit</a>
11 <a href="#">9.671.228</a>	<a href="#">Floating current mirror for RLG discharge control</a>
12 <a href="#">9.641.167</a>	<a href="#">Current mirror circuits with narrow bandwidth bias noise reduction</a>
13 <a href="#">9.638.584</a>	<a href="#">Differential temperature sensor with sensitivity set by current-mirror and resistor ratios without limiting DC bias</a>
14 <a href="#">9.632.522</a>	<a href="#">Current mirror bias circuit with voltage adjustment</a>
15 <a href="#">9.622.303</a>	<a href="#">Current mirror and constant-current LED driver system for constant-current LED driver IC device</a>
16 <a href="#">9.595.310</a>	<a href="#">Circuits for control of time for read operation, using a current mirror circuit to mirror a reference current into the du</a>
17 <a href="#">9.563.223</a>	<a href="#">Low-voltage current mirror circuit and method</a>
18 <a href="#">9.559.641</a>	<a href="#">Current mirror, control method, and image sensor</a>
19 <a href="#">9.548.022</a>	<a href="#">Pixel and organic light emitting display device including current mirror</a>
20 <a href="#">9.497.402</a>	<a href="#">Image lag mitigation for buffered direct injection readout with current mirror</a>

# 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

Jump To

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*

Next 50 Hits

Jump To

Refine Search

tll/(current and mirror)

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

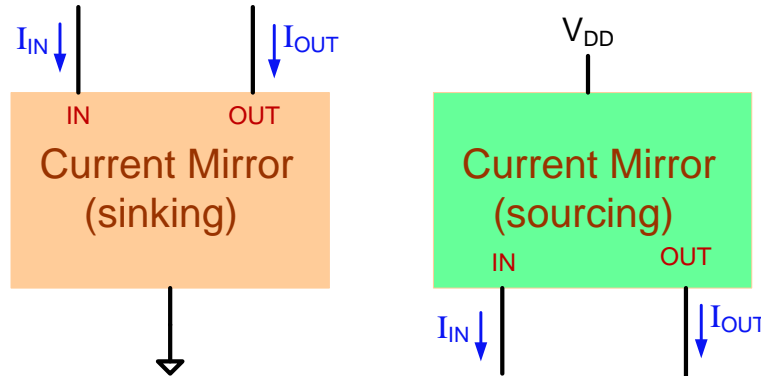
# USPTO search on Feb 2, 2021

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

10 patents with “current and mirror” in title in past year

- 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
- 10 patents from Jan 21, 2020 to Feb 1, 2021

# USPTO search on Jan 21, 2018



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

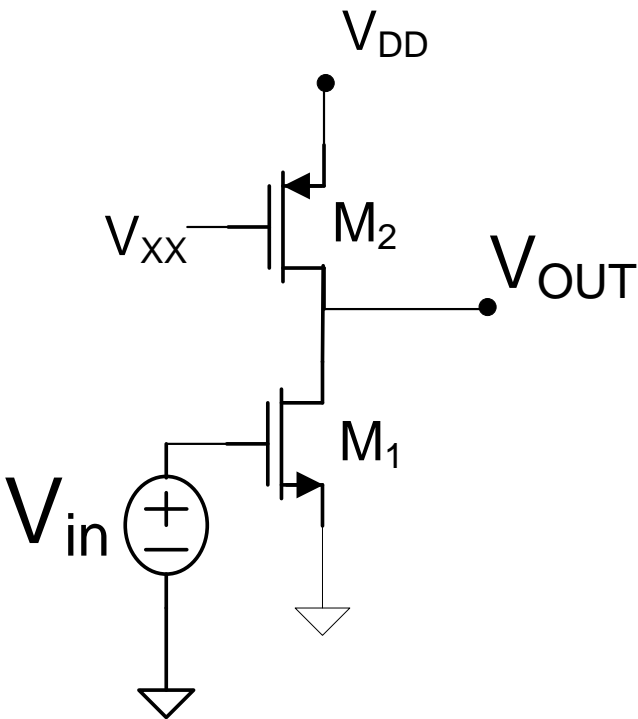
26 patents with “current and mirror” in title from 2018 and 2020 searches

Number of patents/year 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

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



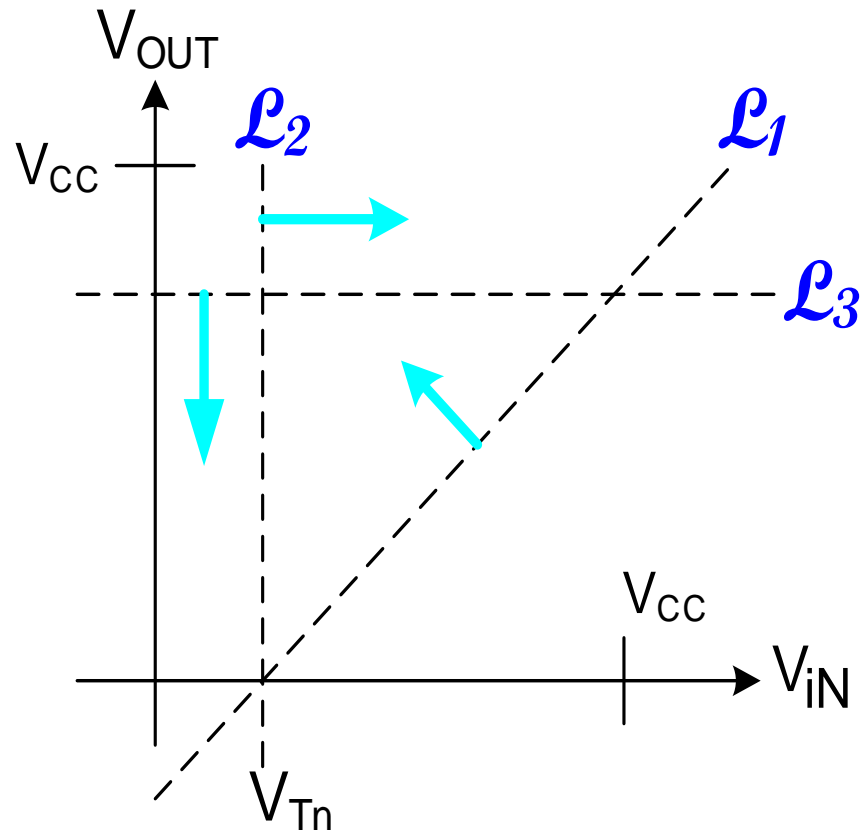
$$V_{XX} - V_{Tp} > V_{OUT}$$

# Signal Swing

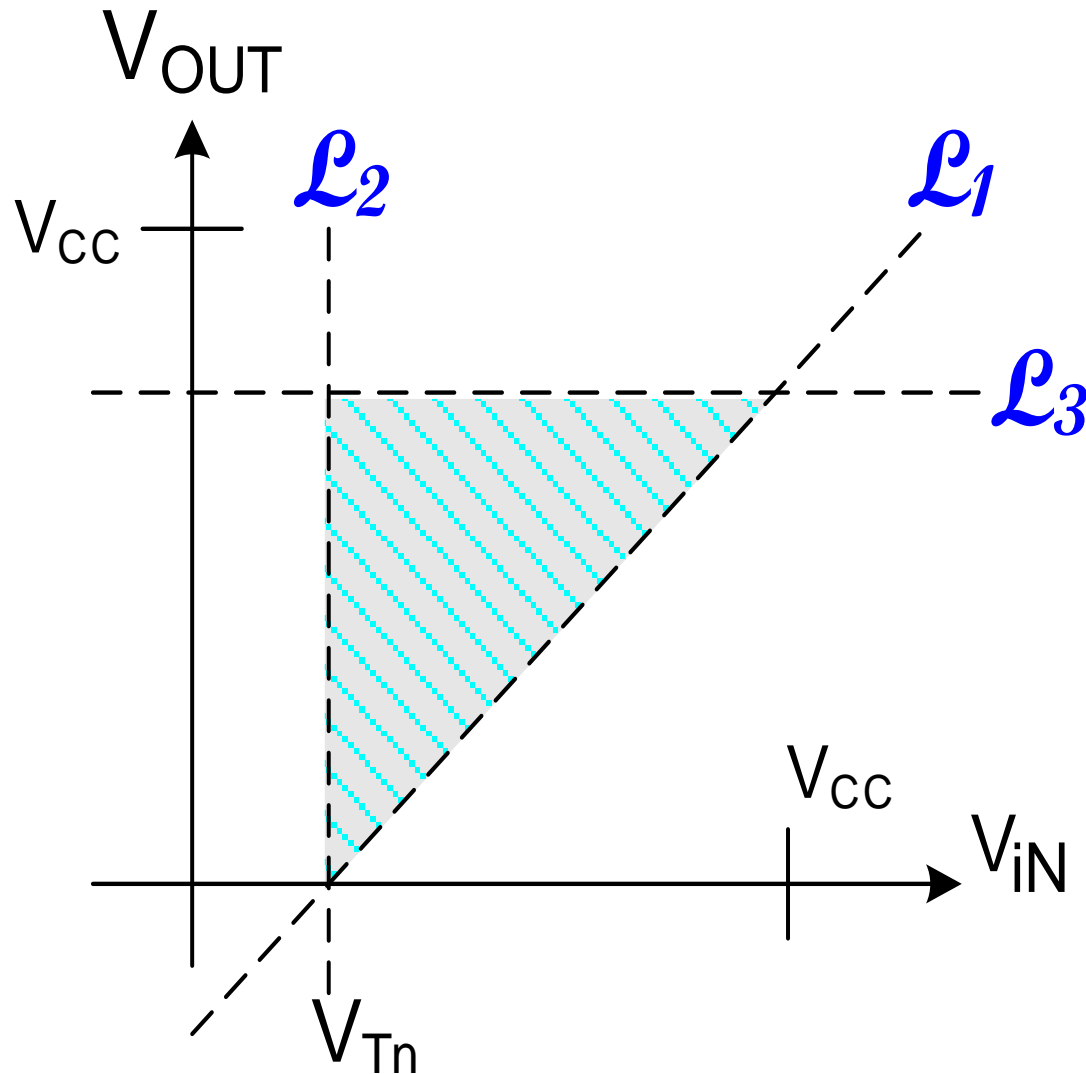
$$\mathcal{L}_1: V_{OUT} > V_{iN} - V_{Tn}$$

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

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

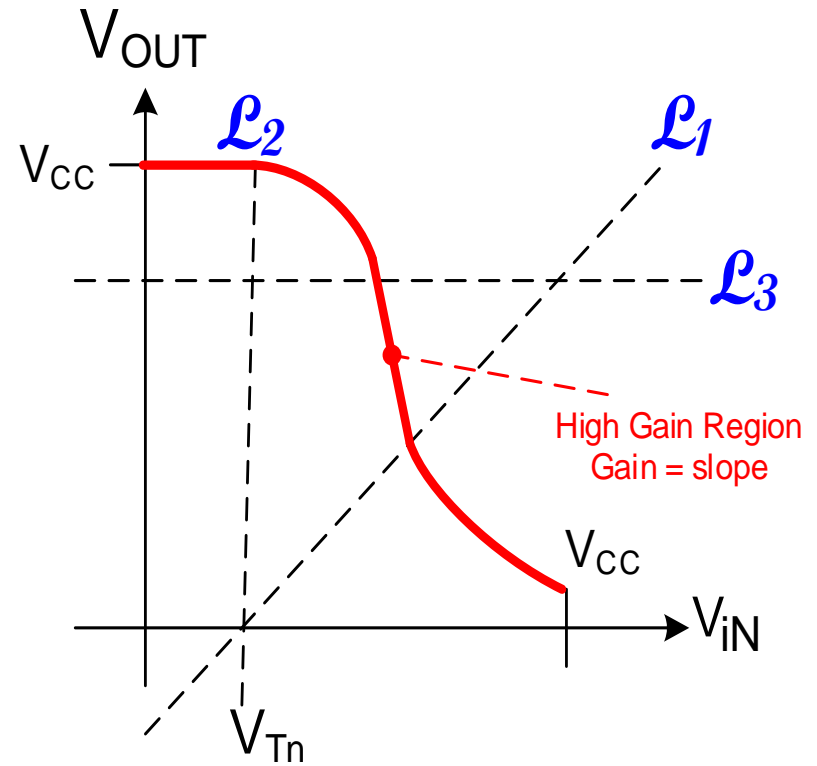
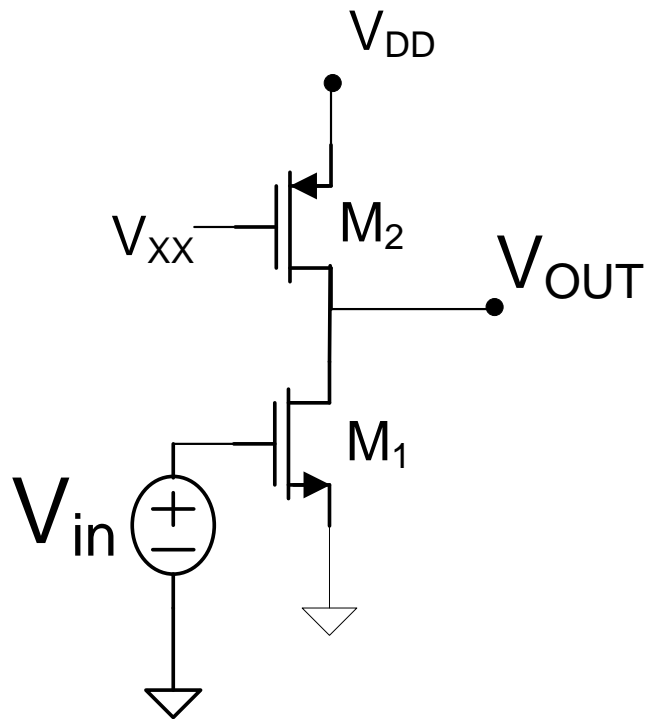


# Signal Swing



- $\mathcal{L}_1: V_{OUT} > V_{iN} - V_{Tn}$
- $\mathcal{L}_2: V_{iN} > V_{Tn}$
- $\mathcal{L}_3: V_{XX} - V_{Tp} > V_{OUT}$

# Signal Swing



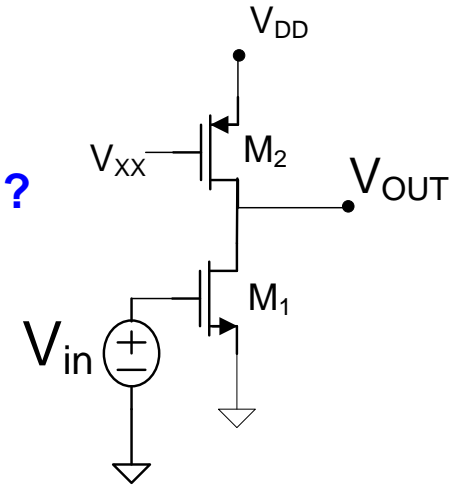
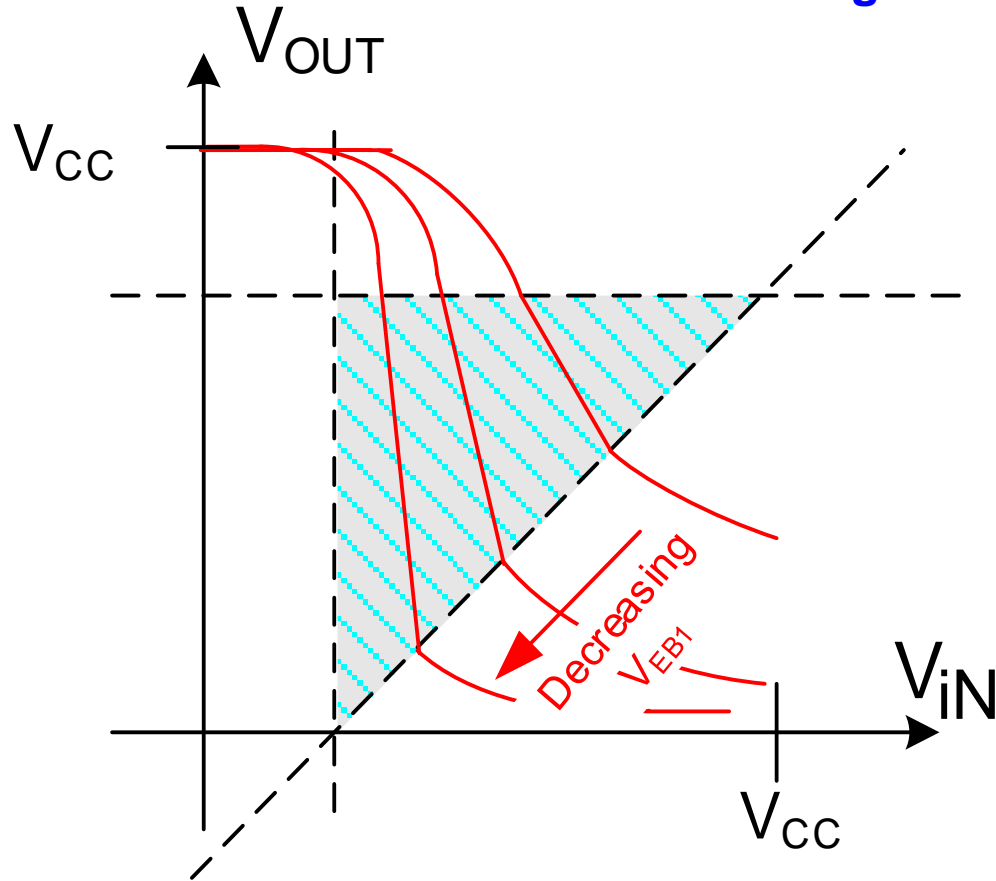
Transfer Characteristics of amplifier

**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  $V_{EB1}$





Stay Safe and Stay Healthy !

**End of Lecture 5**