EE 435

Lecture 4

Fully Differential Single-Stage Amplifier Design

- 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

Review from last lecture:

Where we are at:

Basic Op Amp Design

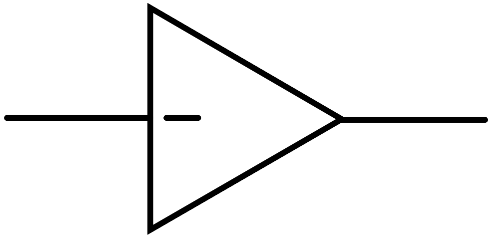
- Fundamental Amplifier Design Issues
- Single-Stage Low Gain Op Amps
- Single-Stage High Gain Op Amps
- Two-Stage Op Amp
- Other Basic Gain Enhancement Approaches

Review from last lecture:

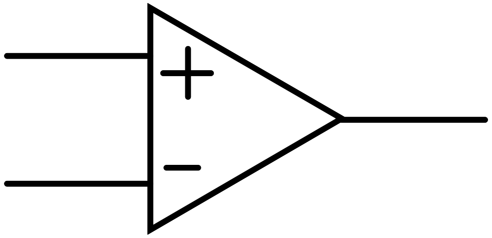
Where we are at:

Single-Stage Low-Gain Op Amps

- Single-ended input



- Differential Input



(Symbol does not distinguish between different amplifier types)

Review from last lecture:

Differential Input Low Gain Op Amps

Will Next Show That :

- Differential input op amps can be readily obtained from single-ended op amps

- Performance characteristics of differential op amps can be directly determined from those of the single-ended counterparts

Review from last lecture:

Counterpart Networks

Definition: The counterpart network of a network is obtained by replacing all n-channel devices with p- channel devices, replacing all p-channel devices with n-channel devices, replacing V_{SS} biases with V_{DD} biases, and replacing all V_{DD} biases with V_{SS} biases.

Review from last lecture:

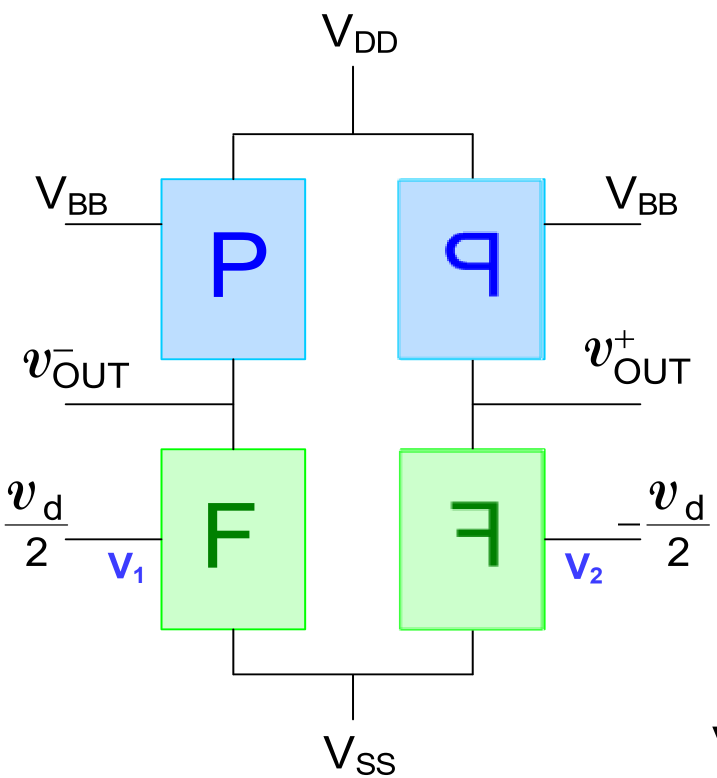
Counterpart Networks

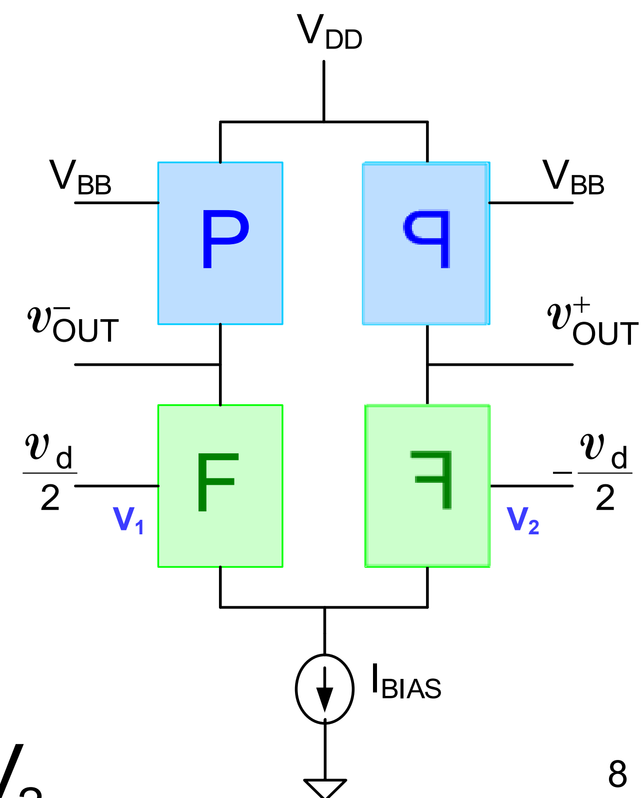
Theorem: The parametric expressions for all small-signal characteristics, such as voltage gain, output impedance, and transconductance of a network and its counterpart network are the same.

Synthesis of fully-differential op amps from symmetric networks and counterpart networks

Review from last lecture:

Theorem: If F is any network with a single input and P is its counterpart network, then the following circuits are fully differential circuits --- "op amps".



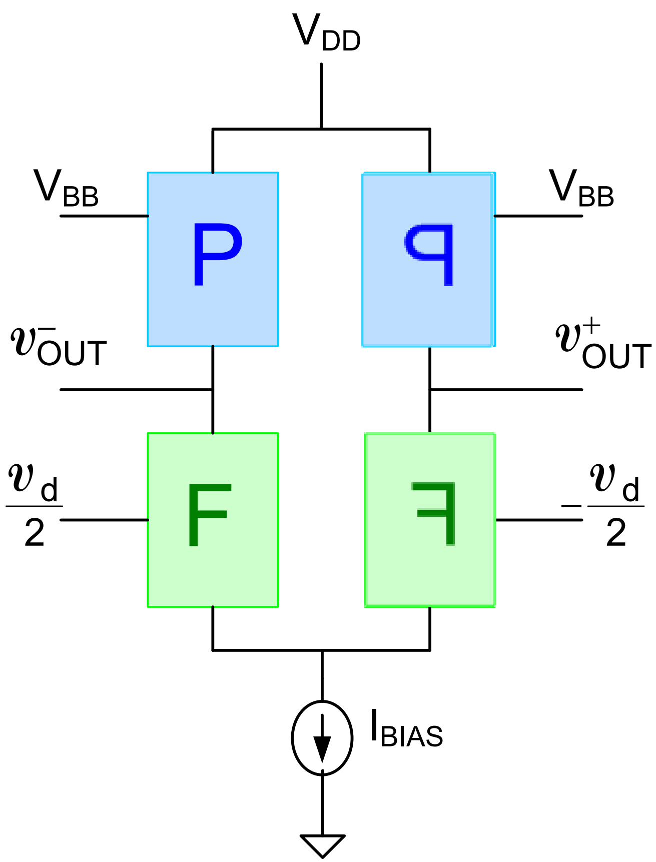


$$V_d = V_1 - V_2$$

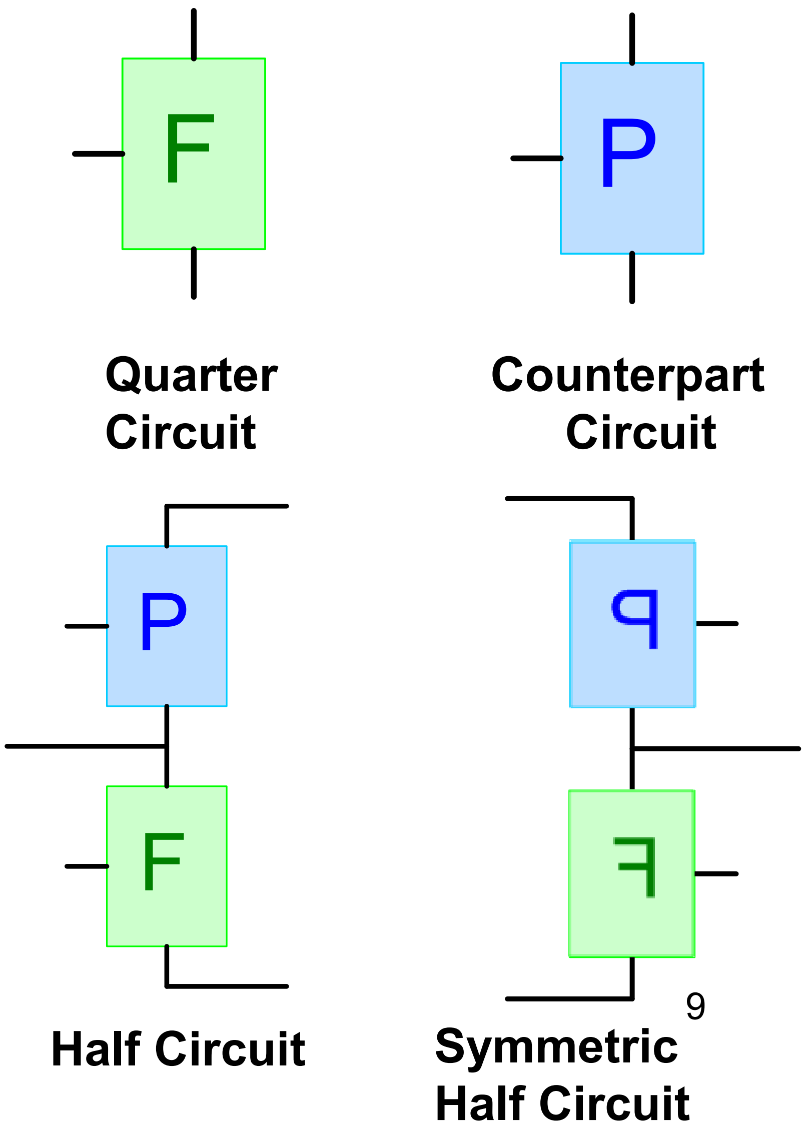
Synthesis of fully-differential op amps from symmetric networks and counterpart networks

Review from last lecture:

Terminology



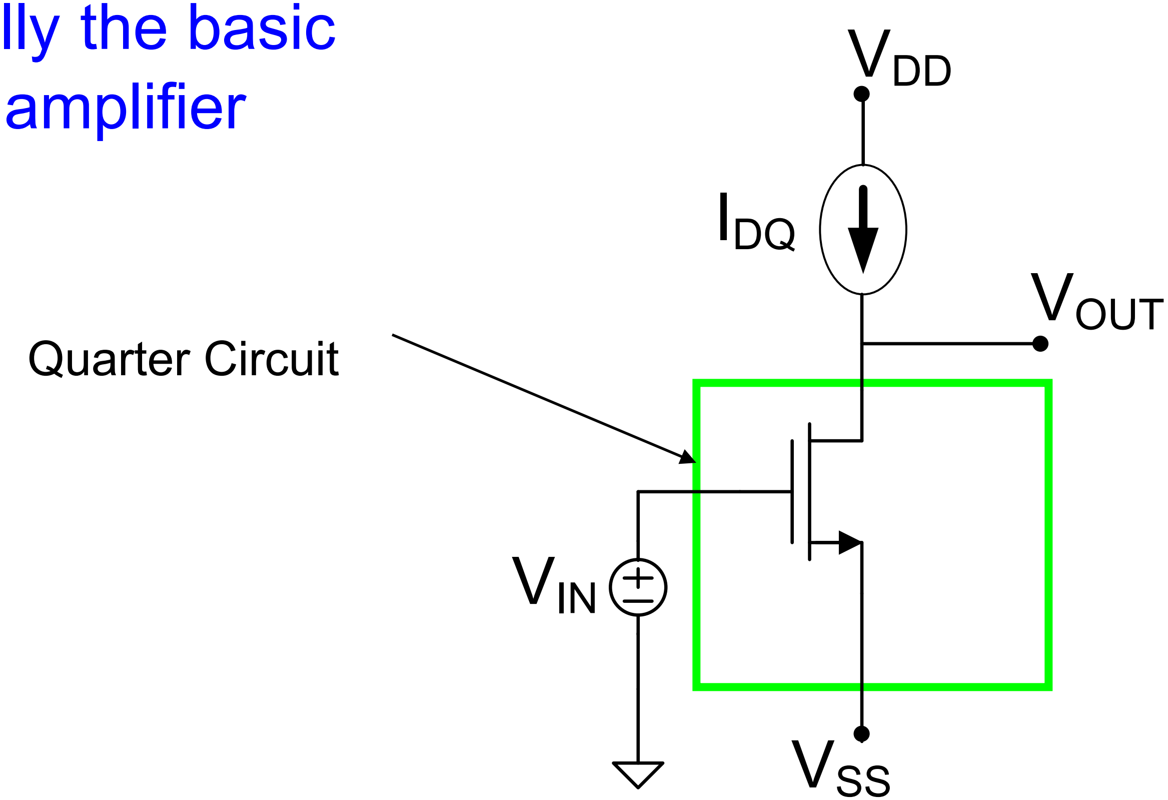
$$V_d = V_1 - V_2$$



Review from last lecture:

Applications of Quarter-Circuit Concept to Op Amp Design

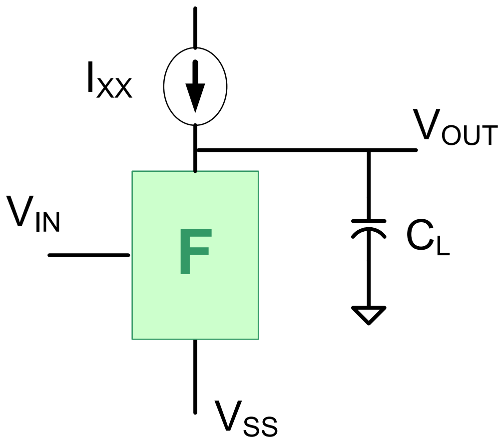
consider initially the basic single-ended amplifier



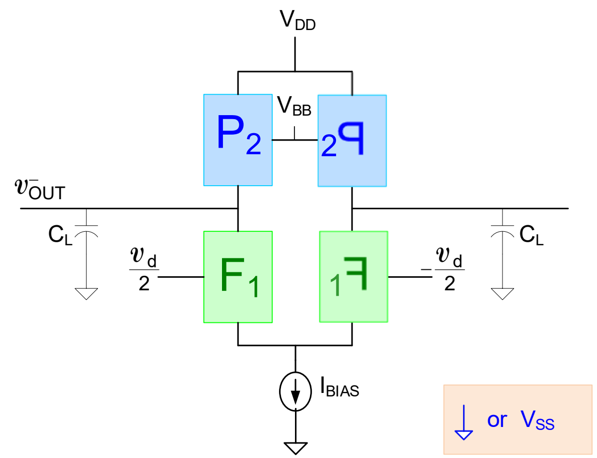
Determination of op amp characteristics from quarter circuit characteristics

-- The "differential" gain --

Small signal Quarter Circuit



Small signal differential amplifier



$$A_{VOQC} = -\frac{G_M}{G}$$

$$A_V = \frac{v_o^-}{v_d} = \frac{-\frac{G_{M1}}{2}}{sC_L + G_1 + G_2}$$

$$BW = \frac{G}{C_L} \qquad GB = \frac{G_M}{C_L}$$

$$A_{V0} = \frac{v_{OUT}^-}{v_d} = \frac{-G_{M1}}{2(G_1 + G_2)}$$

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

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

Note: Factor of 4 reduction of gain if $G_1 = G_2$ (this often occurs)

Note: Factor of 2 increase of BW if $G_1 = G_2$ (this often occurs)

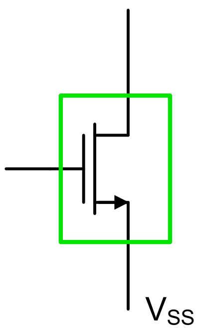
Note: Factor of 2 reduction of GB if $G_1 = G_2$ (this often occurs)

Remember this is applicable to ANY quarter circuit !

Review from last lecture:

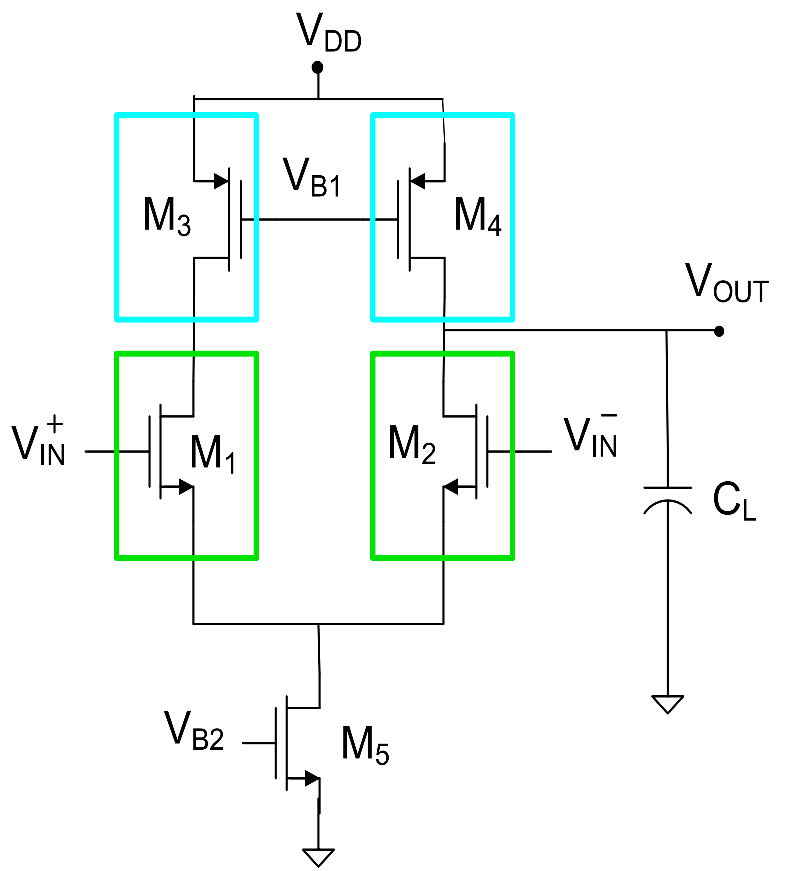
Single-stage low-gain differential op amp

-- The "differential" gain --



Quarter Circuit

Single-Ended Output : Differential Input Gain

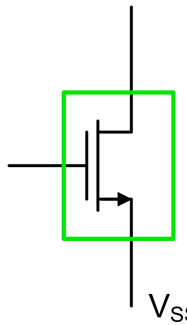


Have synthesized fully differential op amp from quarter circuit !

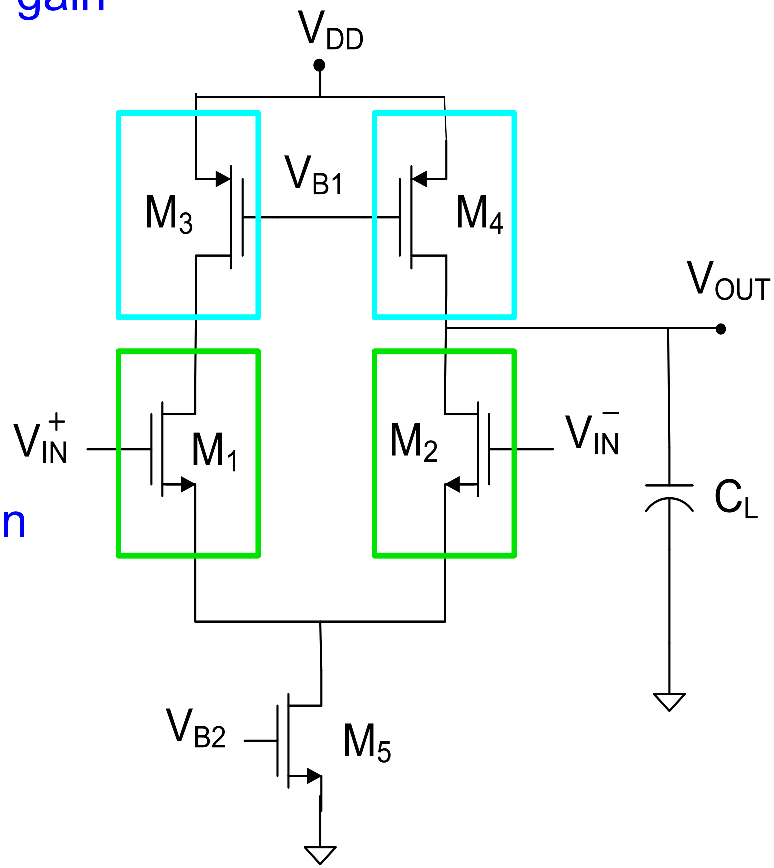
Termed the 5T Op Amp

Single-stage low-gain differential op amp

-- The "differential" gain --



Quarter Circuit



Single-Ended Output : Differential Input Gain

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

$$A_{V0} = \frac{-g_{m1}}{2(g_{o1} + g_{o3})}$$

$$BW = \frac{g_{o1} + g_{o3}}{C_L}$$

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

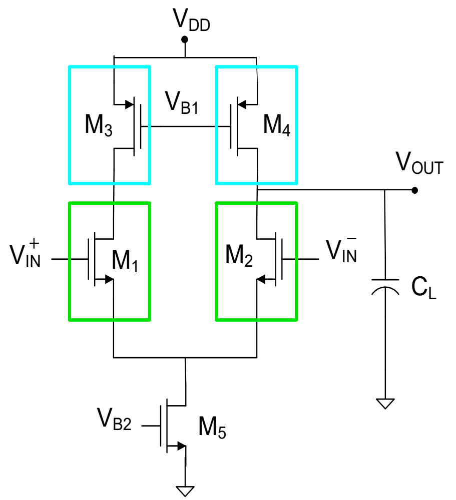
Circuit is Very Sensitive to V_{B1} and V_{B2} !!

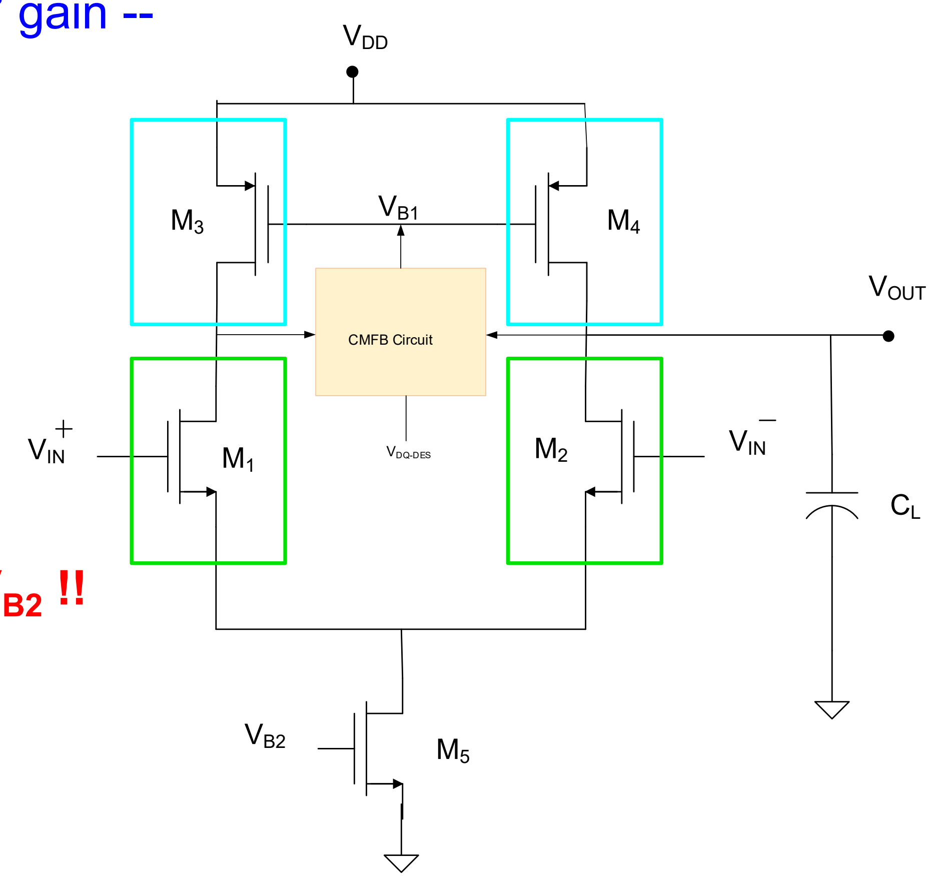
- Have obtained analysis of fully differential op amp directly from quarter circuit !
- Still need to determine what happens if input is not differential !
- **Have almost obtained op amp small-signal characteristics by inspection from quarter circuit !!**

- 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

Single-stage low-gain differential op amp

-- The "differential" gain --





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

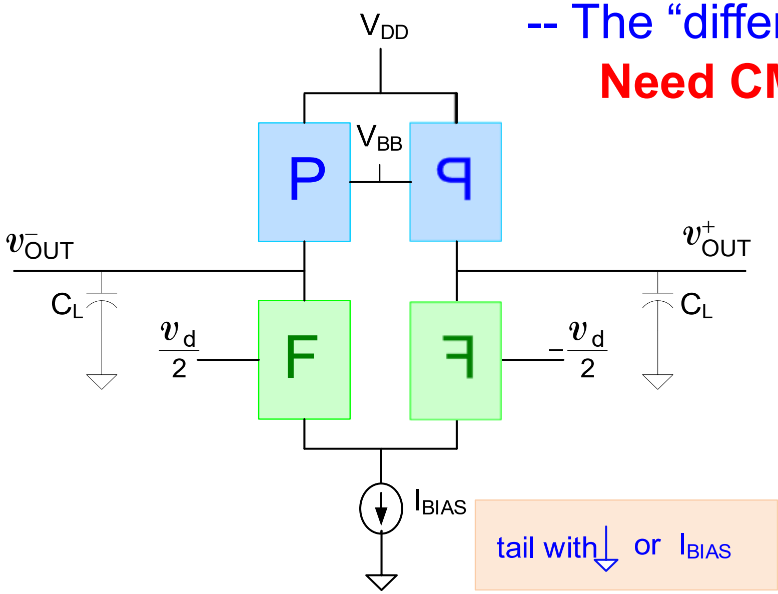
- CMFB circuit determines average value of the drain voltages
- Compares the average to the desired quiescent drain voltages
- Established a feedback signal V_{B1} to set the right Q-point
- Shown for V_{B1} but could alternately be applied to V_{B2}

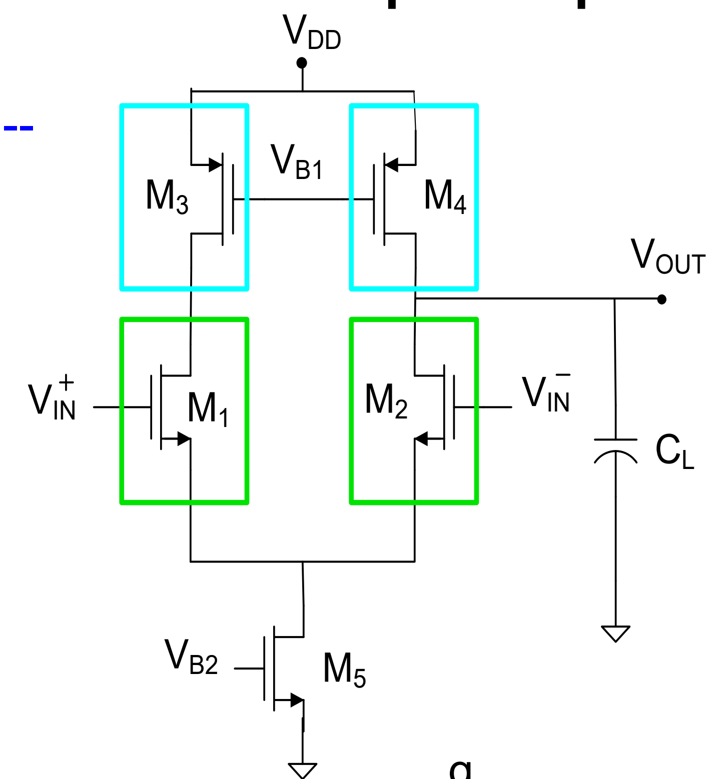
Details about CMFB circuits will be discussed later

Single-stage low-gain differential op amp
Summary

-- The “differential” gain --

Need CMFB circuit





$$A(s)=\frac{v_{OUT}^-}{v_d}=\frac{-\frac{G_M}{2}}{sC_L+G_1+G_2}$$

$$A_{V0}=\frac{-G_{M1}}{2(G_1+G_2)}$$

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

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

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

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

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

Have obtained differential gain of 5T Op Amp by inspection from quarter circuit

- Fully Differential Single-Stage Amplifier
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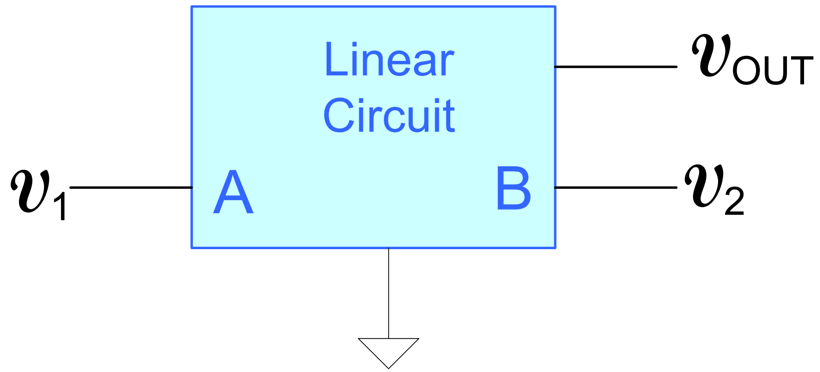
Common-Mode and Differential-Mode Analysis

Consider an output voltage for any linear circuit with two inputs
(i.e. need not be symmetric)



By superposition

$$v_{OUT} = A_1 v_1 + A_2 v_2$$

where A_1 and A_2 are the gains (transfer functions) from inputs 1 and 2 to the output respectively

Define the common-mode and difference-mode inputs by

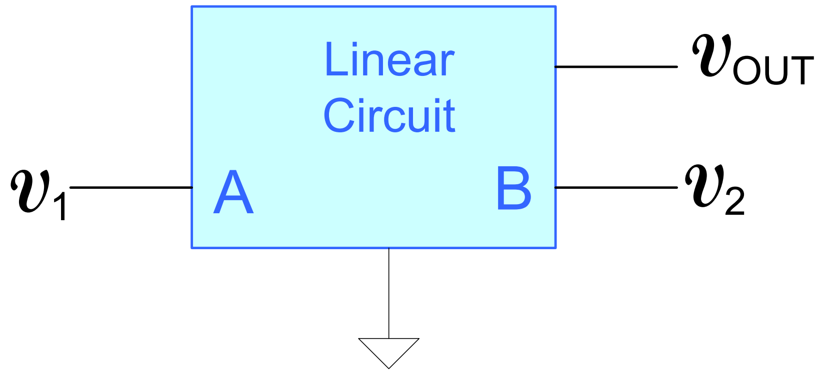
$$v_c = \frac{v_1 + v_2}{2} \qquad v_d = v_1 - v_2$$

These two equations can be solved for v_1 and v_2 to obtain

$$v_1 = v_c + \frac{v_d}{2} \qquad v_2 = v_c - \frac{v_d}{2}$$

Common-Mode and Differential-Mode Analysis

Consider an output voltage for any linear circuit with two inputs



$$v_{OUT} = A_1 v_1 + A_2 v_2$$

Substituting into the expression for v_{OUT}, we obtain

$$v_{OUT} = A_1\left(v_c + \frac{v_d}{2}\right) + A_2\left(v_c - \frac{v_d}{2}\right)$$

Rearranging terms we obtain

$$v_{OUT} = v_c\,(A_1 + A_2) + v_d\left(\frac{A_1 - A_2}{2}\right)$$

If we define A_c and A_d by

$$A_c = A_1 + A_2 \qquad A_d = \frac{A_1 - A_2}{2}$$

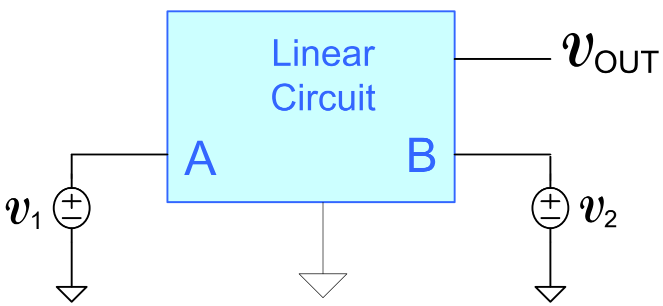
Can express v_{OUT} as

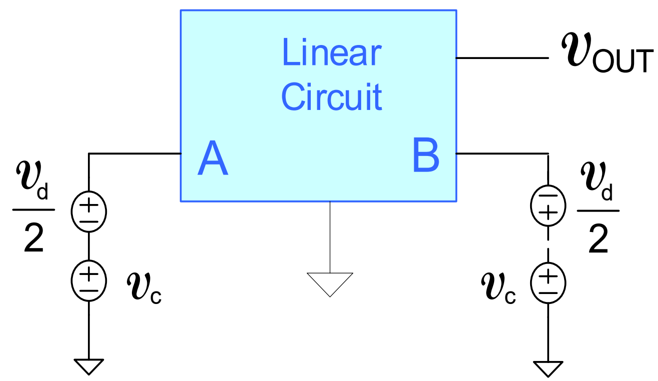
$$v_{OUT} = v_c A_c + v_d A_d$$

Common-Mode and Differential-Mode Analysis

Depiction of singe-ended inputs and common/difference mode inputs

Alternate Equivalent Represntations



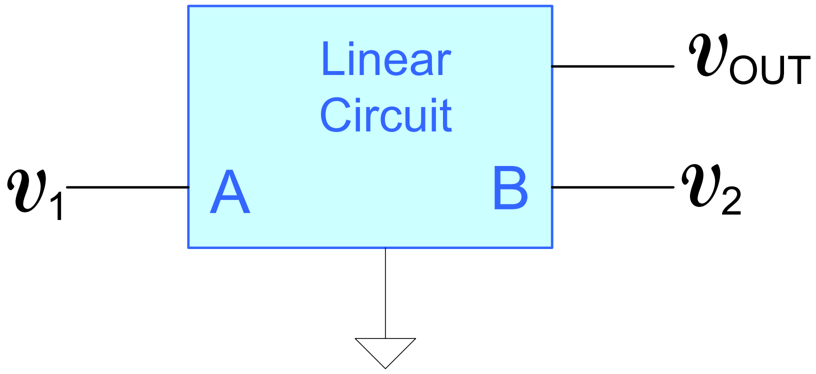


$$v_{OUT} = A_1 v_1 + A_2 v_2 \quad \longleftrightarrow \quad v_{OUT} = v_c A_c + v_d A_d$$

- Applicable to any linear circuit with two inputs and a single output
- Op amps often have symmetry and this symmetry further simplifies analysis

Common-Mode and Differential-Mode Analysis

Consider <u>any</u> output voltage for any linear circuit with two inputs



$$v_{OUT}=A_1v_1+A_2v_2$$

$$A_c=A_1+A_2$$

$$A_d=\frac{A_1-A_2}{2}$$

$$v_{OUT}=v_cA_c+v_dA_d$$

$$v_{OUT}=v_c\left(A_1+A_2\right)+v_d\left(\frac{A_1-A_2}{2}\right)$$

Implication: Can solve any linear two-input circuit by applying superposition with v_1 and v_2 as inputs or with v_c and v_d as inputs. This can be summarized in the following theorem:

Theorem 1: The output for any linear network can be expressed equivalently as $v_{OUT}=A_1v_1+A_2v_2$ or as $v_{OUT}=v_cA_c+v_dA_d$
Superposition can be applied to either v_1 and v_2 to obtain A_1 and A_2 or to v_c and v_d to obtain A_c and A_d

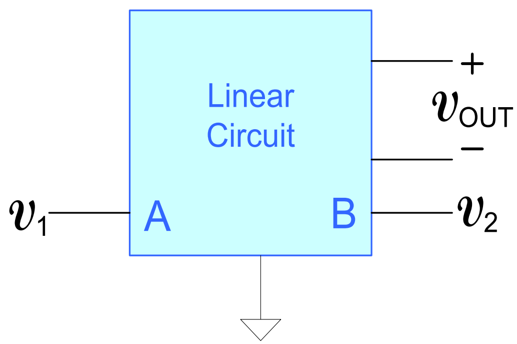
Observation: In a circuit with $A_2= - A_1$, $A_C=0$ we obtain

$$v_{OUT}=v_dA_d$$

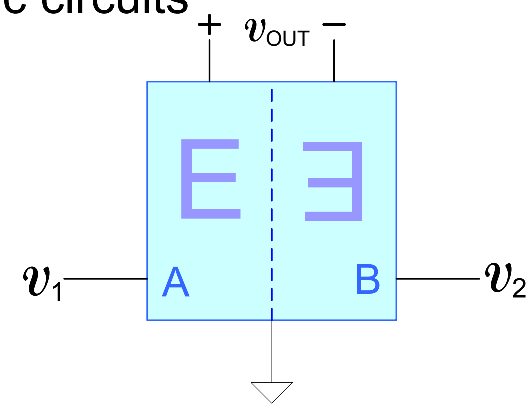
Analysis of op amps up to this point have assumed differential excitation

Common-Mode and Differential-Mode Analysis

Extension to differential outputs and symmetric circuits



Differential Output



Symmetric Circuit with Symmetric Differential Output

Note that this defined output is differential, not single-ended !

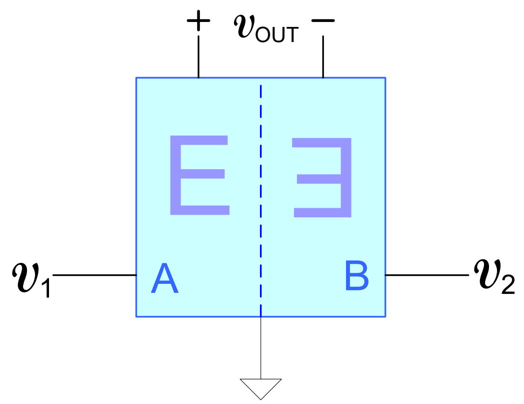
Observation: In a symmetric circuit with a symmetric differential output, $A_C=0$ so can be shown that $v_{OUT}=v_d A_d$ This is summarized in the theorem:

Theorem 2: The symmetric differential output voltage for any symmetric linear network excited at symmetric nodes can be expressed as

$$v_{OUT}=A_d v_d$$

where A_d is the differential voltage gain and the voltage $v_d = v_1 - v_2$

Symmetric Circuit with Symmetric Differential Output



Theorem 2: The symmetric differential output voltage for any symmetric linear network excited at symmetric nodes can be expressed as

$$v_{OUT} = A_d v_d$$

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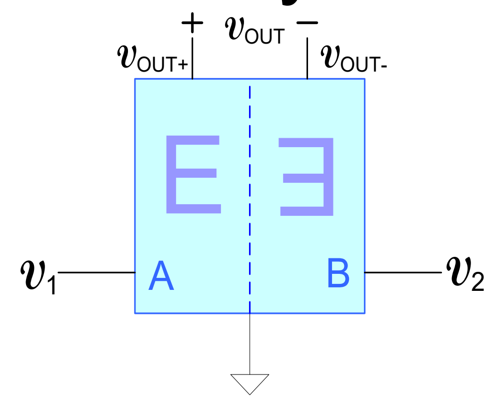
Common-Mode and Differential-Mode Analysis



Proof of Theorem 2 for Symmetric Circuit with Symmetric Differential Output:

By superposition, the single-ended outputs can be expressed as

$$v_{OUT+} = T_{0PA}v_1 + T_{0PB}v_2$$
$$v_{OUT-} = T_{0NA}v_1 + T_{0NB}v_2$$

where T_{0PA}, T_{0PB}, T_{0NA} and T_{0NB} are the transfer functions from the A and B inputs to the single-ended + and - outputs

taking the difference of these two equations we obtain

$$v_{OUT} = v_{OUT+} - v_{OUT-} = (T_{0PA} - T_{0NA})v_1 + (T_{0PB} - T_{0NB})v_2$$

by symmetry, we have

$$T_{OPA} = T_{ONB} \text{ and } T_{ONA} = T_{OPB}$$

thus can express V_{OUT} as

$$v_{OUT} = (T_{0PA} - T_{0NA})(v_1 - v_2)$$

or as

$$v_{OUT} = A_d v_d$$

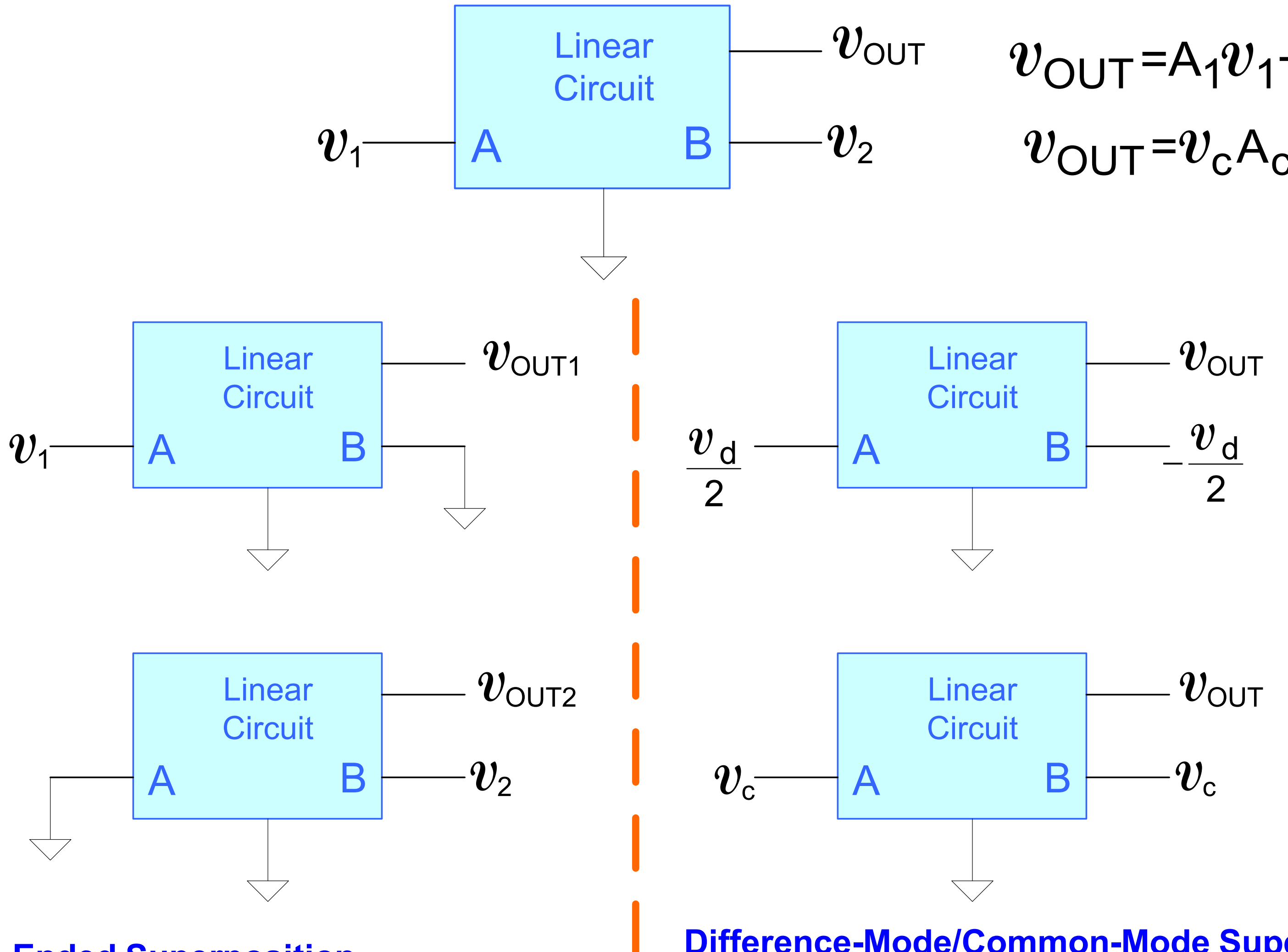
where $A_d = T_{OPA} - T_{ONA}$ and where $v_d = v_1 - v_2$

Common-Mode and Differential-Mode Analysis

Consider <u>any</u> output voltage for any linear circuit with two inputs

$$v_{OUT} = A_1 v_1 + A_2 v_2$$

$$v_{OUT} = v_c A_c + v_d A_d$$

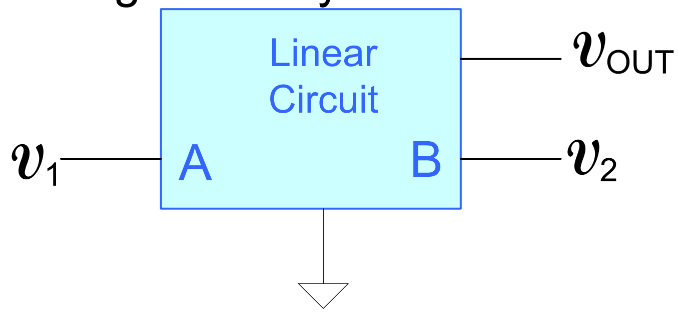


Single-Ended Superposition

Difference-Mode/Common-Mode Superposition

Common-Mode and Differential-Mode Analysis

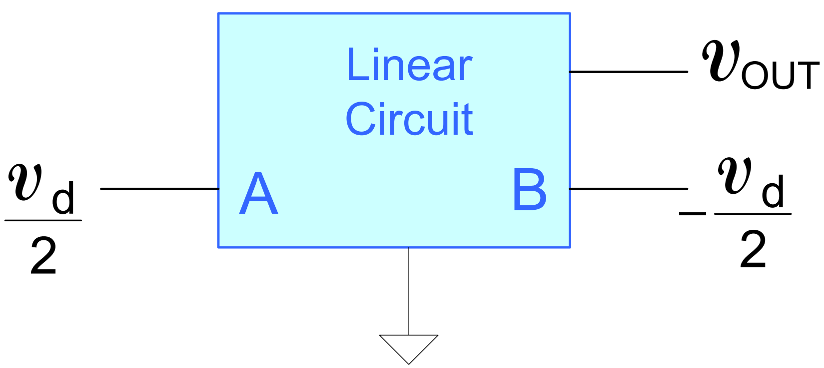
Consider an output voltage for any linear circuit with two inputs

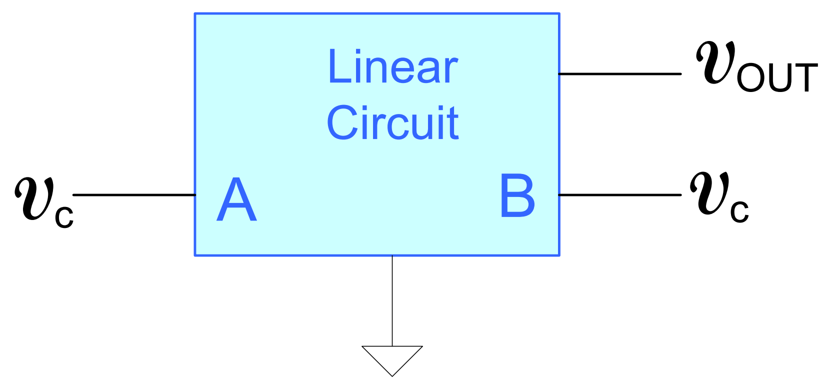


$$v_{OUT} = v_c A_c + v_d A_d$$

- **Difference-Mode/Common-Mode Superposition is almost exclusively used for characterizing Amplifiers that are designed to have a large differential gain and a small common-mode gain**

- **Analysis to this point has been focused only on the circuit on the left**



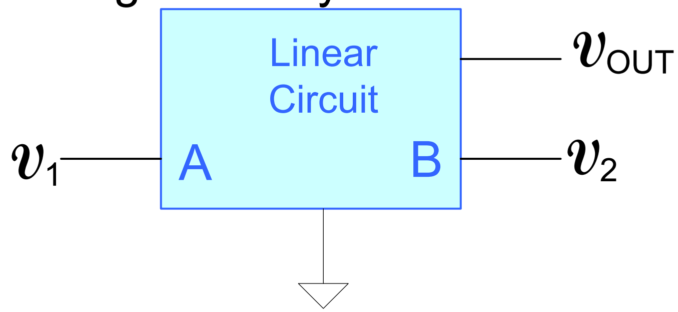


Note: Previous analysis was correct, just did not address whether the circuit had any common mode gain.

Will now get the total output of an amplifier circuit !

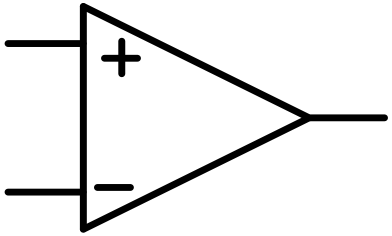
Common-Mode and Differential-Mode Analysis

Consider an output voltage for any linear circuit with two inputs



$$v_{OUT} = v_c A_c + v_d A_d$$

Does Conventional Wisdom Address the Common Mode Gain Issue?



Does Conventional Wisdom Address the Common Mode Gain Issue?

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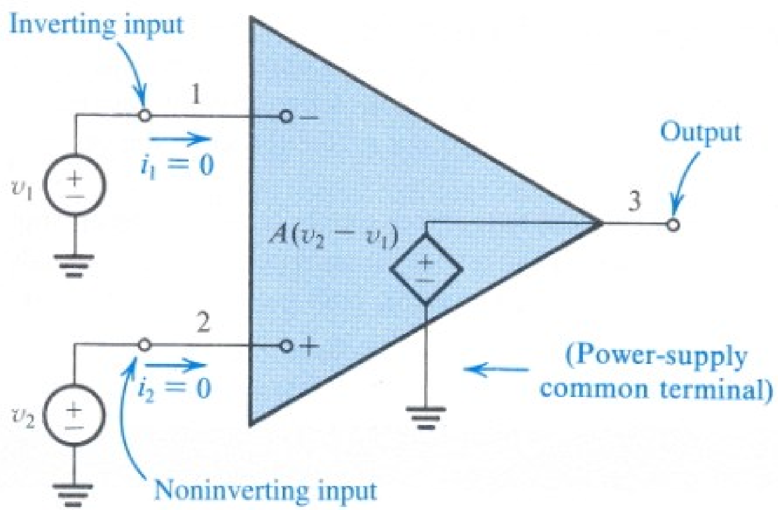

FIGURE 2.3 Equivalent circuit of the ideal op amp.

Yes – Common-Mode Gain was Addressed

Does Conventional Wisdom Address the Common Mode Gain Issue?

66 CHAPTER 2 OPERATIONAL AMPLIFIERS

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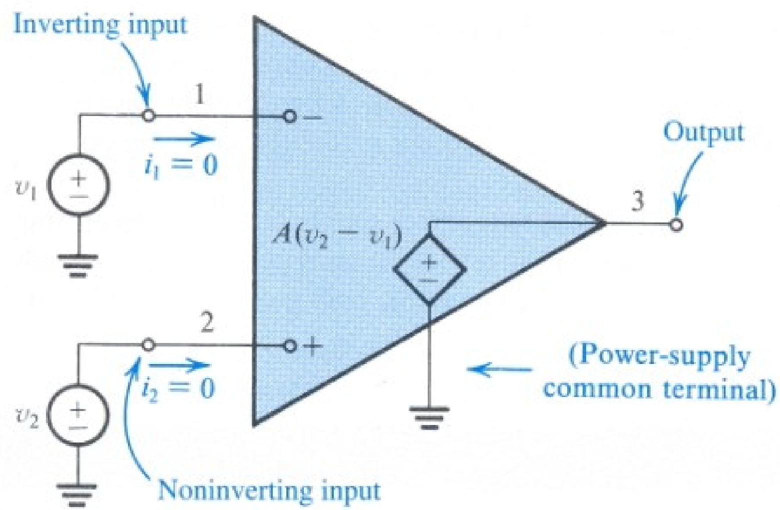


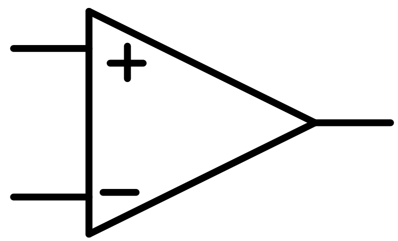
FIGURE 2.3 Equivalent circuit of the ideal op amp.

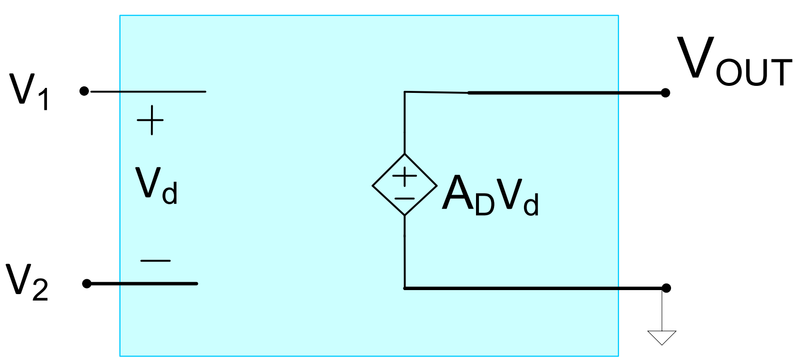
TABLE 2.1 Characteristics of the Ideal Op Amp
1. Infinite input impedance
2. Zero output impedance
3. Zero common-mode gain or, equivalently, infinite common-mode rejection
4. Infinite open-loop gain *A*
5. Infinite bandwidth

Yes – Common-Mode Gain was Addressed

How is Common-Mode Gain Modeled?

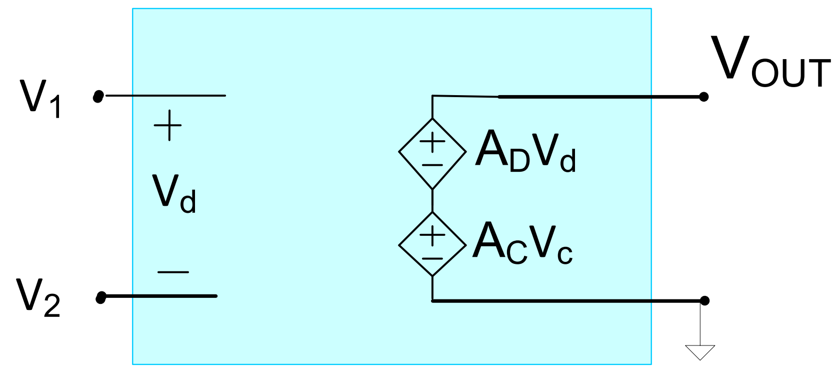
If Op Amp is a Voltage Amplifier with infinite input impedance, zero output impedance, and one terminal of the output is grounded





Ideal Differential Voltage Amplifier

$$V_d = V_1 - V_2$$

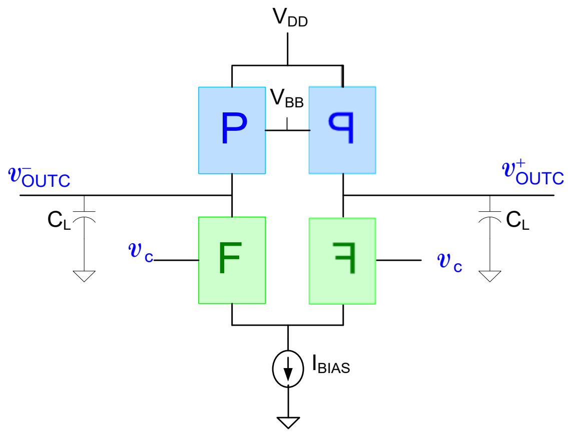


Ideal Voltage Amplifier

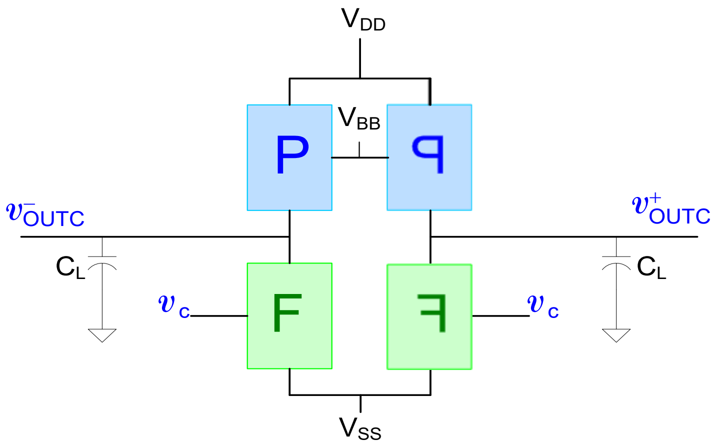
$$V_d = V_1 - V_2 \qquad V_c = \frac{V_1 + V_2}{2}$$

- 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

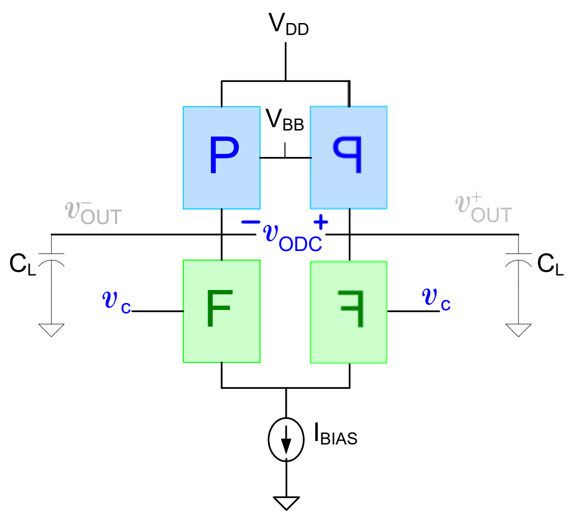
Performance with Common-Mode Input



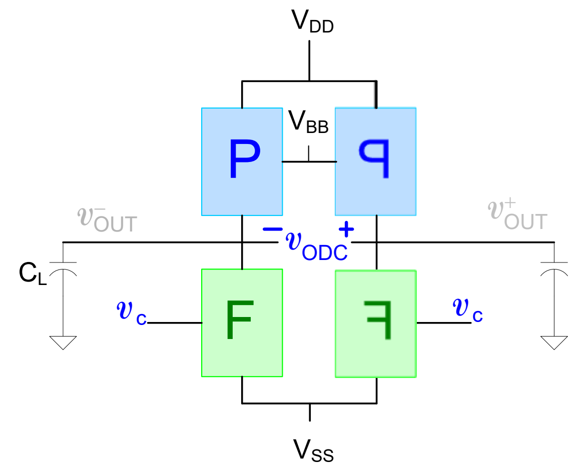
Single-Ended Outputs
Tail-Current Bias



Single-Ended Outputs
Tail-Voltage Bias



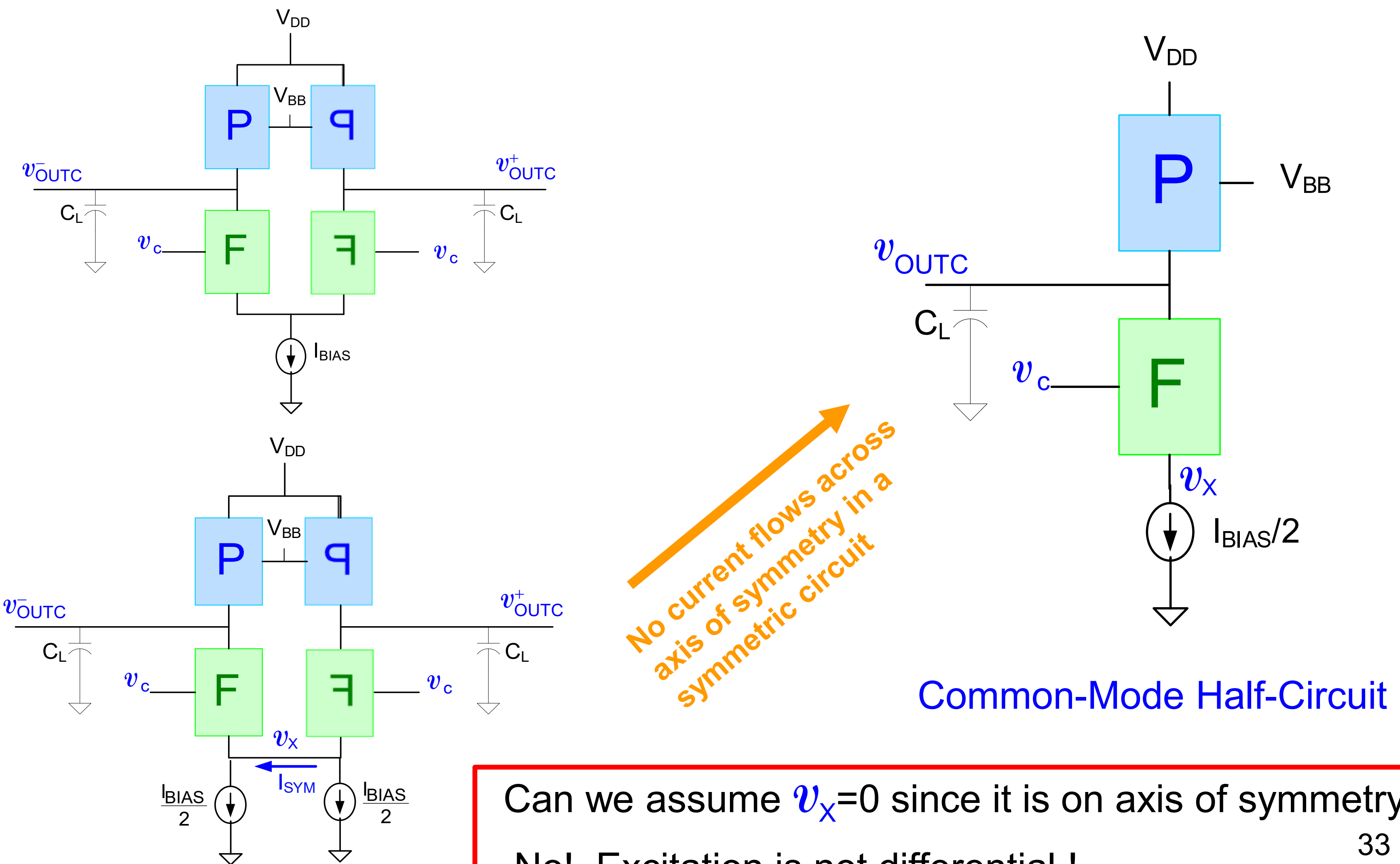
Differential Output
Tail Current Bias



Differential Output
Tail Voltage Bias

Performance with Common-Mode Input

Consider tail-current bias amplifier

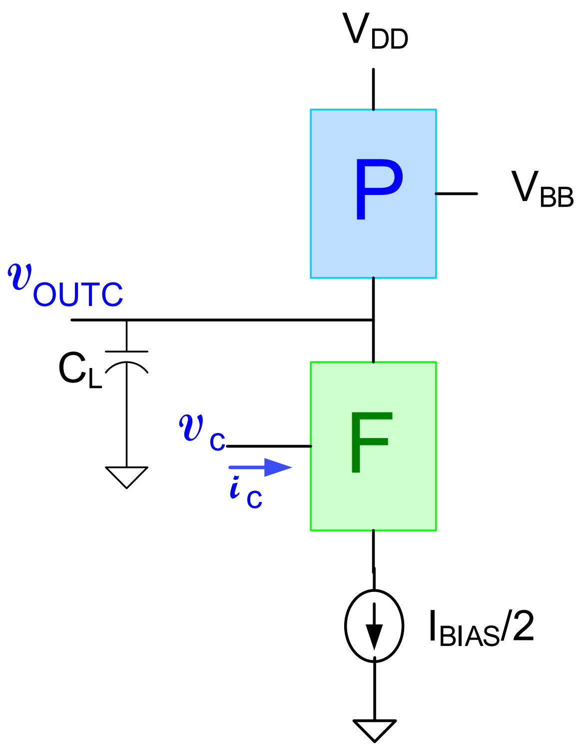


Can we assume v_X=0 since it is on axis of symmetry?

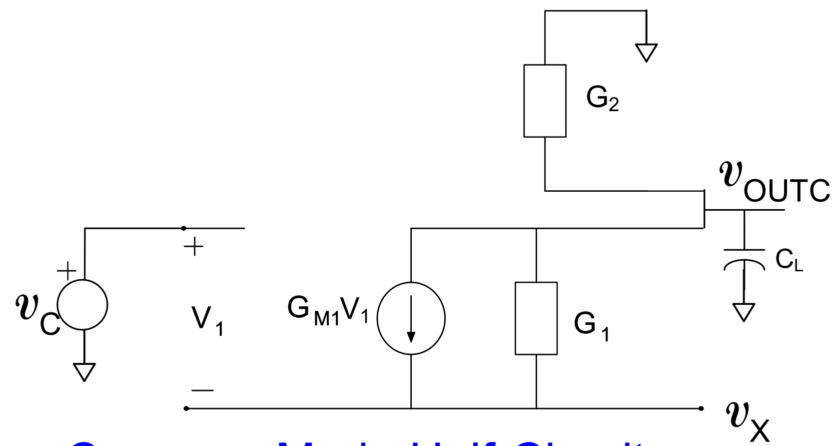
No! Excitation is not differential !

Performance with Common-Mode Input

Consider tail-current bias amplifier with i_c=0



Common-Mode Half-Circuit
(large signal: nonlinear)



Common-Mode Half-Circuit
(small-signal linear)

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

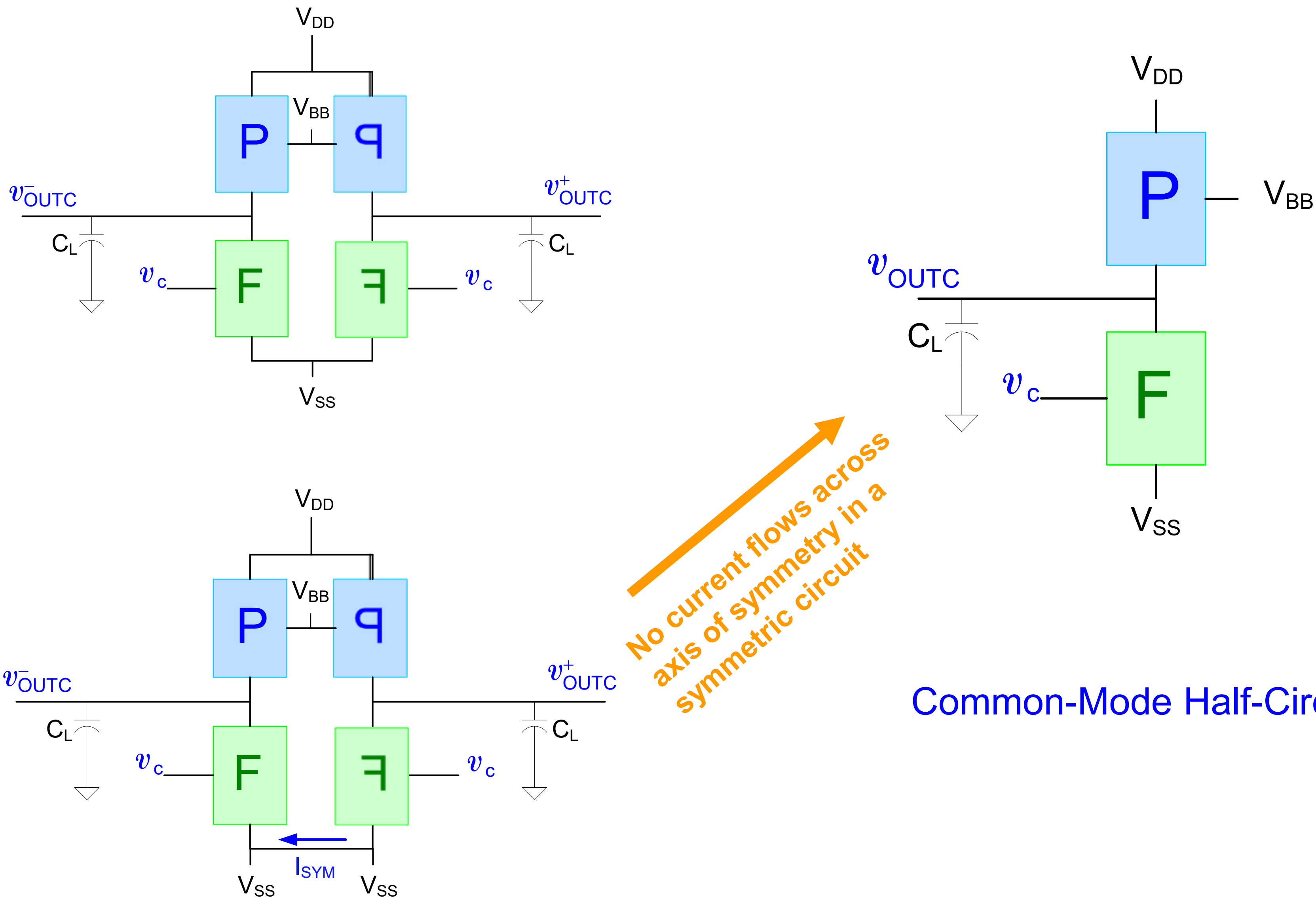
Solving, we obtain

$v_{OUTC}=0$ 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. Analysis with nonideal current source is simple and will be discussed later)

Performance with Common-Mode Input

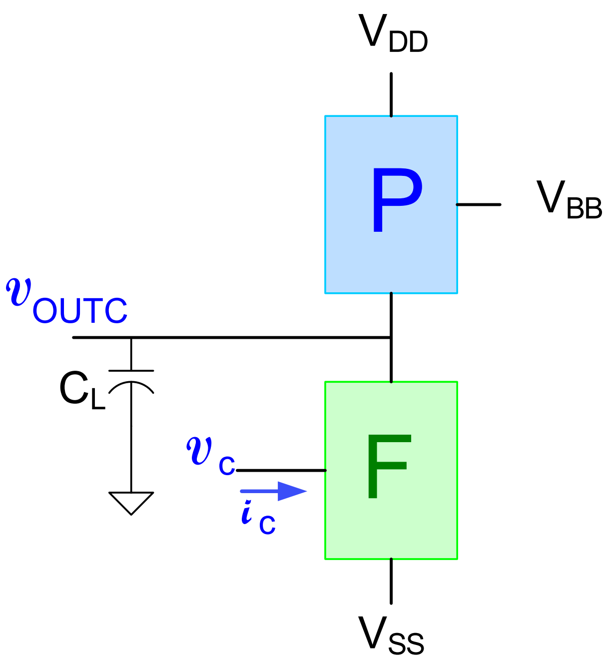
Consider tail-voltage bias amplifier with i_c=0



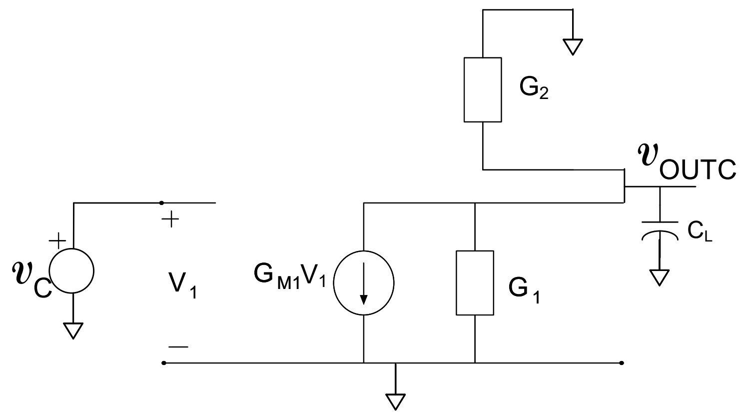
Common-Mode Half-Circuit

Performance with Common-Mode Input

Consider tail-voltage bias amplifier with i_c=0



Common-Mode Half-Circuit
(large signal: nonlinear)



Common-Mode Half-Circuit
(small signal: linear)

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

Solving, we obtain

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

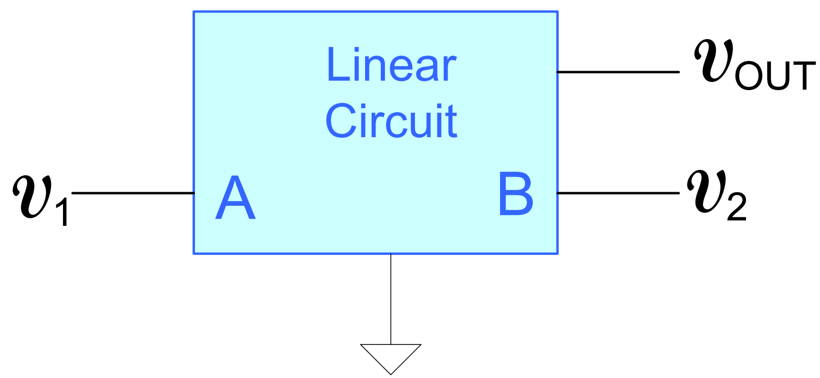
This circuit has a rather large common-mode gain and will not reject common-mode signals

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

- 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

Overall Small-Signal Analysis

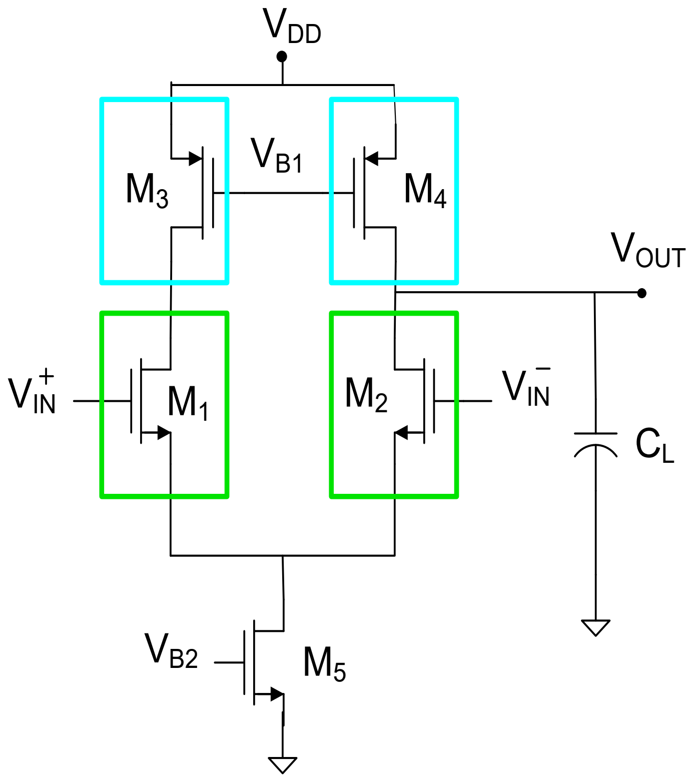
As stated earlier, with common-mode gain and difference-mode gains available



$$v_{OUT} = v_c A_c + v_d A_d$$

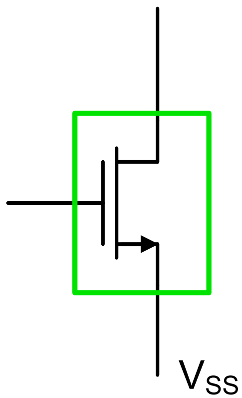
- Fully Differential Single-Stage Amplifier
  - General Differential Analysis
  - 5T Op Amp from simple quarter circuit
  - Biasing with CMFB circuit
  - Common-mode and differential-mode analysis
  - Common Mode Gain
  - Overall Transfer Characteristics
- Design of 5T Op Amp
- Slew Rate

Design of 5T op amp

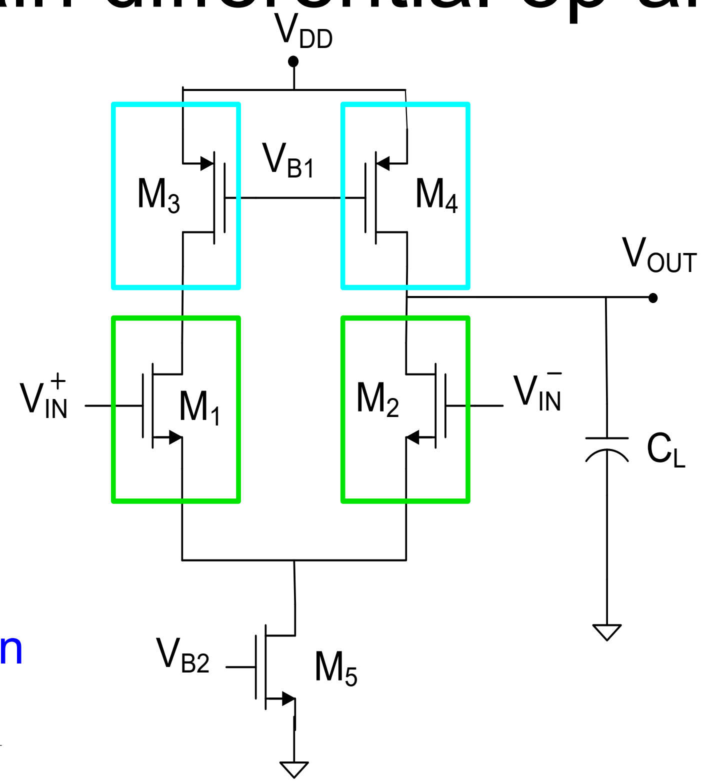


Recall

Single-stage low-gain differential op amp



Quarter Circuit



Single-Ended Output : Differential Input Gain

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

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

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

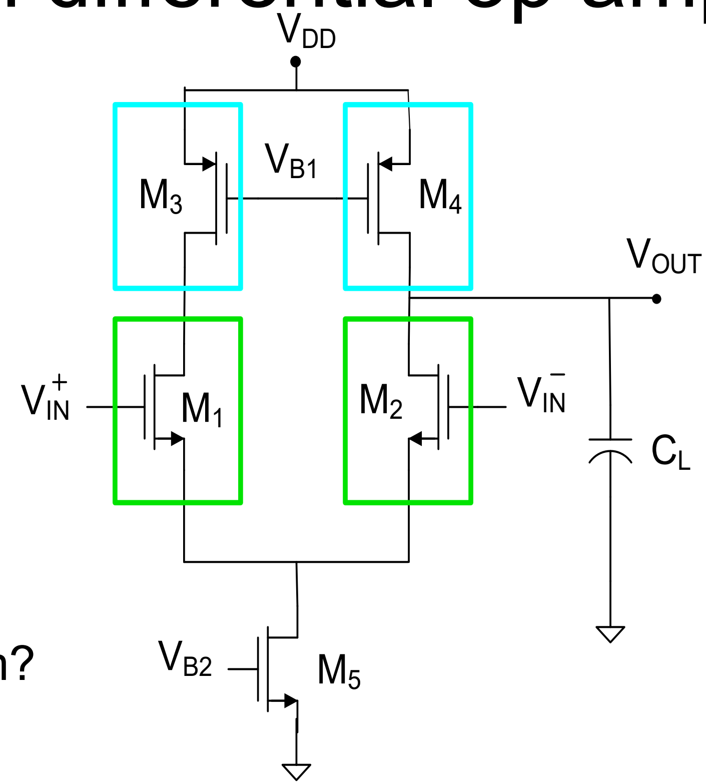
Need a CMFB circuit to establish V_{B1}

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)

Natural Parameters (assuming symmetry):

Need a CMFB circuit to establish V_{B1}

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

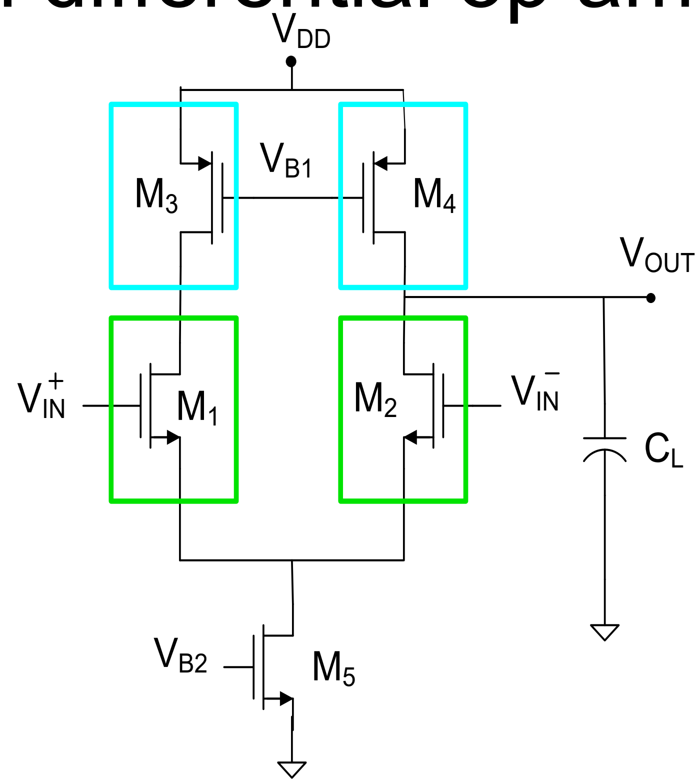
Constraints: $I_{D5} \simeq 2I_{D3}$

Net Degrees of Freedom: 4

- Expressions for A_0 and GB were obtained from quarter-circuit
- Expressions for A_0 and GB in terms of natural parameters for quarter circuit were messy
- Can show that expressions for A_0 and GB in terms of natural parameters for 5T amplifier are also messy

Can a set of practical design parameters be identified?

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

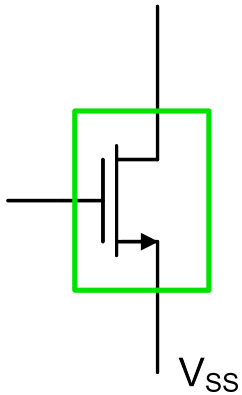
Net Degrees of Freedom: 4

Practical Parameters:

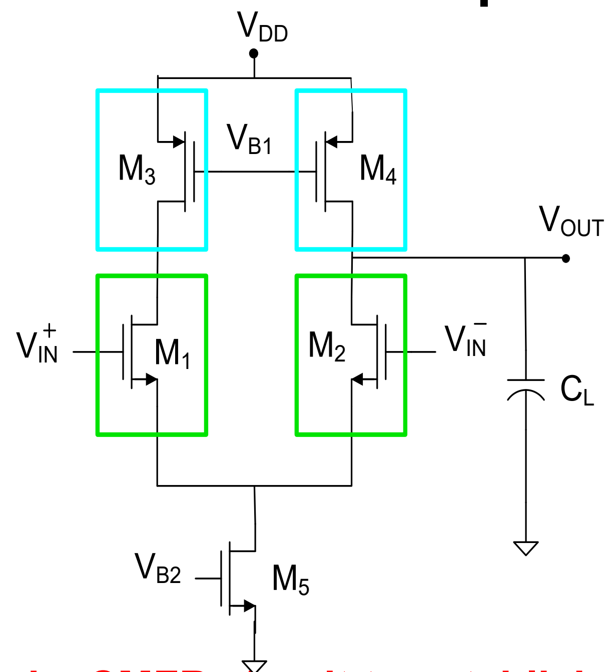
$$\{V_{EB1}, V_{EB3}, V_{EB5}, P\}$$

Will now express small-signal performance characteristics in terms of Practical Parameters

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



Quarter Circuit



Single-Ended Output : Differential Input Gain

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

$$A_o = \frac{\frac{g_{m1}}{2}}{g_{O1} + g_{O3}}$$

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

Need a CMFB circuit to establish V_{B1}

$$I_{D1Q} = I_{D3Q}$$

$$g_{m1} = \frac{2I_{D1Q}}{V_{EB1}}$$

$$g_{o1} = \lambda_1 I_{D1Q}$$

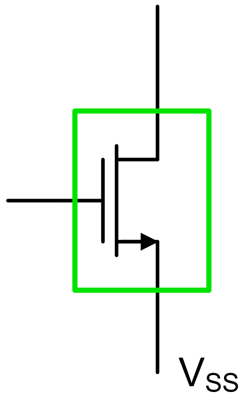
$$g_{o3} = \lambda_3 I_{D3Q}$$

Practical Parameters:

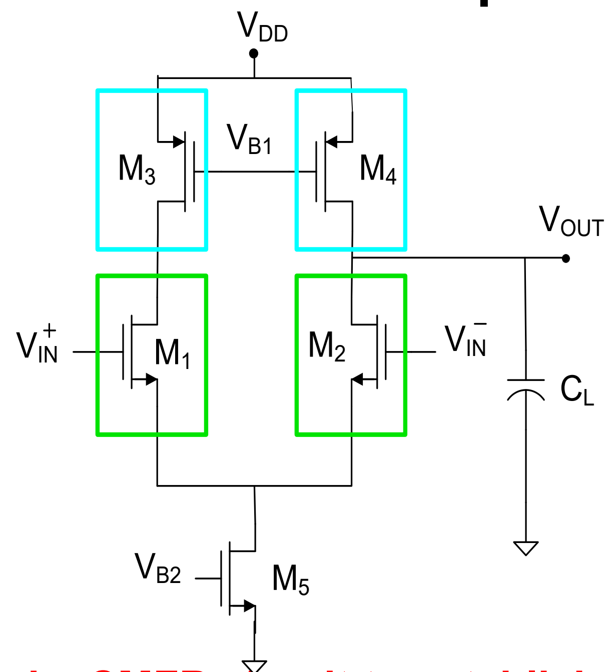
$$\{V_{EB1}, V_{EB3}, V_{EB5}, P\}$$

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

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



Quarter Circuit



Single-Ended Output : Differential Input Gain

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

$$A_o = \frac{\frac{g_{m1}}{2}}{g_{O1} + g_{O3}}$$

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

Need a CMFB circuit to establish V_{B1}

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

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 !

Practical Parameters:

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

Is this an attractive feature?

How should the remaining 2 DOF be used?

Stay Safe and Stay Healthy !

End of Lecture 4