# Analog IC Design

## Lecture 11
## Differential Amplifier

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# Outline

- Recapping previous key results
- Single-ended (SE) vs differential operation
- Pseudo differential amplifier
  - Common-mode (CM) and differential analysis
- Differential amplifier (differential pair)
  - Common-mode (CM) and differential analysis
- Effect of mismatch in load and input pair
  - Common-mode rejection ratio (CMRR)
- Frequency response of differential amplifier
  - Common-mode (CM) and differential analysis

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# MOSFET in Saturation

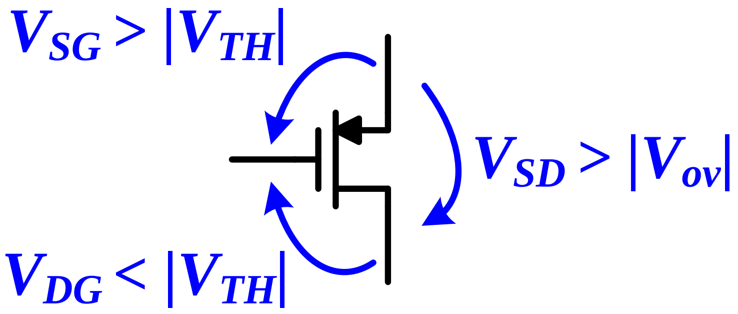
- The channel is pinched off if the difference between the gate and drain voltages is not sufficient to create an inversion layer

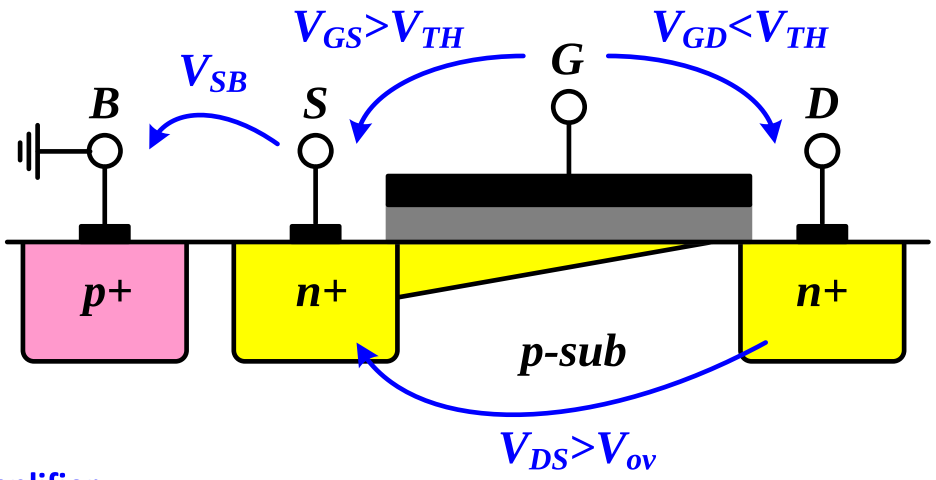
$$V_{GD} \leq V_{TH} \quad or \quad V_{DS} \geq V_{ov}$$

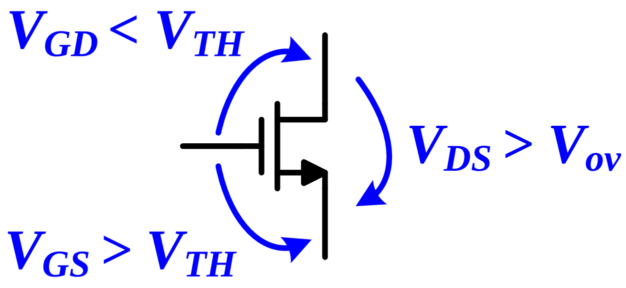
- Square-law (long channel MOS)

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

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



# Regions of Operation Summary

**OFF (Subthreshold)**

$V_{GS} < V_{TH}$

**ON**

$V_{GS} > V_{TH}$

**Triode**

$V_{DS} < V_{ov}$

Or

$V_{GD} > V_{TH}$

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

**Pinch-Off (Saturation)**

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

Or

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

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

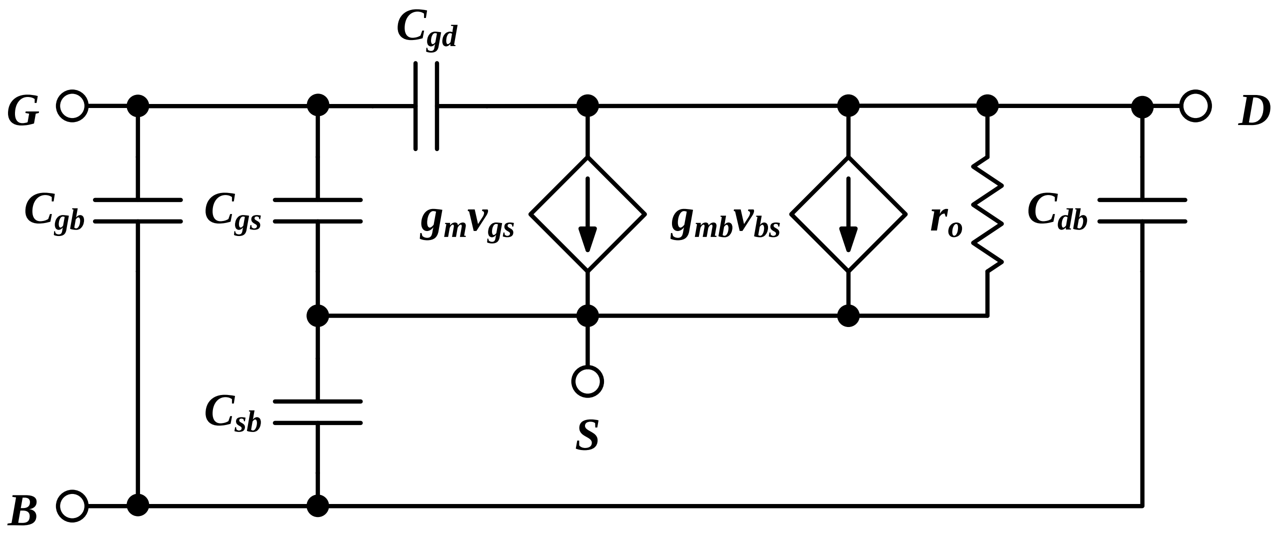
# High Frequency Small Signal Model

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

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

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

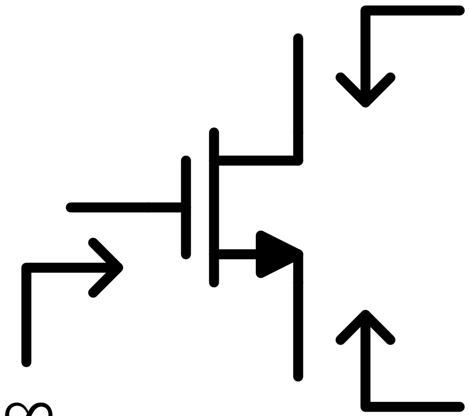
$$C_{gb} \approx 0 \qquad C_{gs} \gg C_{gd} \qquad C_{sb} > C_{db}$$



# Rin/out Shortcuts Summary

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

H.I.N.



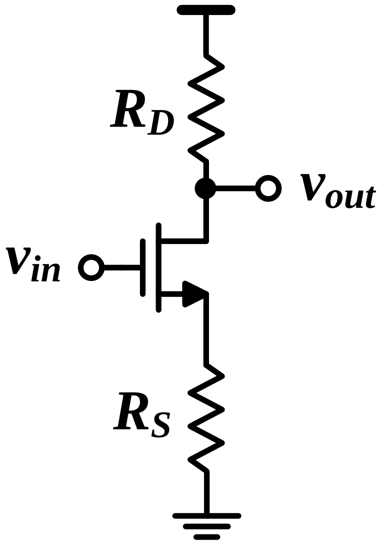
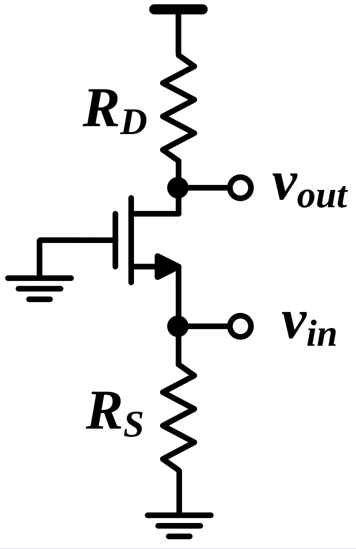
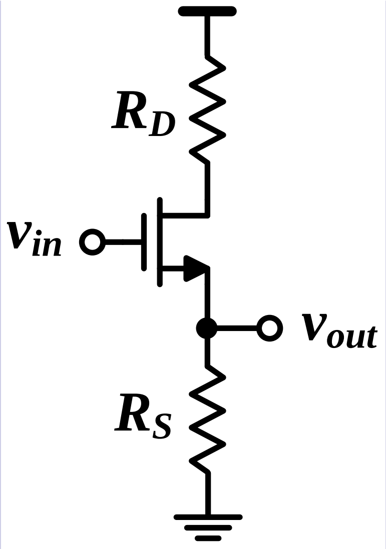
$\infty$

At low frequencies **ONLY**

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

L.I.N.

# Summary of Basic Topologies

| | CS | CG | CD (SF) |
|---|---|---|---|
| |  |  |  |
| | Voltage & current amplifier | Voltage amplifier<br>Current buffer | Voltage buffer<br>Current amplifier |
| **Rin** | $\infty$ | $R_S \| \| \dfrac{1}{g_m + g_{mb}}\left(1 + \dfrac{R_D}{r_o}\right)$ | $\infty$ |
| **Rout** | $R_D \| \| r_o[1 + (g_m + g_{mb})R_S]$ | $R_D \| \| r_o$ | $R_S \| \| \dfrac{1}{g_m + g_{mb}}\left(1 + \dfrac{R_D}{r_o}\right)$ |
| **Gm** | $\dfrac{-g_m}{1 + (g_m + g_{mb})R_S}$ | $g_m + g_{mb}$ | $\dfrac{g_m}{1 + R_D/r_o}$ |

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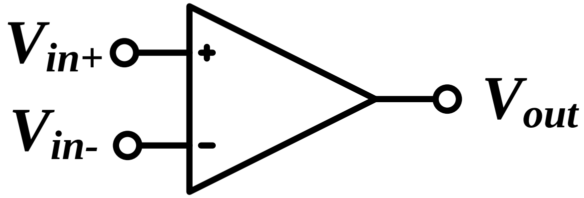
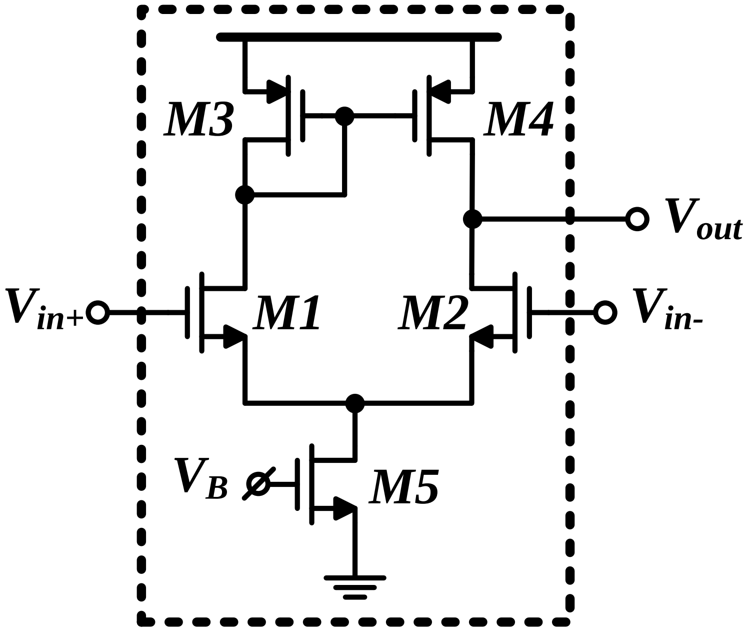
# Have You Seen a Diff Amp Before?

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



# Single-Ended (SE) vs Differential

- SE: measured with respect to a fixed potential (usually the ground)

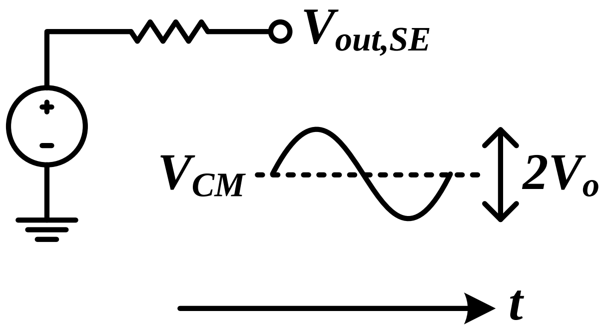
$$V_{out,SE} = V_o \sin \omega t + V_{CM}$$

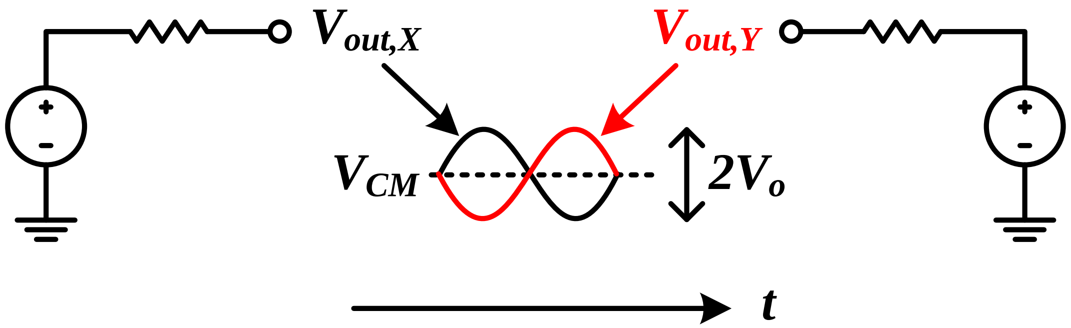
  - Single-ended peak-to-peak swing is $2V_o$

- Diff: measured between two nodes that have **equal and opposite** signals around a common-mode (CM) level

$$\begin{aligned} V_{out,diff} &= V_X - V_Y \\ &= (V_o \sin \omega t + V_{CM}) - (-V_o \sin \omega t + V_{CM}) \\ &= 2V_o \sin \omega t \end{aligned}$$

  - Differential peak-to-peak swing is $4V_o$

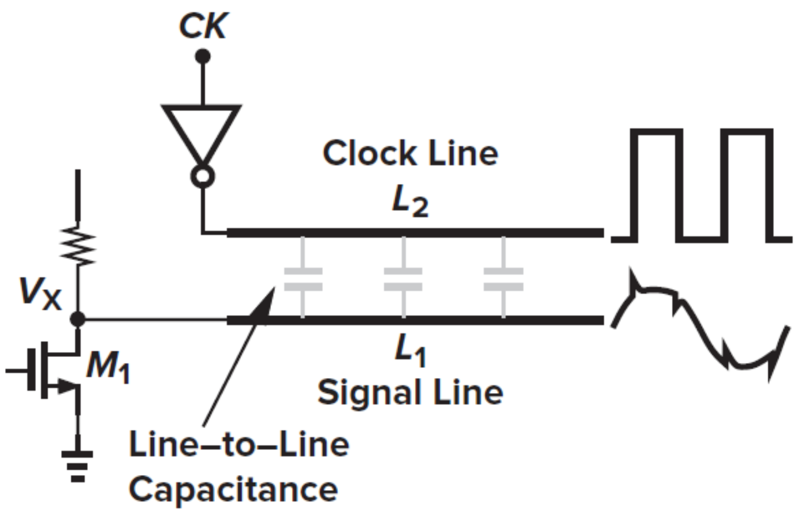


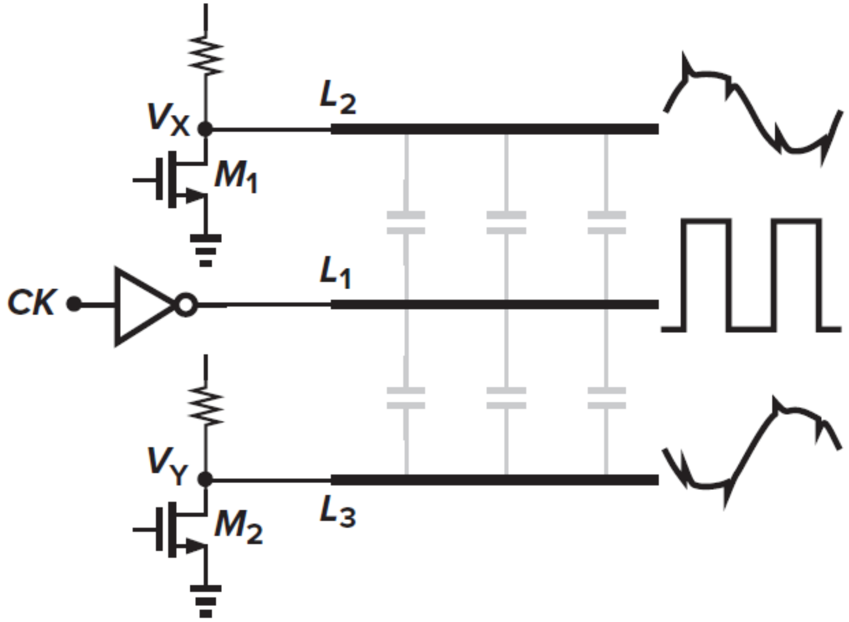



# Why Differential?

$$V_{out,SE} = V_o \sin \omega t + V_{CM} + V_{CMnoise}$$

$$\begin{aligned} V_{out,diff} &= V_X - V_Y \\ &= (V_o \sin \omega t + V_{CM} + V_{CMnoise}) - (-V_o \sin \omega t + V_{CM} + V_{CMnoise}) \\ &= 2V_o \sin \omega t \end{aligned}$$




[Razavi, 2017]

# Why Differential?

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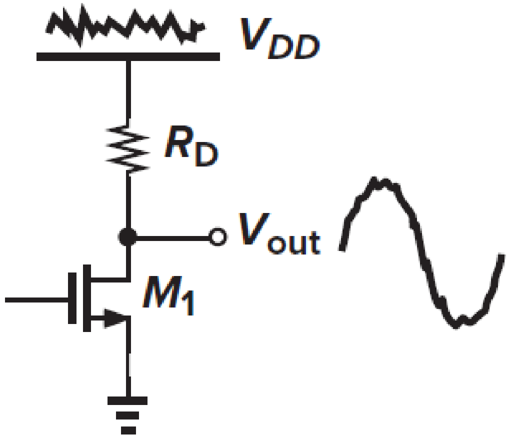
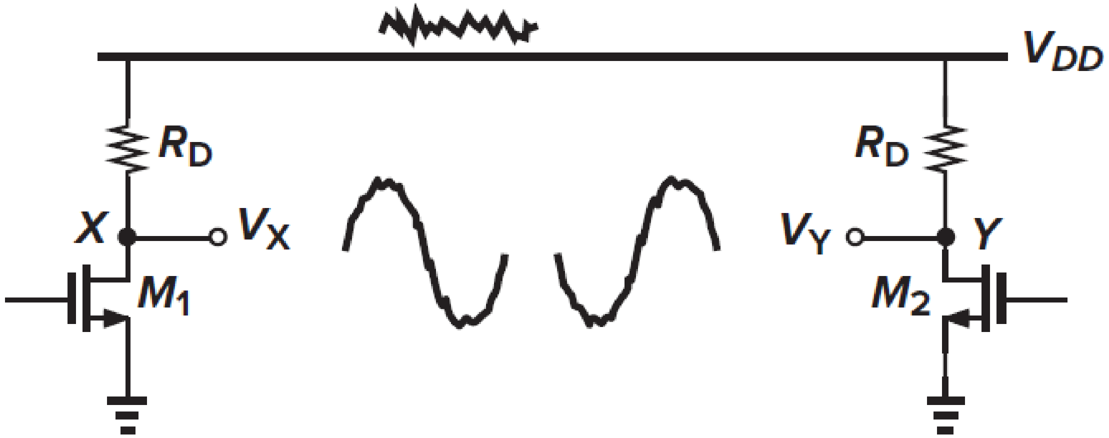


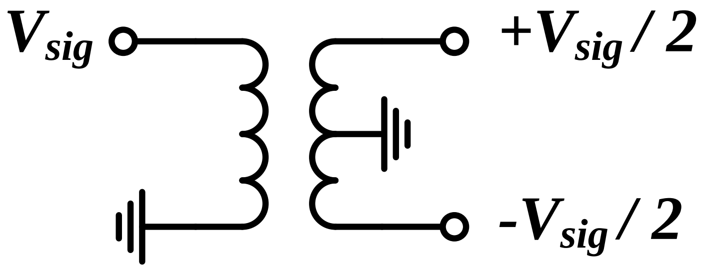

[Razavi, 2017]

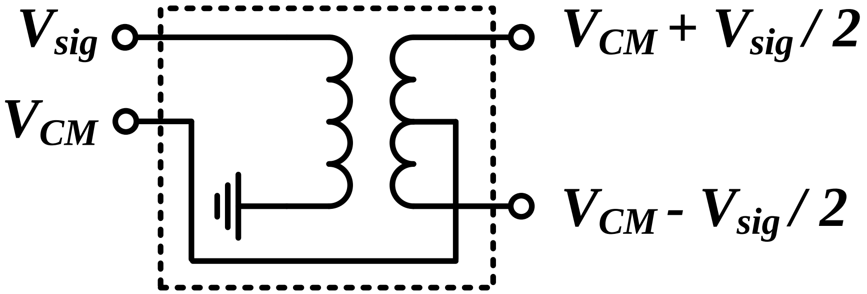
# Why Differential?

- Pros
  - **Common-mode (CM) noise rejection**
  - **Simpler biasing (no need for bypass or coupling capacitors)**
  - Larger maximum signal swing
  - Higher linearity
- Cons
  - Doubling the area
  - Doubling the power consumption
- The advantages of differential operation by far outweigh the disadvantages
- Differential operation has become the de facto choice in today's high-performance analog and mixed-signal circuits

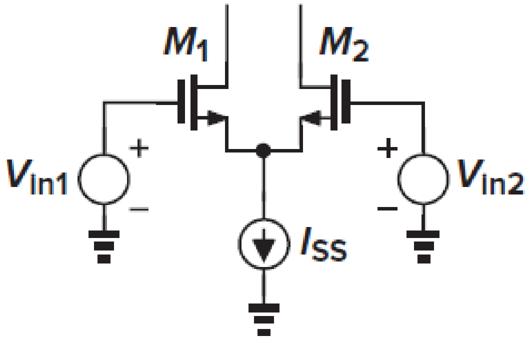
# SE ↔ Differential

- A center-tapped transformer can be used for SE to differential conversion and vice versa.
  - Used frequently in simulation testbenches.
  - Also known as balanced-to-unbalanced conversion (balun).
    - Differential → balanced
    - Single-ended → unbalanced
- There are other circuits that can be used to achieve this goal.

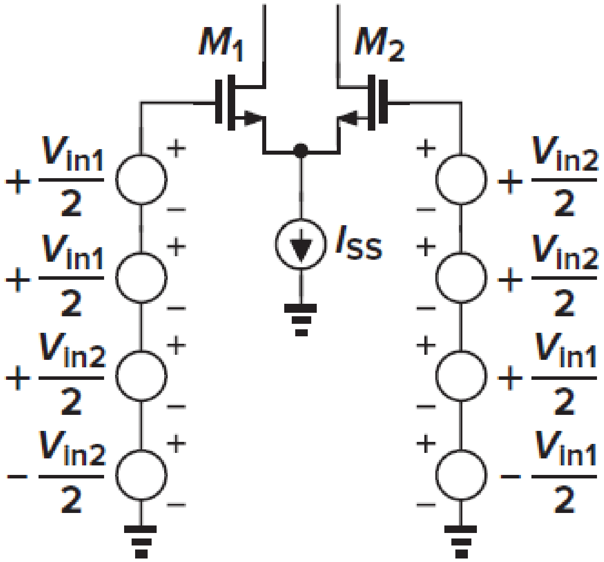


# Diff Amp with Arbitrary Inputs




(a)

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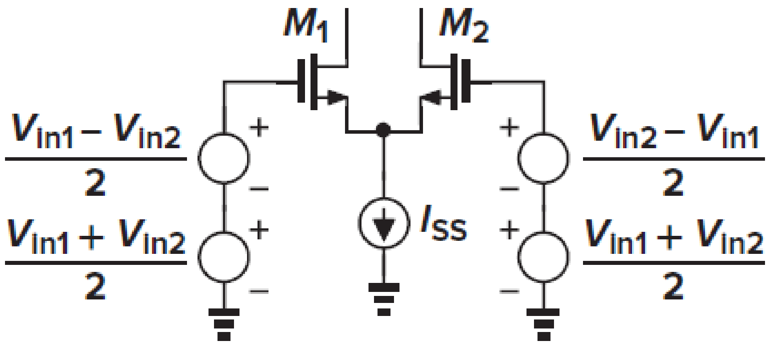


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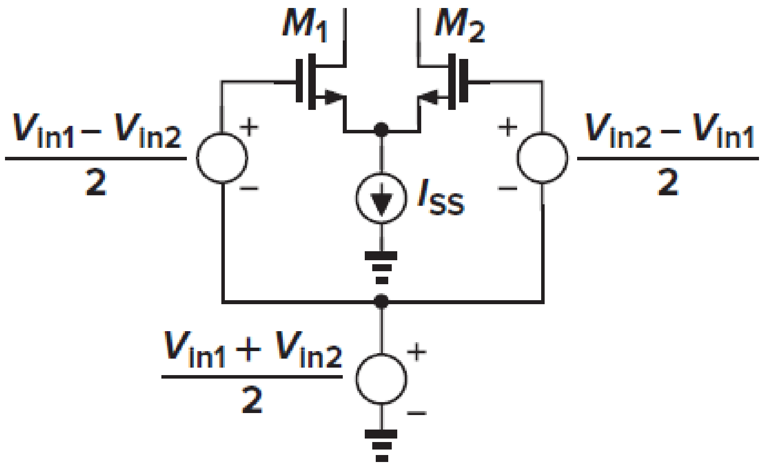



(d)

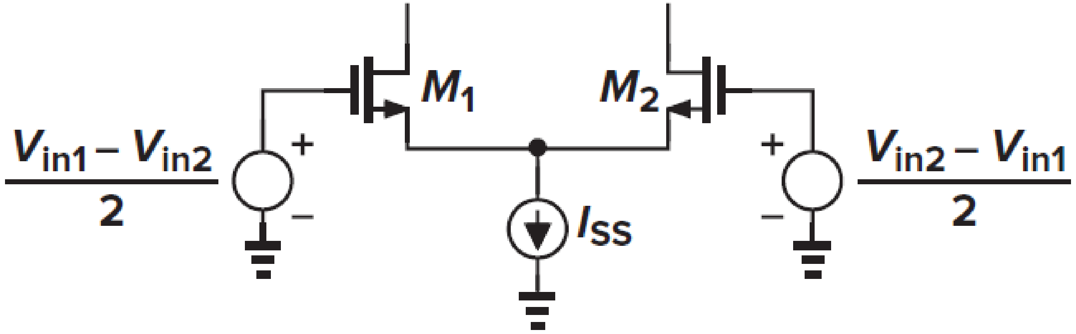
[Razavi, 2017]

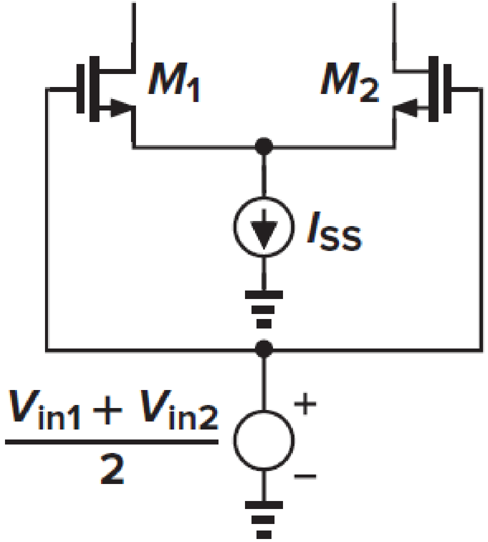
# Separate CM and Diff by Superposition

$$v_{id} = v_{in1} - v_{in2}$$

$$v_{id1} = \frac{v_{id}}{2} \quad \text{and} \quad v_{id2} = -\frac{v_{id}}{2}$$

$$v_{iCM} = \frac{v_{in1} + v_{in2}}{2}$$




[Razavi, 2017]

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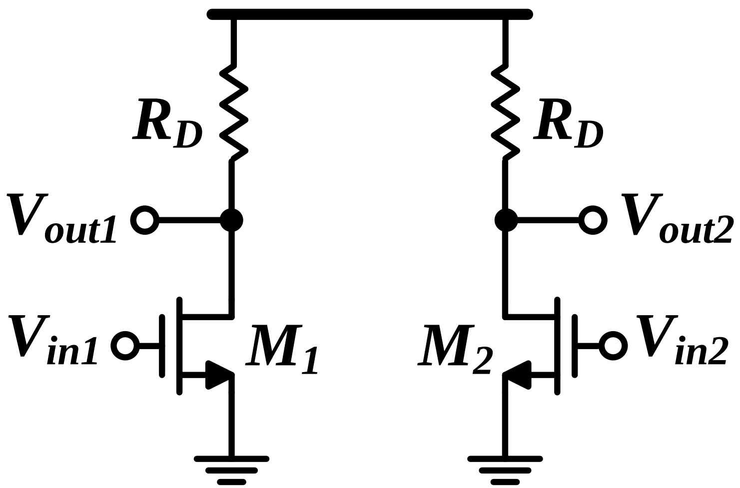
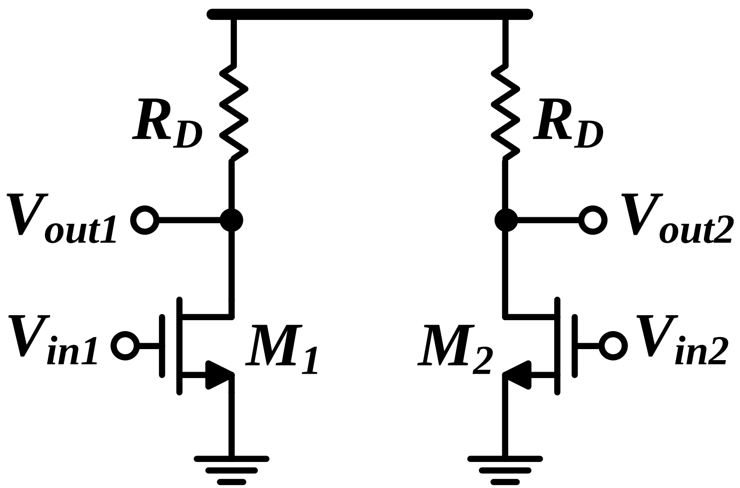
# "Pseudo" Diff Amp

A. Small signal analysis
   1. Diff small signal analysis
   2. CM small signal analysis
B. Large signal analysis
   1. Diff large signal analysis
   2. CM large signal analysis



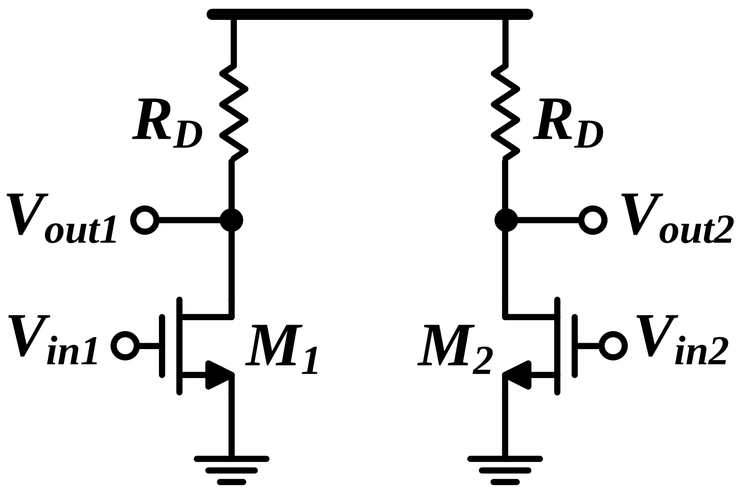
# A1. Diff Small Signal Analysis

- $v_{in1} = \frac{v_{id}}{2}$ and $v_{in2} = -\frac{v_{id}}{2}$
- $v_{out1} = -g_m R_D \left(\frac{v_{id}}{2}\right)$ and $v_{out2} = -g_m R_D \left(-\frac{v_{id}}{2}\right)$
- $v_{od} = v_{out1} - v_{out2} = -g_m R_D (v_{id})$
- $A_{vd} = \frac{v_{od}}{v_{id}} = -g_m R_D = \frac{v_{out1}}{v_{in1}} = \frac{v_{out2}}{v_{in2}} = A_{v,SE}$



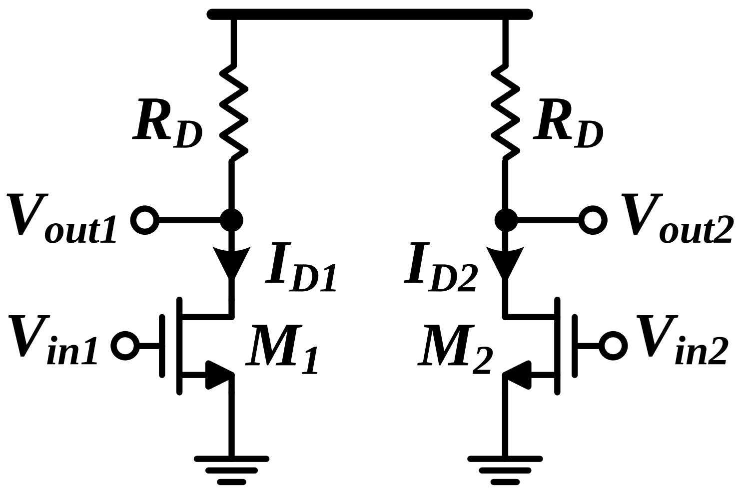
# A2. CM Small Signal Analysis

- $v_{in1} = v_{iCM}$ and $v_{in2} = v_{iCM}$
- $v_{out1} = -g_m R_D (v_{iCM})$ and $v_{out2} = -g_m R_D (v_{iCM})$
- $v_{oCM} = \frac{v_{out1} + v_{out2}}{2} = -g_m R_D (v_{iCM})$
- $A_{vCM} = \frac{v_{oCM}}{v_{iCM}} = -g_m R_D = A_{vd} \rightarrow A_{vd}/A_{vCM} = 1$
- The output CM level is sensitive to the input CM level
- CM input is not "completely" rejected



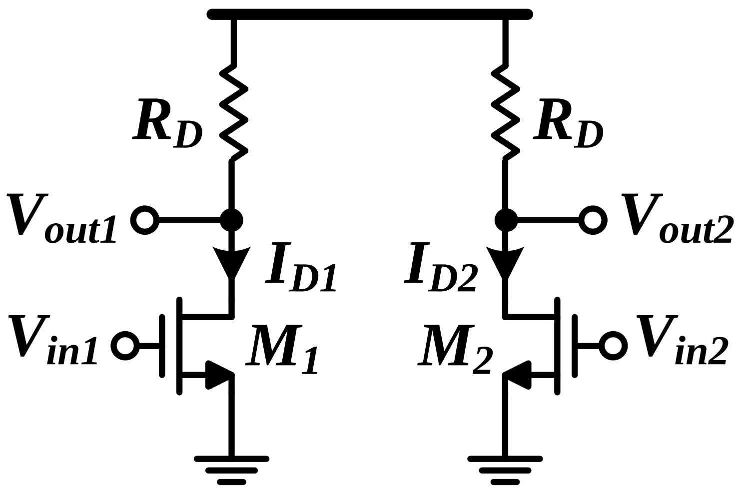
# B1. Diff Large Signal Analysis

- Assume large differential signal is applied
- The two sides act as two independent CS amplifiers
- Ex: $V_{in1} \uparrow and\ V_{in2} \downarrow$
  - M2 will turn OFF: $I_{D2} = 0$
  - $I_{D1}$ will increase following square law (expansive characteristics)
  - Eventually M1 goes out of saturation and $I_{D1}$ saturates at $\frac{V_{DD}}{R_D}$



# B2. CM Large Signal Analysis

- The two sides act as two independent CS amplifiers
- The transistors are biased by the input CM level
- The OP point is sensitive to the input CM level
- Ex: $V_{iCM} \uparrow = V_{in1} \uparrow = V_{in2} \uparrow$
  - $I_{D1}$ and $I_{D2}$ will increase following square law
  - Eventually M1 and M2 go out of saturation and $I_{D1,2} \approx \frac{V_{DD}}{R_D}$



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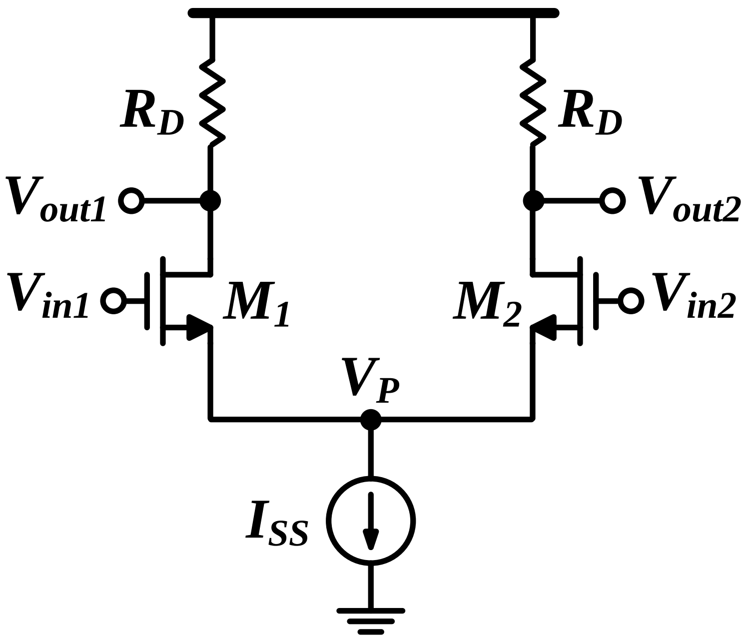
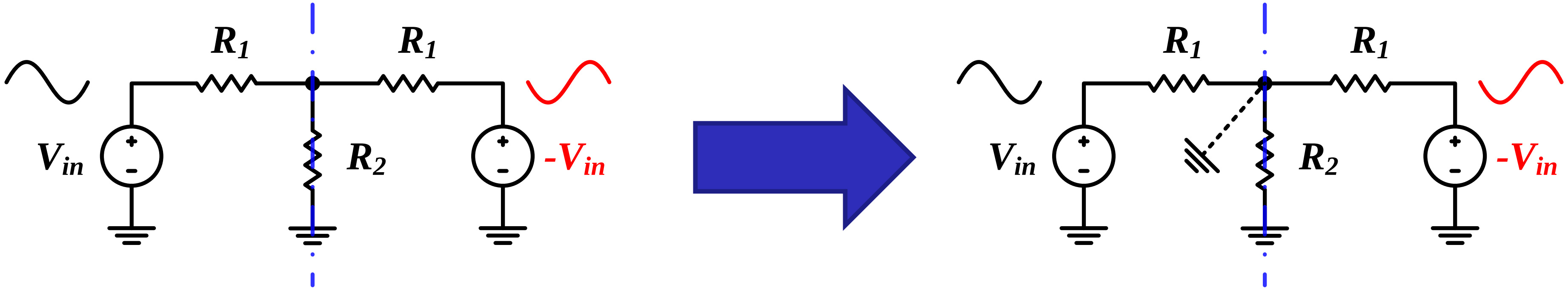
# “True” Diff Amp (Diff Pair)

A. Small signal analysis
    1. Diff small signal analysis
    2. CM small signal analysis
B. Large signal analysis
    1. Diff large signal analysis
    2. CM large signal analysis



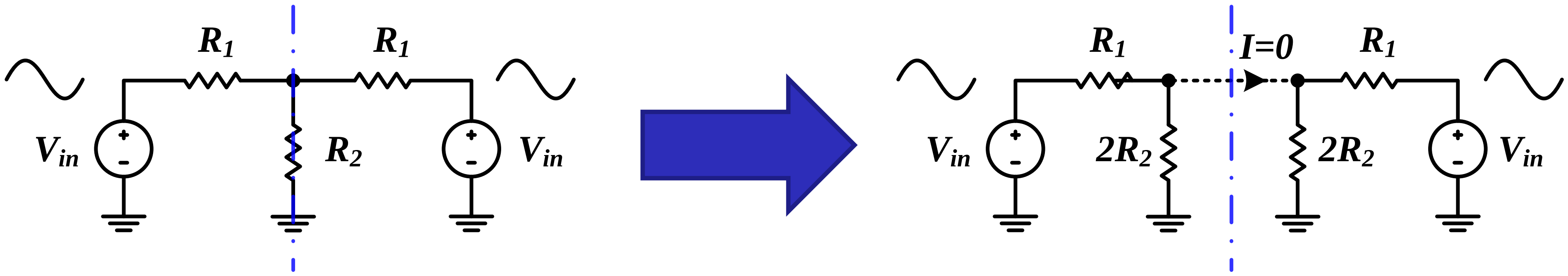
# Half-Circuit Principle (Differential Input)

- If a circuit is **<u>perfectly symmetric</u>**, the analysis can be greatly simplified by dividing it into two half-circuits.
- If the input to a symmetric circuit is DIFFERNTIAL
  - Any point ON THE AXIS OF SYMMETRY can be treated as a **<u>virtual ground</u>**.
- The circuit is divided into two identical half-circuits.



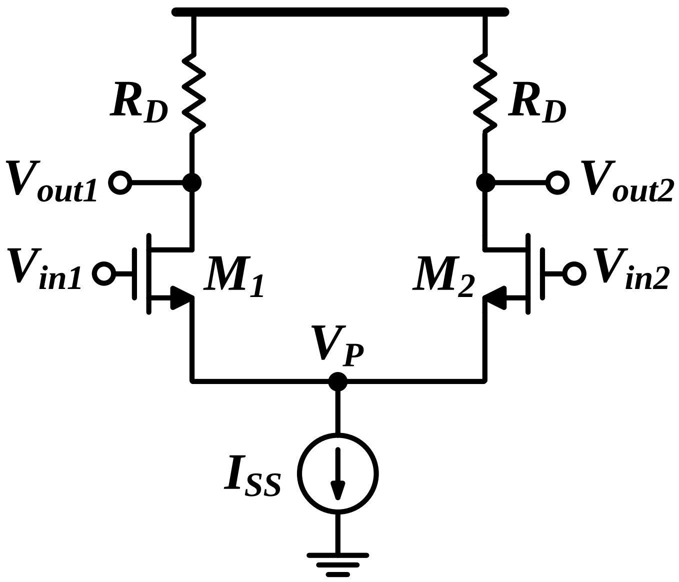
# Half-Circuit Principle (CM Input)

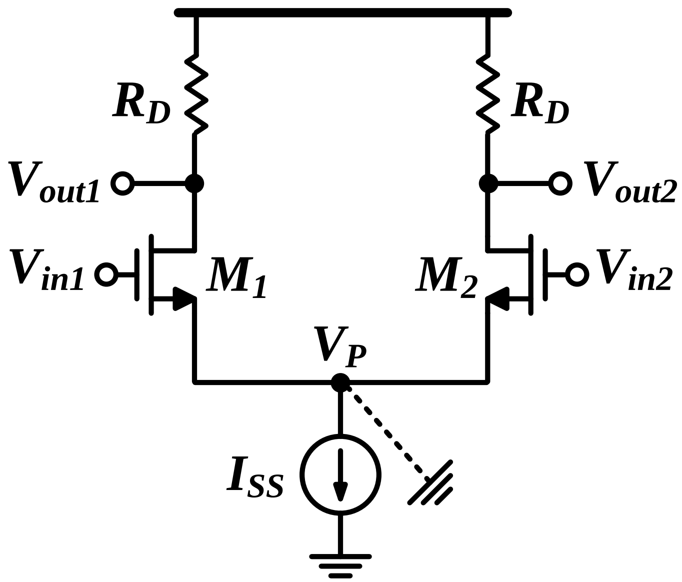
- If a circuit is **perfectly symmetric**, the analysis can be greatly simplified by dividing it into two half-circuits.
- If the input to a symmetric circuit is CM
  - Any wire CROSSING THE AXIS OF SYMMETRY can be treated as **open-circuit**.
- The circuit is divided into two identical half-circuits.



# A1. Diff Small Signal Analysis

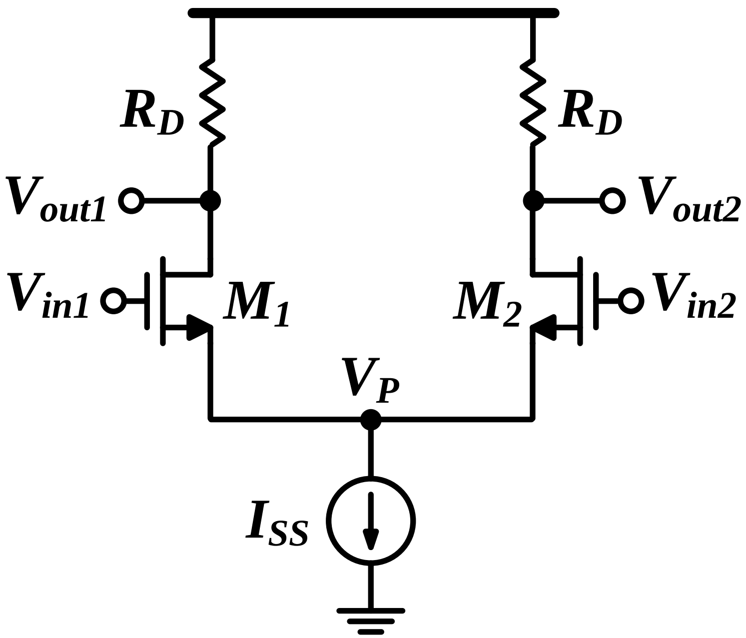
- METHOD #1: **Half-Circuit Principle (exploit symmetry)**
- $v_{in1} = -v_{in2} = v_{id}/2$: $V_P$ acts as virtual ground → same as pseudo
- $v_{out1} = -g_m R_D \left(\frac{v_{id}}{2}\right)$ and $v_{out2} = -g_m R_D \left(-\frac{v_{id}}{2}\right)$
- $v_{od} = v_{out1} - v_{out2} = -g_m R_D (v_{id})$
- $A_{vd} = \frac{v_{od}}{v_{id}} = -g_m R_D = \frac{v_{out1}}{v_{in1}} = \frac{v_{out2}}{v_{in2}} = A_{v,half-circuit} = A_{v,SE}$



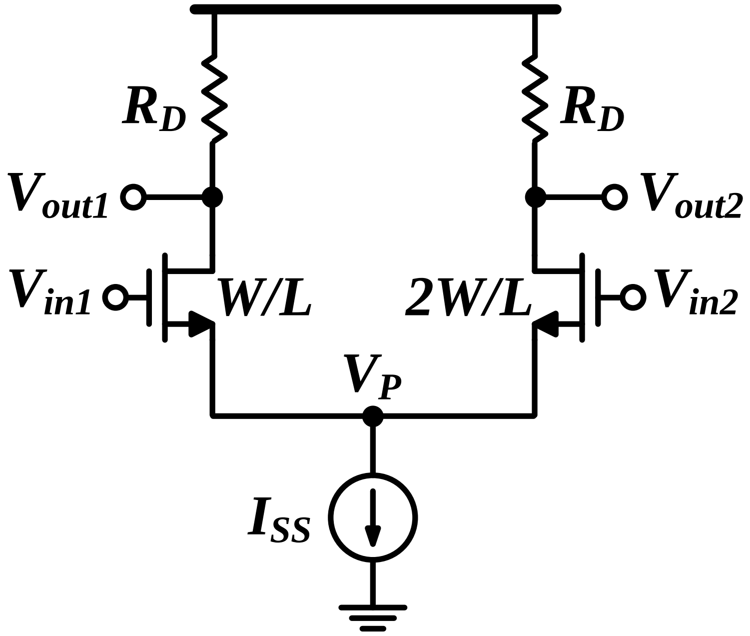
# A1. Diff Small Signal Analysis

- METHOD #2: **Super-position (H.W.)**
- For $v_{in1}$ to $v_{out1}$: CS (M1) degenerated by M2
- For $v_{in1}$ to $v_{out2}$: CD (M1) + CG (M2)
- Similarly for $v_{in2}$
- Same result as half-circuit principle
- Lengthy analysis! (but may be necessary if not symmetric)



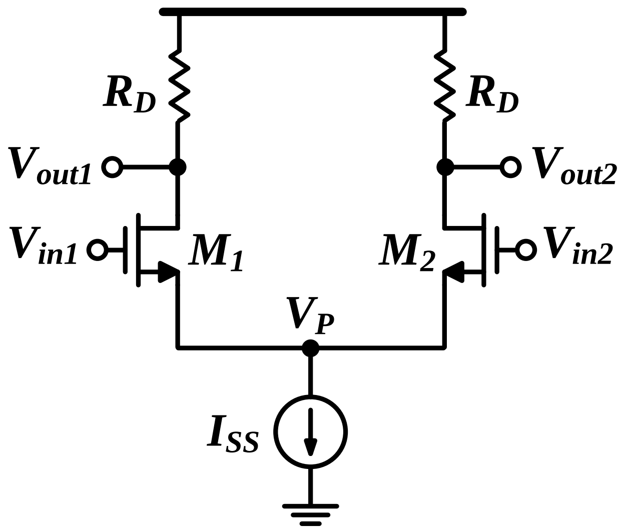
# A1. Diff Small Signal Analysis

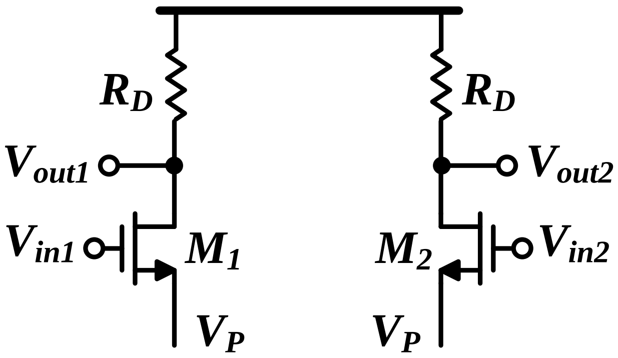
- Half-circuit principle does not work in this case



# A2. CM Small Signal Analysis

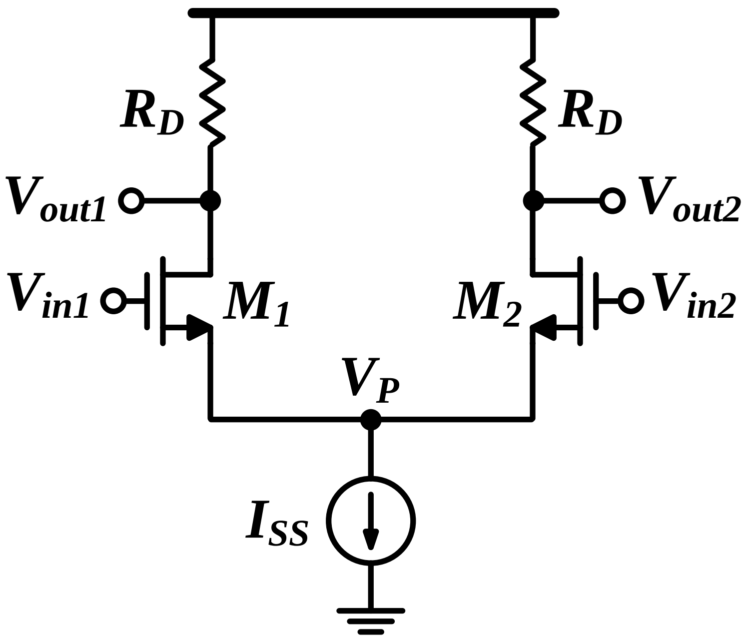
- METHOD #1: **Half-Circuit Principle (exploit symmetry)**
- $v_{out1} = 0$ and $v_{out2} = 0$
- $v_{oCM} = \frac{v_{out1}+v_{out2}}{2} = 0$
- $A_{vCM} = \frac{v_{oCM}}{v_{iCM}} = 0 = A_{v,half-circuit} \rightarrow A_{vd}/A_{vCM} \rightarrow \infty$
- The CM output is NOT sensitive to the CM input
- CM input is "completely" rejected (compare with pseudo diff amp)



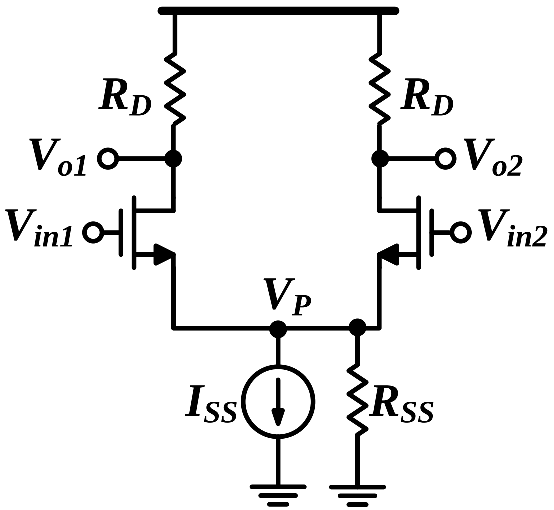
# A2. CM Small Signal Analysis

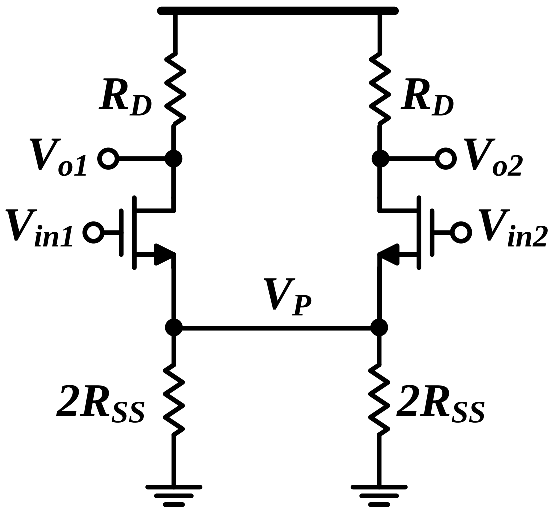
- METHOD #2: **Super-position (H.W.)**
- For $v_{in1}$ to $v_{out1}$: CS (M1) degenerated by M2
- For $v_{in1}$ to $v_{out2}$: CD (M1) + CG (M2)
- Similarly for $v_{in2}$
- Same result as half-circuit principle
- Lengthy analysis! (but may be necessary if not symmetric)

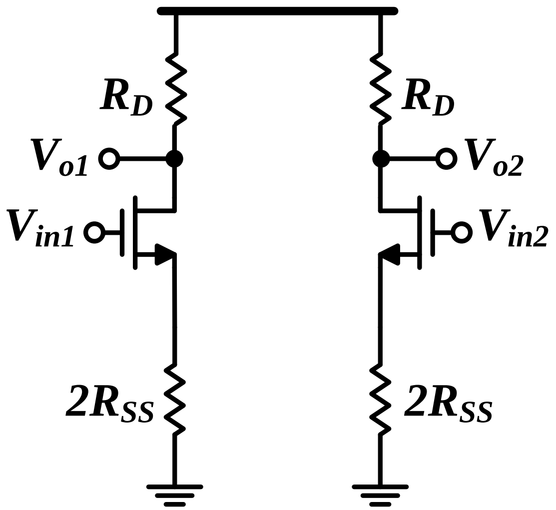


# A2. CM Small Signal Analysis ($\boldsymbol{R_{SS}} \neq \infty$)

- METHOD #1: **Half-Circuit Principle (exploit symmetry)**
- $A_{vCM} = \frac{v_{oCM}}{v_{iCM}} = \frac{-g_m R_D}{1+2(g_m+g_{mb})R_{SS}} = A_{v,half-circuit}$
- $A_{vd}/A_{vCM} \approx 2(g_m + g_{mb})R_{SS} \gg 1$
- CM input is “partially” rejected (compare with pseudo diff amp)



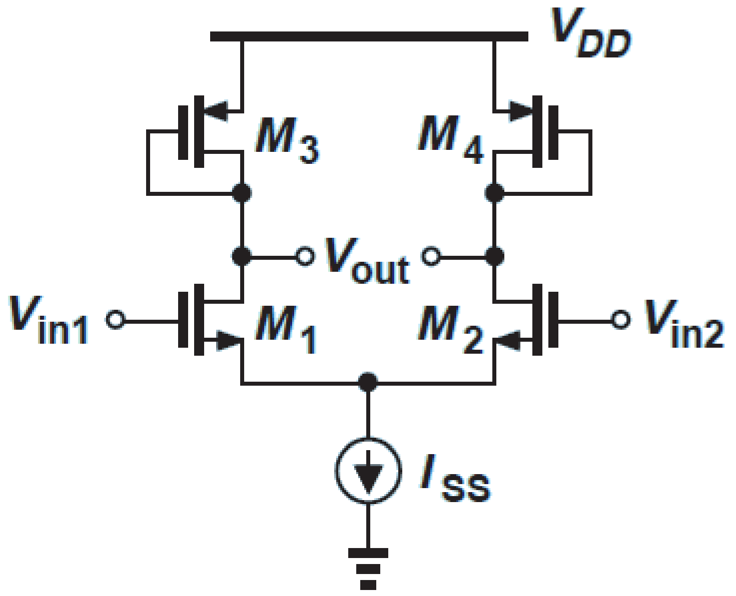



# Recapping Small Signal Analysis

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

# Quiz

- Assume symmetry and $g_m r_o \gg 1$. Calculate $A_{vd}$.

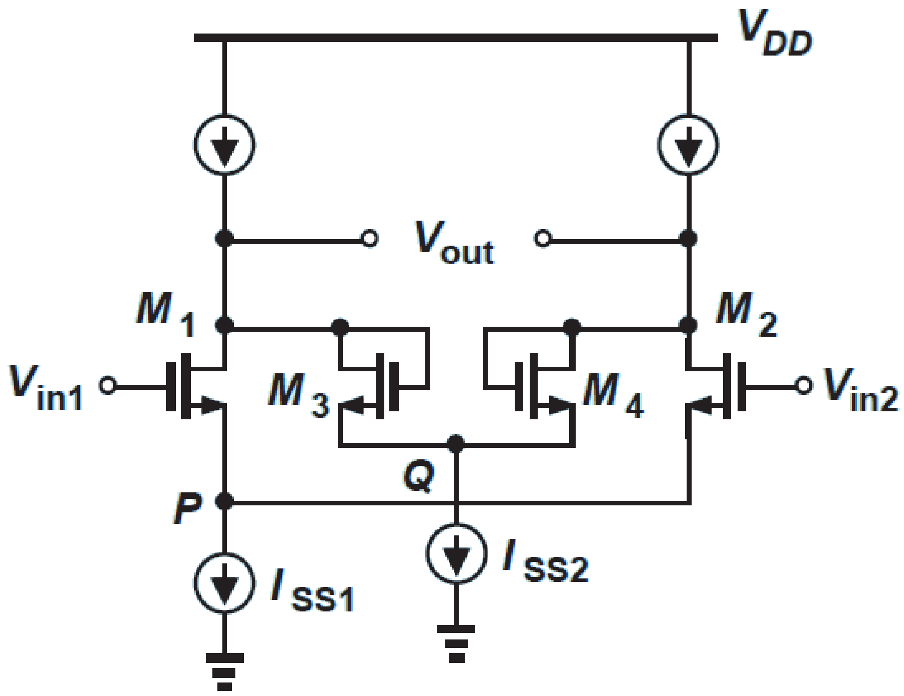





[Razavi, 2014]

# Quiz

- Assume symmetry and $g_m r_o \gg 1$. Calculate $A_{vd}$.

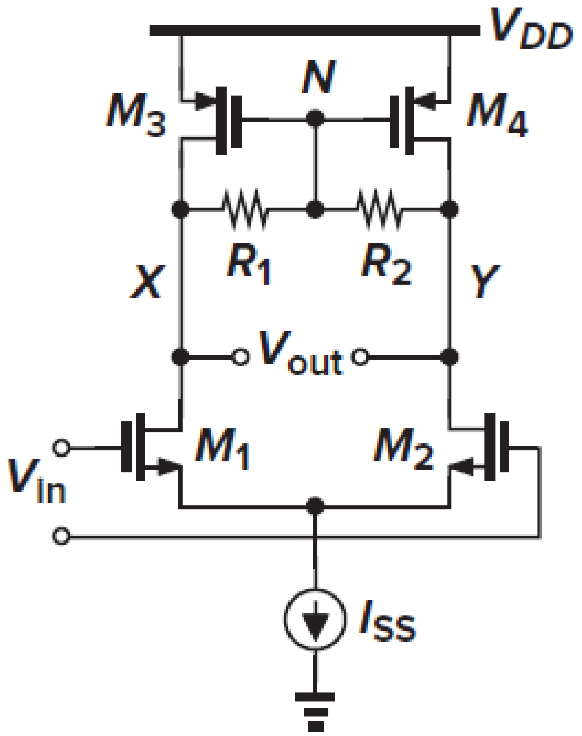





[Razavi, 2014]

# Quiz

- Assume symmetry and neglect channel length modulation (CLM). Calculate $A_{vd}$.

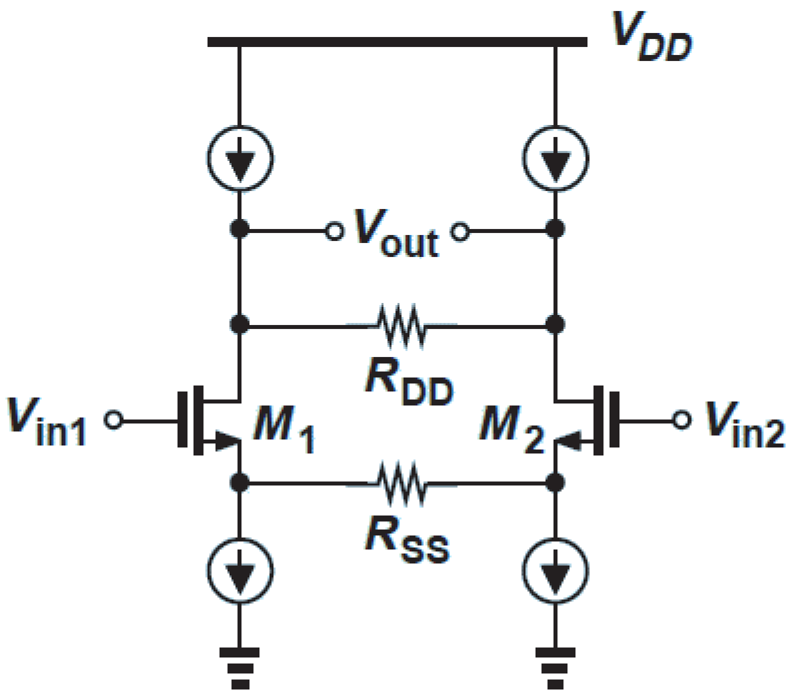





[Razavi, 2017]

# Quiz

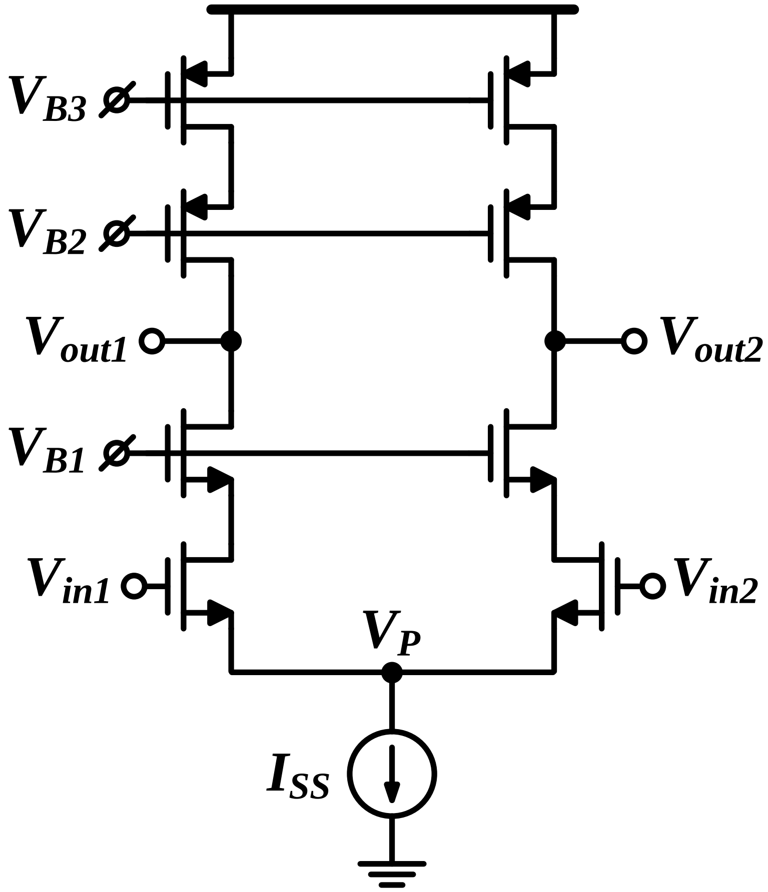
- Assume symmetry and assume $g_{m1}R_{SS} \gg 1$. Neglect CLM and body effect. Calculate $A_{vd}$.




[Razavi, 2014]

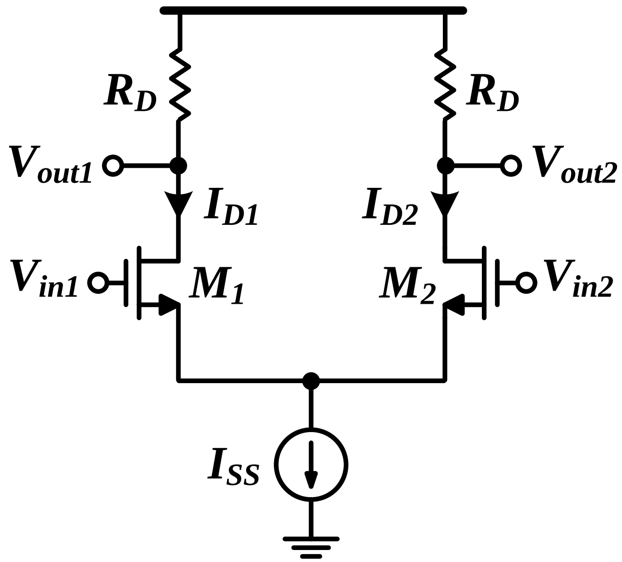
# Quiz

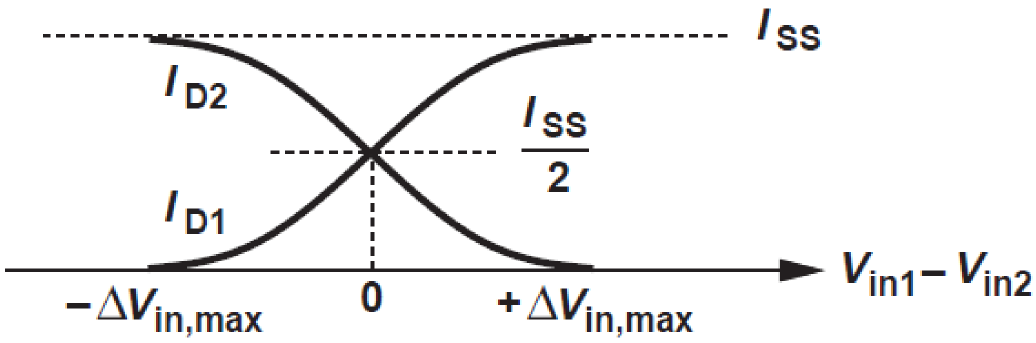
- Assume symmetry, neglect body effect, and assume all transistors have the same $g_m$ and $r_o$. Calculate $A_{vd}$.



# B1. Diff Large Signal Analysis

- The large signal differential input voltage steers the tail current from one side to another
  - Current-steering
- Current fully steered at $V_{id} \approx \Delta V_{in,max} \approx \sqrt{2} V_{ov,eq}$ (why?)
- The current has compressive characteristics (compare to pseudo diff amplifier)
- The slope at $V_{id} = 0$ is equal to …?



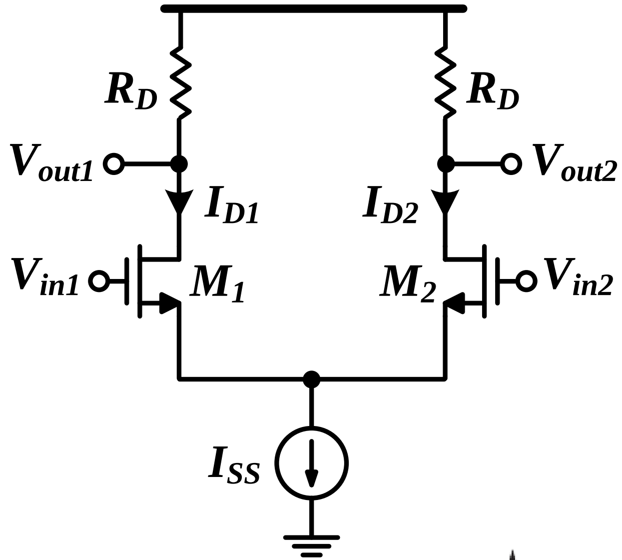



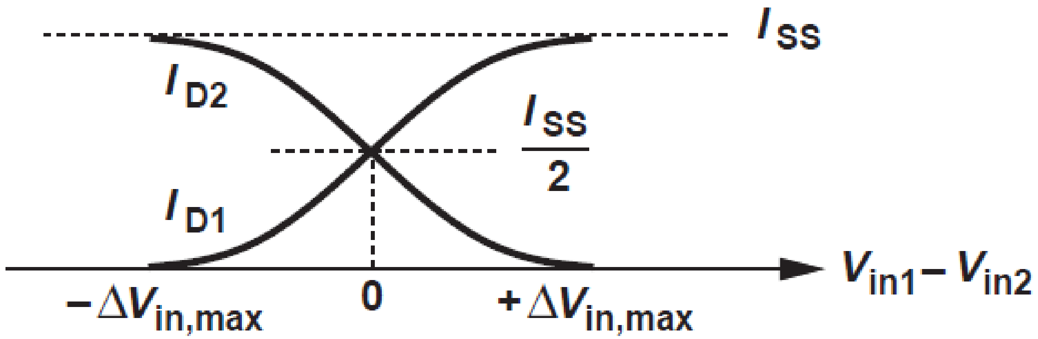


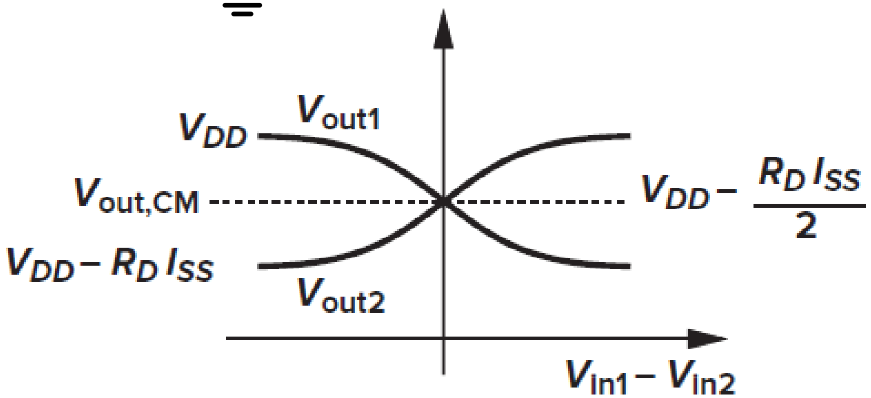
[Razavi, 2014]

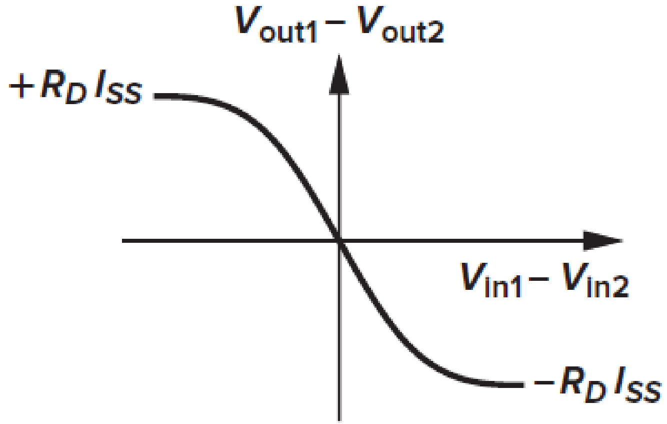
# B1. Diff Large Signal Analysis

- Maximum differential peak-to-peak output $= 2I_{SS}R_D$
- The slope at $V_{id} = 0$ is equal to …?



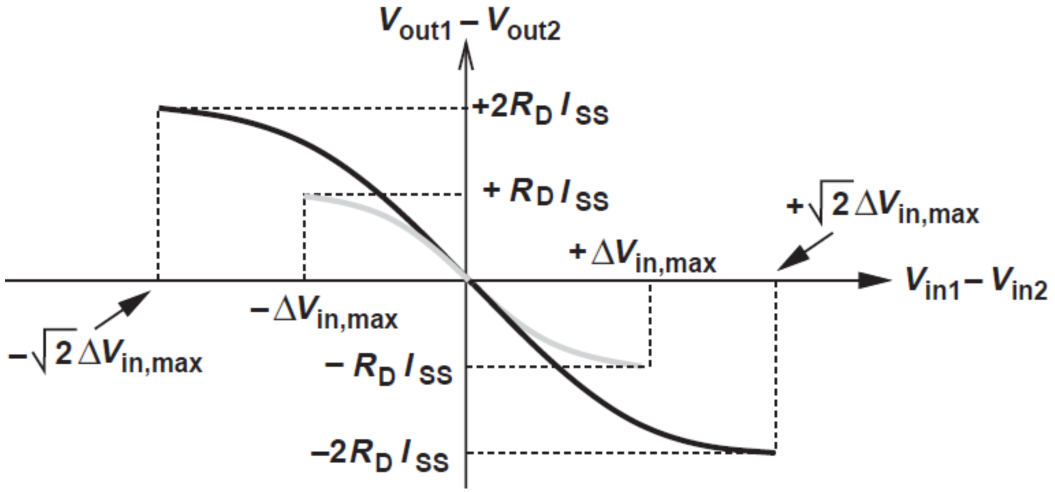



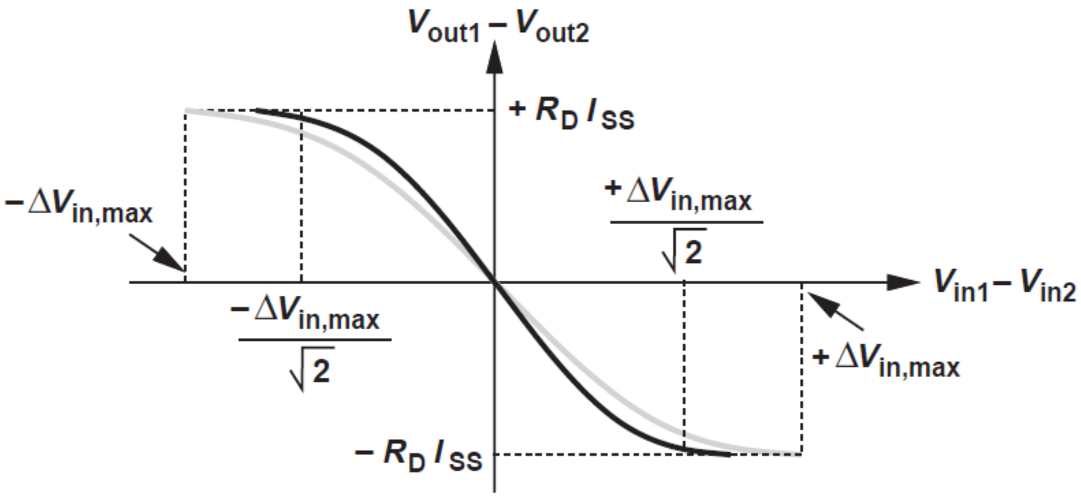

[Razavi, 2014]

# B1. Diff Large Signal Analysis

- If tail current is doubled




- If aspect ratio is doubled





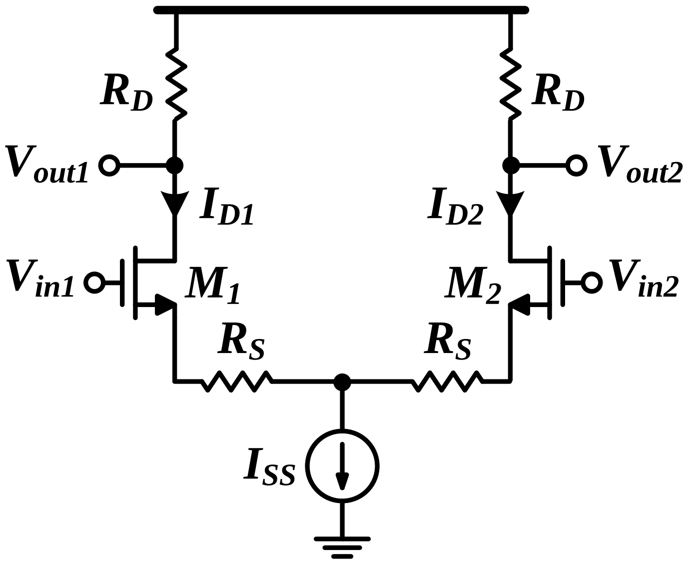

[Razavi, 2014]

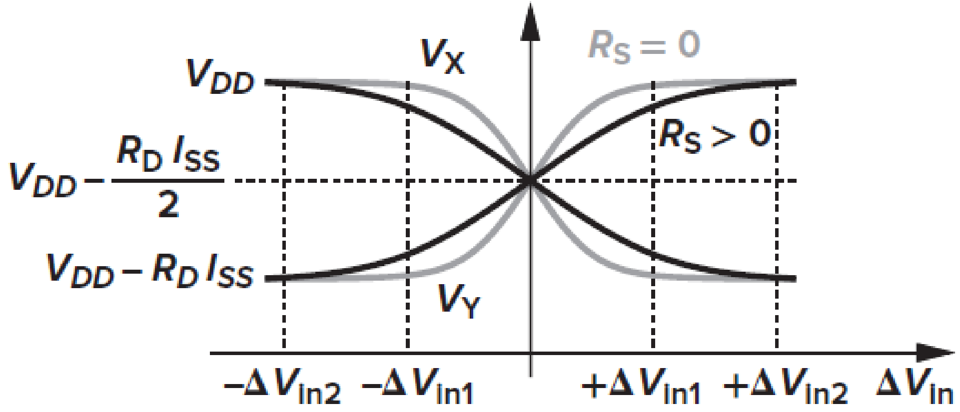
# B1. Diff Large Signal Analysis

- The linear range can be increased by
  - Increasing $V_{ov,eq}$ (decreasing $W$)
  - Degeneration

$$\Delta V_{in2} = \Delta V_{in1} + I_{SS} R_S$$

- Linearity improved, but gain and headroom reduced




[Razavi, 2017]

# B1. Diff Large Signal Analysis

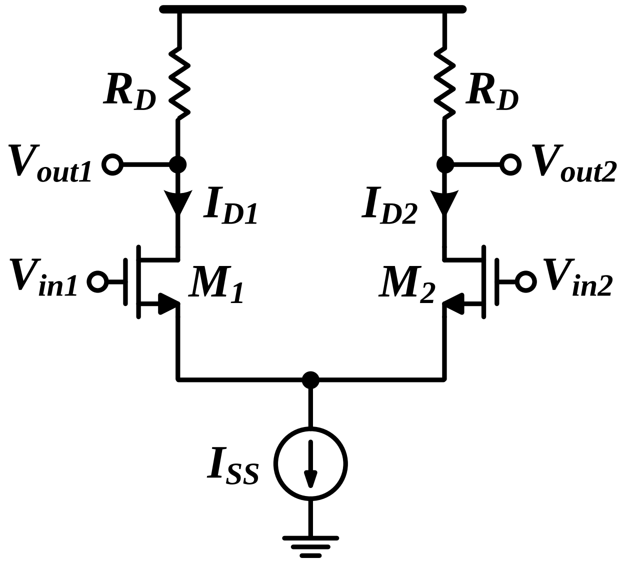
- Analytical large signal solution for $I_{D1,2}$ can be derived by solving two equations:

$$V_{in1} - V_{in2} = V_{GS1} - V_{GS2}$$
$$I_{D1} + I_{D2} = I_{SS}$$

- Substituting with square law and solving (see [Sedra, 2015]):

$$I_{D1} = \frac{I_{SS}}{2} + \frac{I_{SS}}{V_{ov,eq}} \frac{V_{id}}{2} \sqrt{1 - \left(\frac{V_{id}/2}{V_{ov,eq}}\right)^2}$$

$$I_{D2} = \frac{I_{SS}}{2} - \frac{I_{SS}}{V_{ov,eq}} \frac{V_{id}}{2} \sqrt{1 - \left(\frac{V_{id}/2}{V_{ov,eq}}\right)^2}$$



# B2. CM Large Signal Analysis

- The CM input ($V_{iCM} = V_{in1} = V_{in2}$) does not affect the bias point of M1,2 ($I_{D1,2}$) and the CM output level
  - Bias point is defined by the tail current source
  - No need for coupling capacitors between diff stages!
  - Compare to pseudo diff amplifier

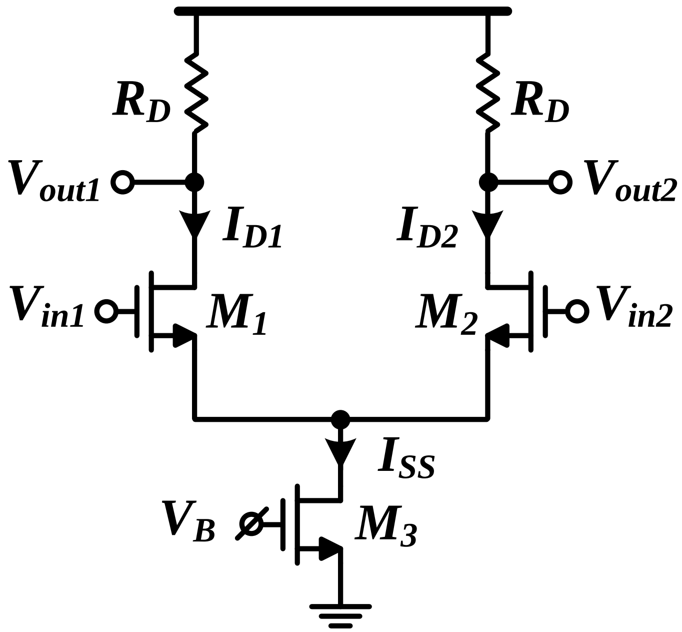
- But all transistors must be in saturation

- M3 in sat:

$$V_{iCM} \geq V_{TH1} + V_{ov1} + V_{ov3}$$

- M1,2 in sat:

$$V_{iCM} \leq V_{DD} - \frac{I_{SS}}{2} R_D + V_{TH1}$$



# Max Allowable Signal Swing

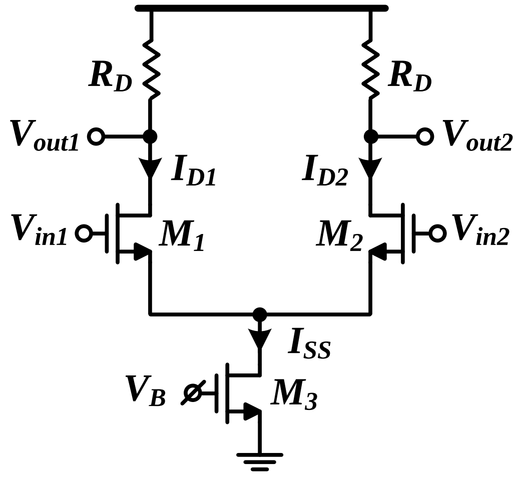
- Max output is $V_{DD}$: $V_{out,max} = V_{DD}$
- Min output is set by keeping M1,2 in sat: $V_{out,min} = V_{iCM} - V_{TH1}$
- Max peak-to-peak differential output swing

$$= 2 \times \left(V_{out,max} - V_{out,min}\right) = 2 \times \left(V_{DD} - (V_{iCM} - V_{TH1})\right)$$

- If $V_{iCM}$ is set to its min value: $V_{iCM} = V_{TH1} + V_{ov1} + V_{ov3}$

$$= 2 \times (V_{DD} - V_{ov1} - V_{ov3})$$

- Deduced intuitively noting that M1 and M3 are vertically stacked
- For SE amp: Max peak-to-peak output swing $= (V_{DD} - V_{ov1})$



# Outline

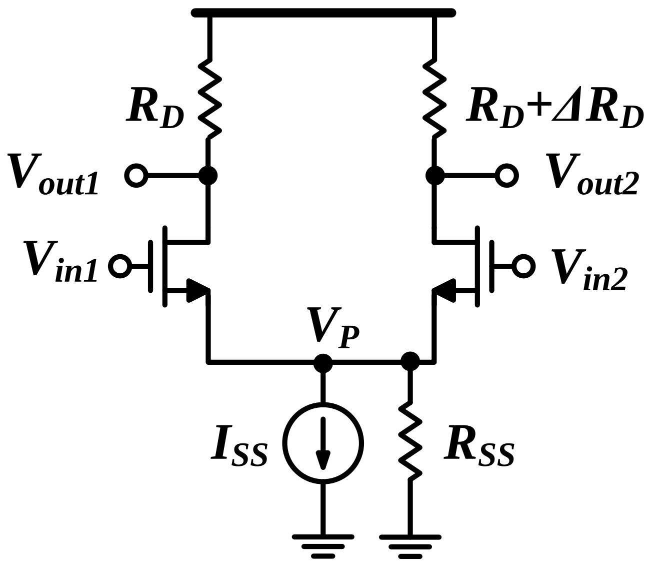
- ❑ Recapping previous key results
- ❑ Single-ended (SE) vs differential operation
- ❑ Pseudo differential amplifier
  - Common-mode (CM) and differential analysis
- ❑ Differential amplifier (differential pair)
  - Common-mode (CM) and differential analysis
- ❑ Effect of mismatch in load and input pair
  - Common-mode rejection ratio (CMRR)
- ❑ Frequency response of differential amplifier
  - Common-mode (CM) and differential analysis

# Effect of Mismatch (in Load)

- Most dangerous effect: CM to diff conversion
- Example #1: Mismatch in load resistance
  - If $\Delta R_D/r_o \ll 1$ then we can apply half-circuit principle at $V_P$

$$A_{vCM2d} = \frac{v_{od}}{v_{iCM}} = \frac{v_{out1} - v_{out2}}{v_{iCM}} = -\left(\frac{g_m R_D}{1 + 2g_m R_{SS}} - \frac{g_m(R_D + \Delta R_D)}{1 + 2g_m R_{SS}}\right)$$

$$= \frac{g_m \Delta R_D}{1 + 2g_m R_{SS}} \approx \frac{\Delta R_D}{2R_{SS}}$$



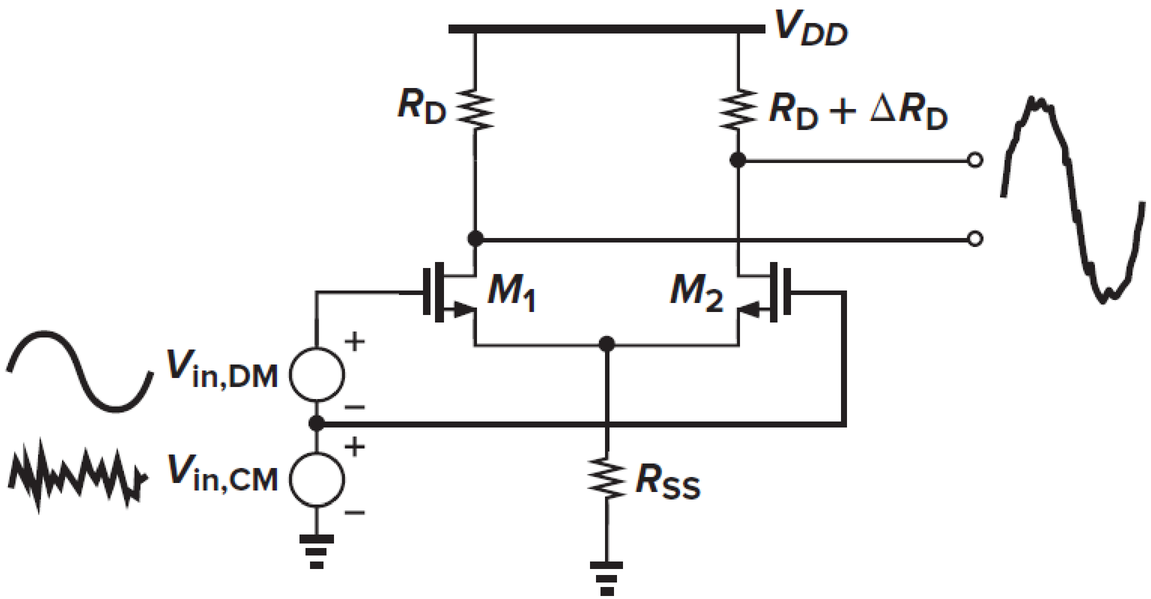
# Effect of Mismatch (in Load)

- Most dangerous effect: CM to diff conversion

$$A_{vCM2d} \approx \frac{\Delta R_D}{2R_{SS}}$$

- Common-mode rejection ratio (CMRR) (@low frequency!)

$$CMRR = \frac{A_{vd}}{A_{vCM2d}} \approx 2g_m R_{SS} \frac{R_D}{\Delta R_D}$$



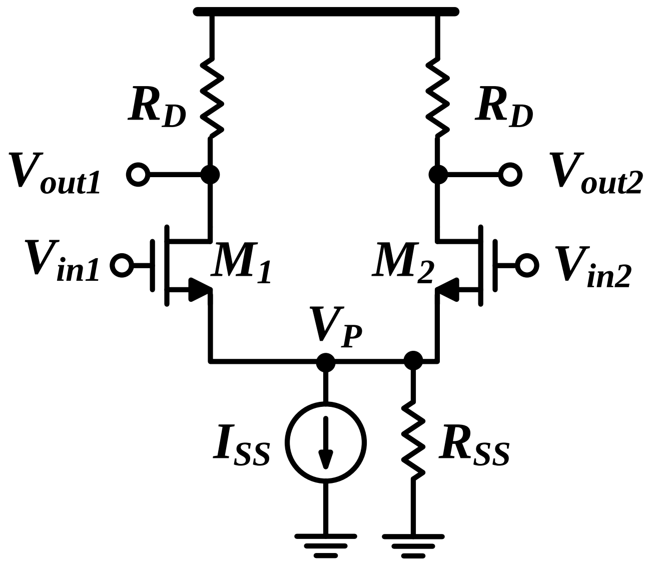

[Razavi, 2017]

# Effect of Mismatch (in Input Pair)

- Most dangerous effect: CM to diff conversion
- Example #2: Mismatch in input pair: $g_{m2} = g_{m1} + \Delta g_m$
  - Half-circuit cannot be used → use superposition

$$A_{vCM2d} = \frac{v_{od}}{v_{iCM}} = \frac{v_{out1} - v_{out2}}{v_{iCM}} = -\frac{g_{m1}R_D}{1 + g_{m1}\left(\frac{1}{g_{m2}}||R_{SS}\right)} + \frac{g_{m2}R_D}{1 + g_{m2}\left(\frac{1}{g_{m1}}||R_{SS}\right)}$$

$$= \frac{\Delta g_m R_D}{1 + (g_{m1} + g_{m2})R_{SS}} \approx \frac{\Delta g_m R_D}{2g_{m1,2}R_{SS}}$$



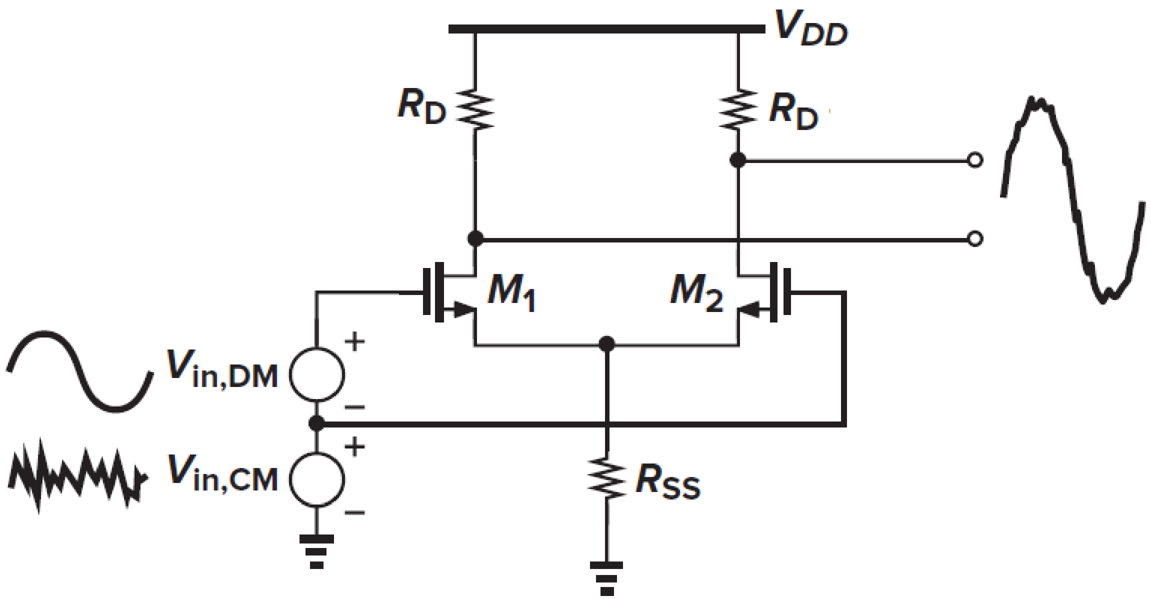
# Effect of Mismatch (in Input Pair)

- Most dangerous effect: CM to diff conversion

$$A_{vCM2d} \approx \frac{\Delta g_m R_D}{1 + 2g_{m1,2}R_{SS}} \approx \frac{\Delta g_m R_D}{2g_{m1,2}R_{SS}}$$

- Common-mode rejection ratio (CMRR) (@low frequency!)

$$CMRR = \frac{A_{vd}}{A_{vCM2d}} \approx \left(1 + 2g_{m1,2}R_{SS}\right)\frac{g_{m1,2}}{\Delta g_m} \approx 2g_{m1,2}R_{SS}\frac{g_{m1,2}}{\Delta g_m}$$




[Razavi, 2017]

# Outline

- Recapping previous key results
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- Differential amplifier (differential pair)
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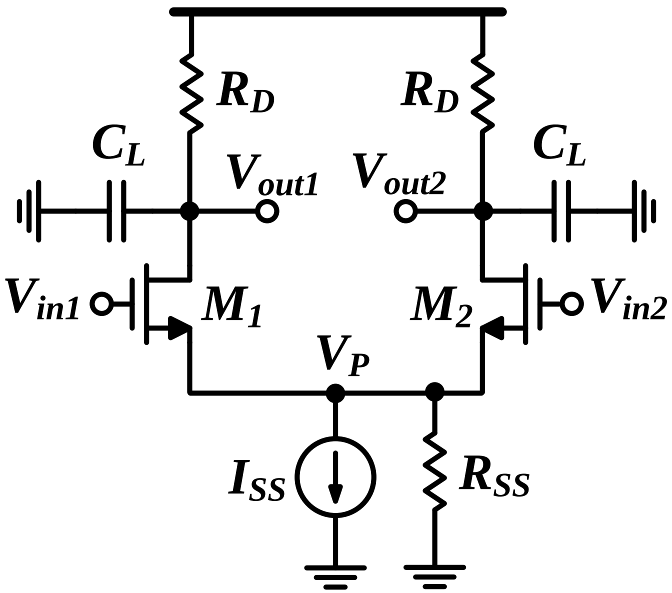
- Effect of mismatch in load and input pair
  - Common-mode rejection ratio (CMRR)
- Frequency response of differential amplifier
  - Common-mode (CM) and differential analysis

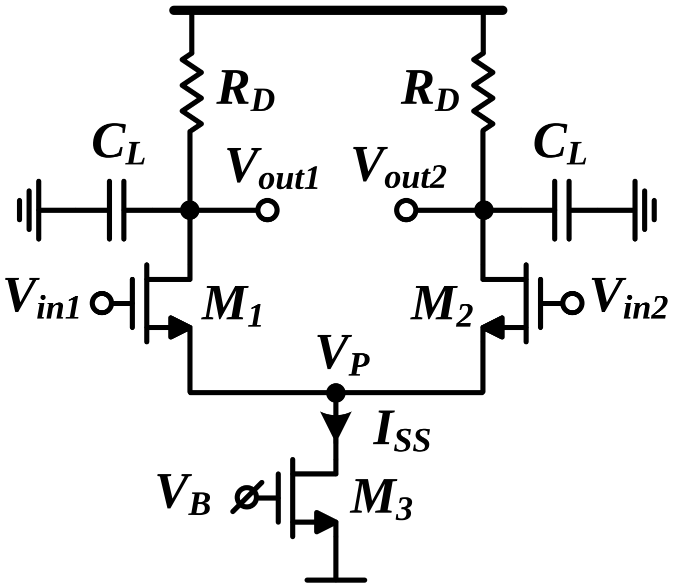
# Diff Frequency Response

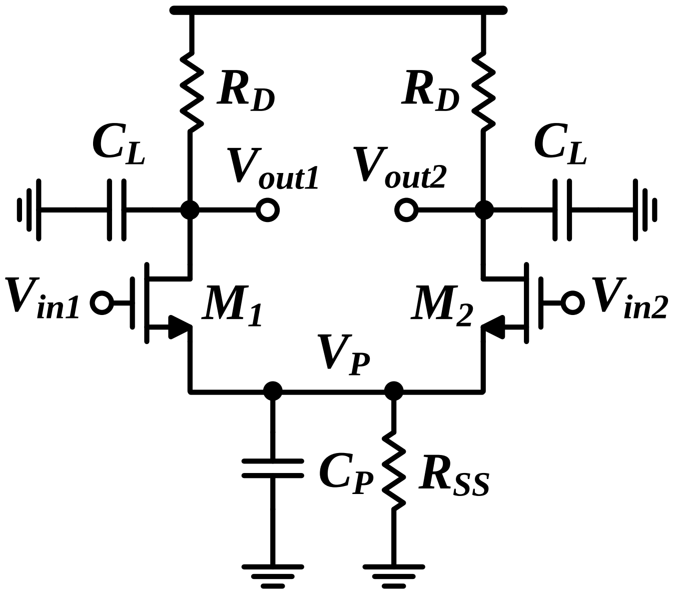
- The frequency response of the diff amp is itself the frequency response of the half-circuit
  - $V_P$ is virtual ground
- Note that the number of poles/zeros in the diff amp is the same as the number of poles/zeros in the half-circuit
  - The two halves are added, not multiplied
  - Ex: $A(s) = \frac{A_O/2}{1+\frac{s}{\omega_p}} + \frac{A_O/2}{1+\frac{s}{\omega_p}} = \frac{A_O}{1+\frac{s}{\omega_p}}$ (what if there is mismatch?)



# CM Frequency Response

- $C_P$ degrades tail current source impedance at high frequency
- $C_P \approx C_{db3} + C_{gd3} + C_{sb1} + C_{sb2}$
- Trade-off between headroom and CMRR
  - M1-M3 are made wide to decrease $V_{ov}$ → More $g_m$ and more headroom
  - But $C_P$ increases, and degrades CMRR
  - $C_P$ resembles the bypass capacitor used in discrete CS amplifier



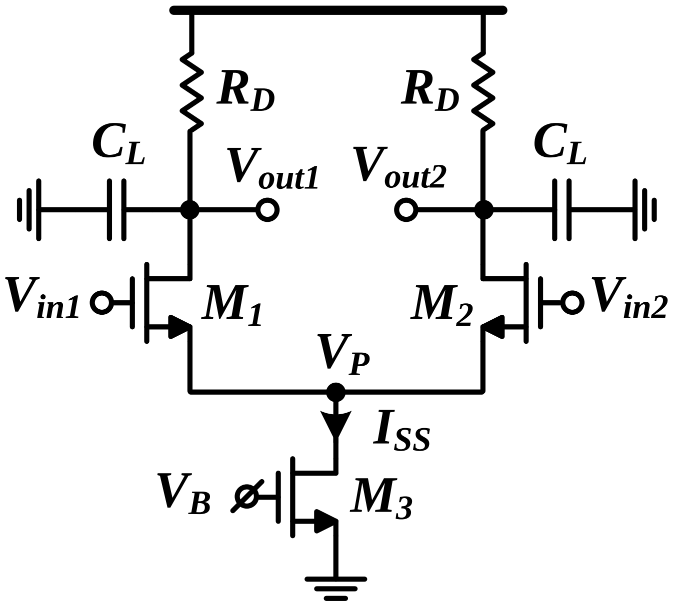



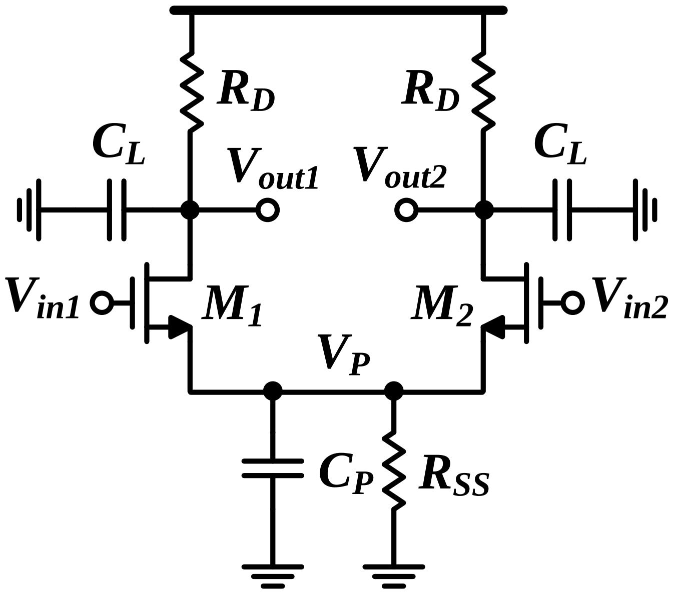
# CM Frequency Response

- Mismatch in input pair (M1 and M2)

  @Low frequency: $A_{vCM2d} \approx \frac{\Delta g_m R_D}{1+(g_{m1}+g_{m2})R_{SS}}$

  @High frequency: $A_{vCM2d} \approx \frac{\Delta g_m \left(R_D || \frac{1}{sC_L}\right)}{1+(g_{m1}+g_{m2})\left(R_{SS} || \frac{1}{sC_P}\right)}$



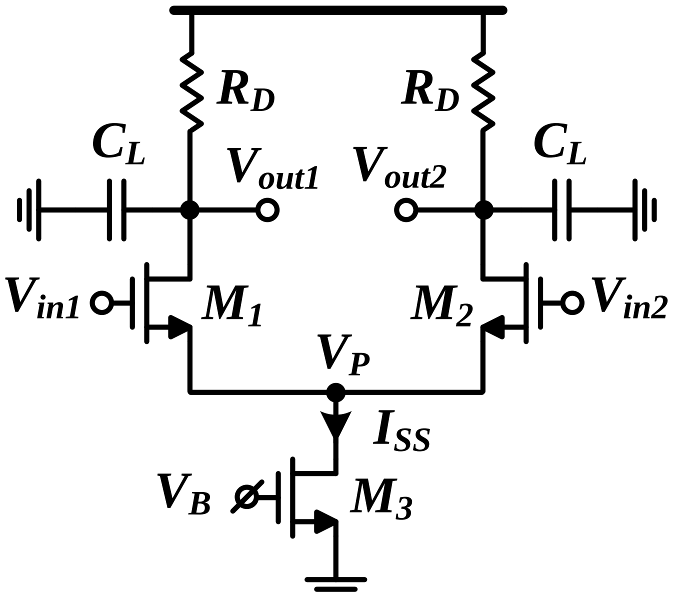



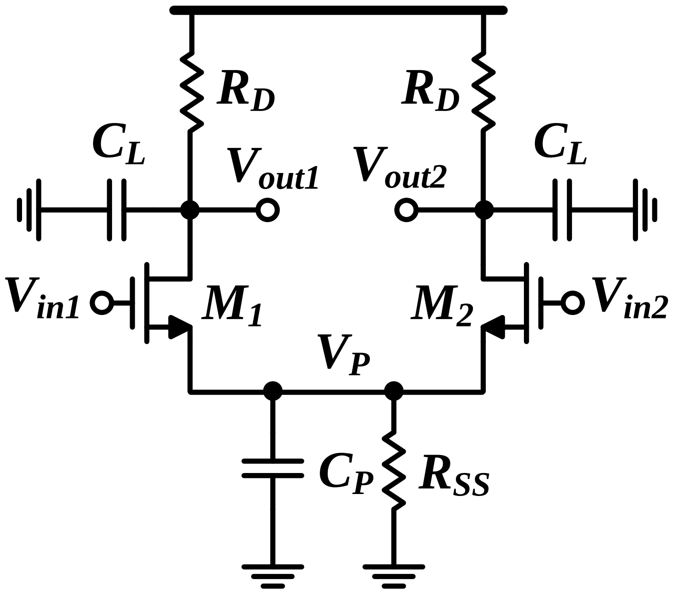
# CM Frequency Response

- Mismatch in input pair (M1 and M2)

@Low frequency: $CMRR = \frac{A_{vd}}{A_{vCM2d}} \approx (1 + 2g_{m1,2}R_{SS})\frac{g_{m1,2}}{\Delta g_m}$

@High frequency: $CMRR = \frac{A_{vd}(s)}{A_{vCM2d}(s)} \approx \left[1 + 2g_{m1,2}\left(R_{SS}||\frac{1}{sC_P}\right)\right]\frac{g_{m1,2}}{\Delta g_m}$



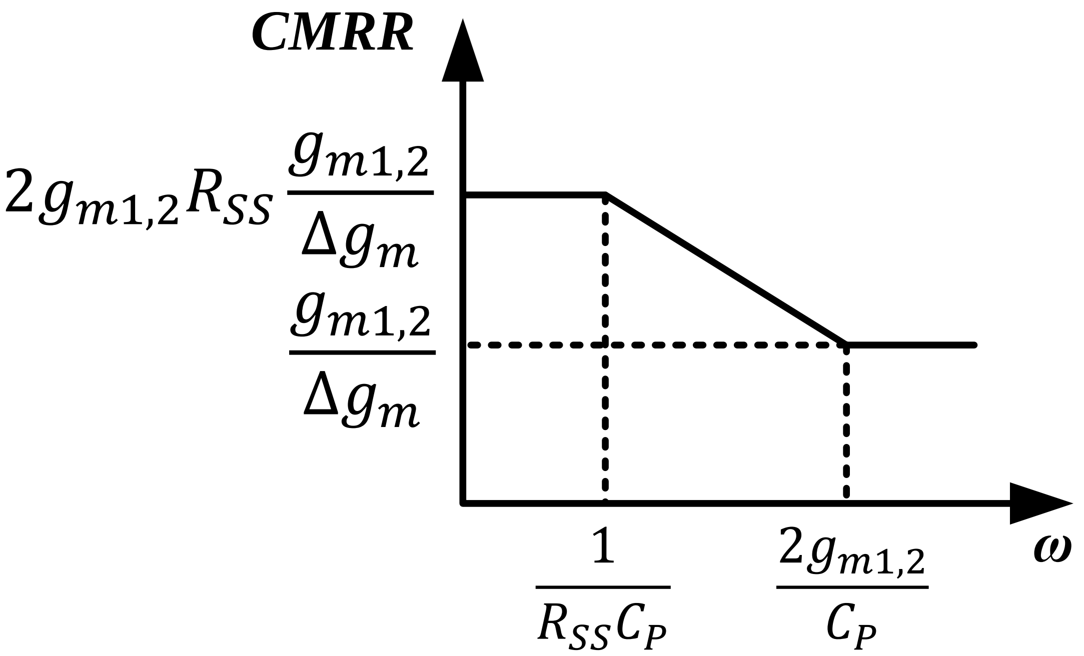



# CM Frequency Response

- Mismatch in input pair (M1 and M2)

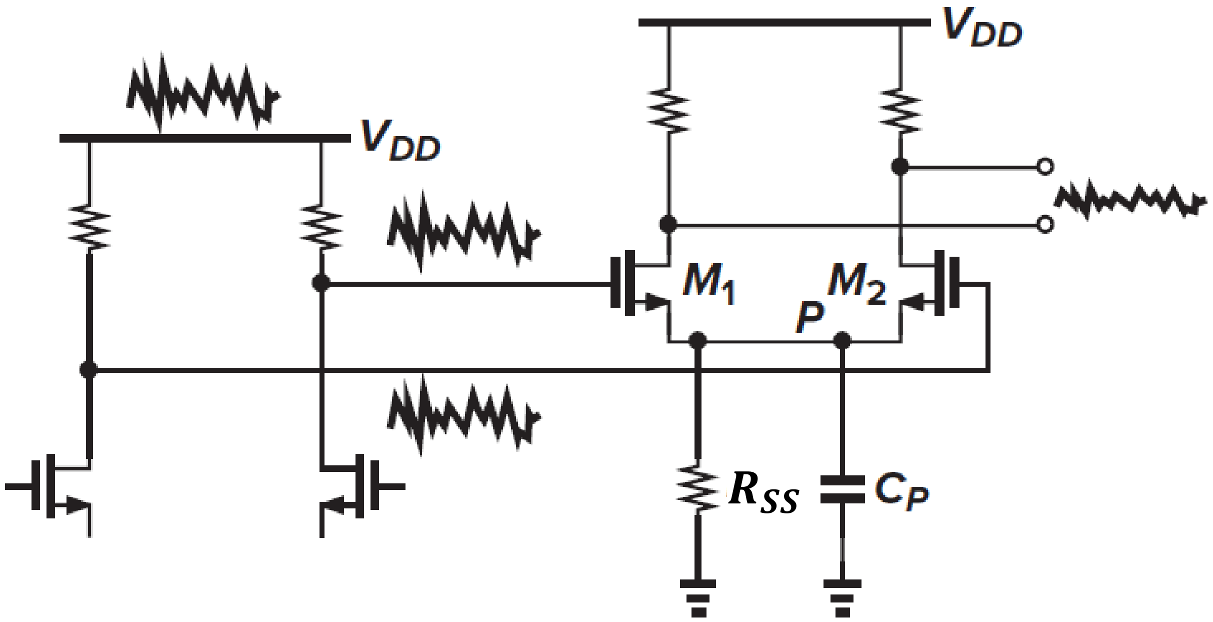
$$CMRR = \frac{A_{vd}(s)}{A_{vCM2d}(s)} \approx \left[1 + 2g_{m1,2}\left(R_{SS}||\frac{1}{sC_P}\right)\right]\frac{g_{m1,2}}{\Delta g_m}$$

$$\approx \frac{1 + s\frac{C_P}{2g_{m1,2}}}{1 + sR_{SS}C_P} \cdot 2g_{m1,2}R_{SS}\frac{g_{m1,2}}{\Delta g_m}$$



# CM Frequency Response

- High frequency supply noise is a very serious issue
- Again: There is a trade-off between headroom (and $g_m$) and CMRR
  - More serious for low supply voltage




[Razavi, 2017]

# Thank you!

# References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- B. Razavi, “Design of Analog CMOS Integrated Circuits,” McGraw-Hill, 2nd ed., 2017
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