Lecture 11: CMOS Amplifiers: The Differential Pair - First Part

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Reference: Razavi (Fundamentals) - Chapter 10

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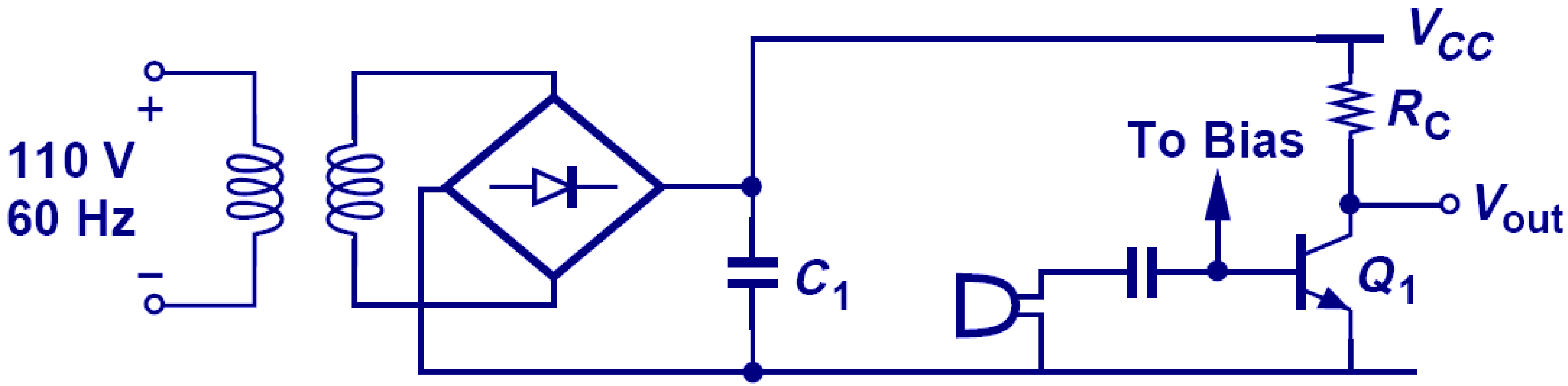
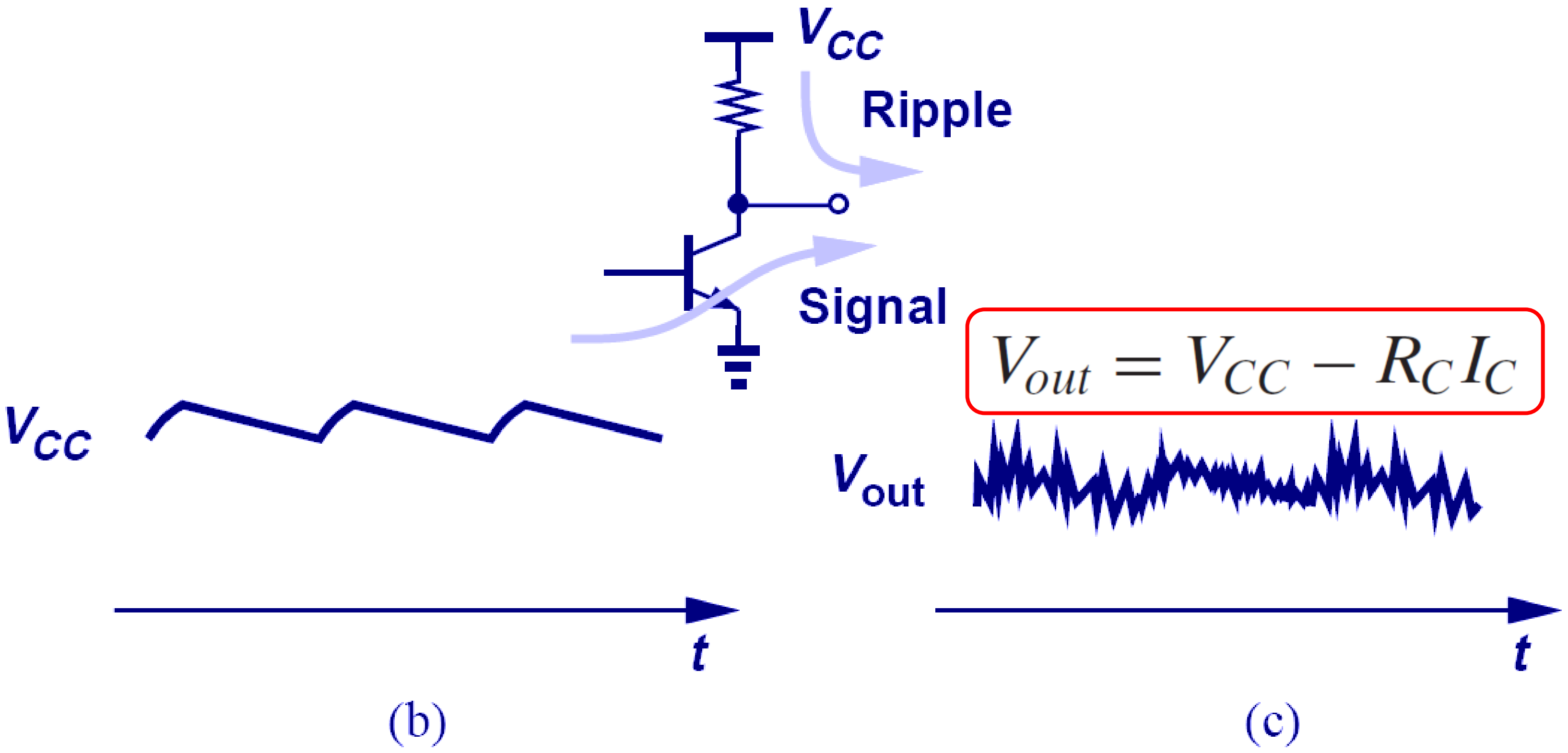
Audio Amplifier Example



- An audio amplifier takes a rectified AC voltage as its supply and amplifies an audio signal from a microphone.

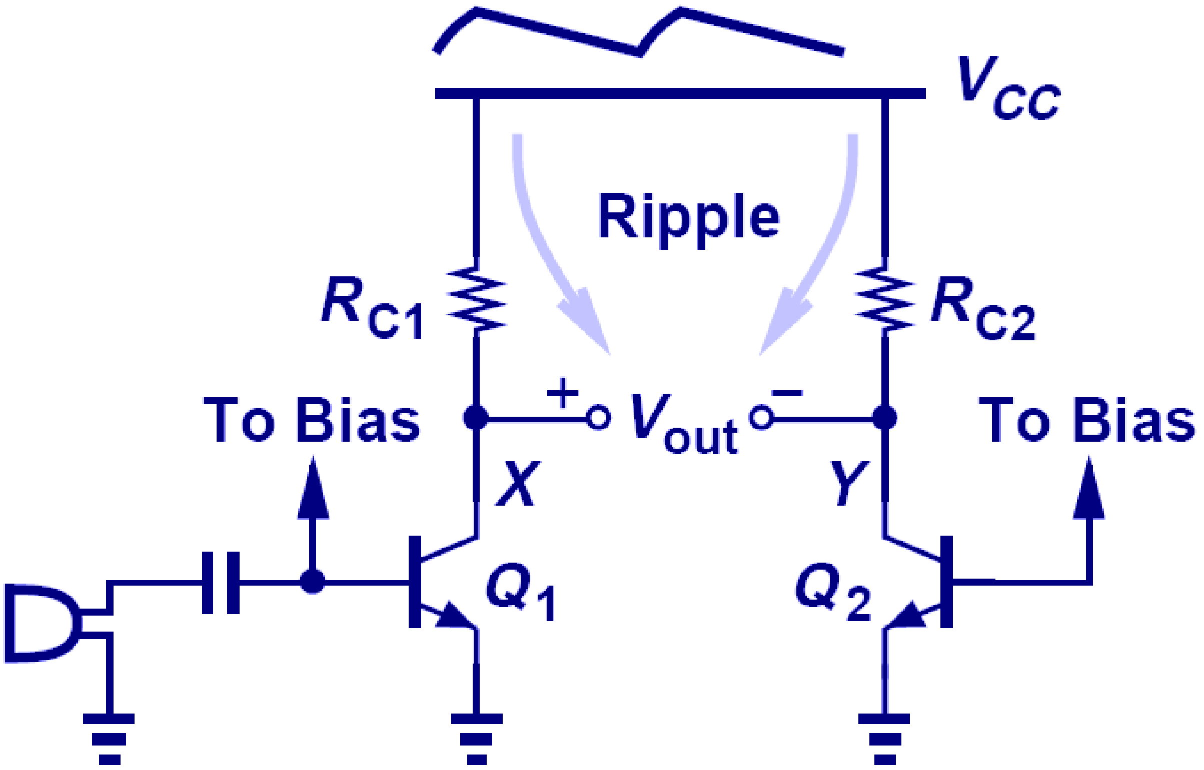
"Humming" Noise in Audio Amplifier Example



➢ **However, VCC contains a ripple from rectification that leaks to the output and is perceived as a "humming" noise by the user.**

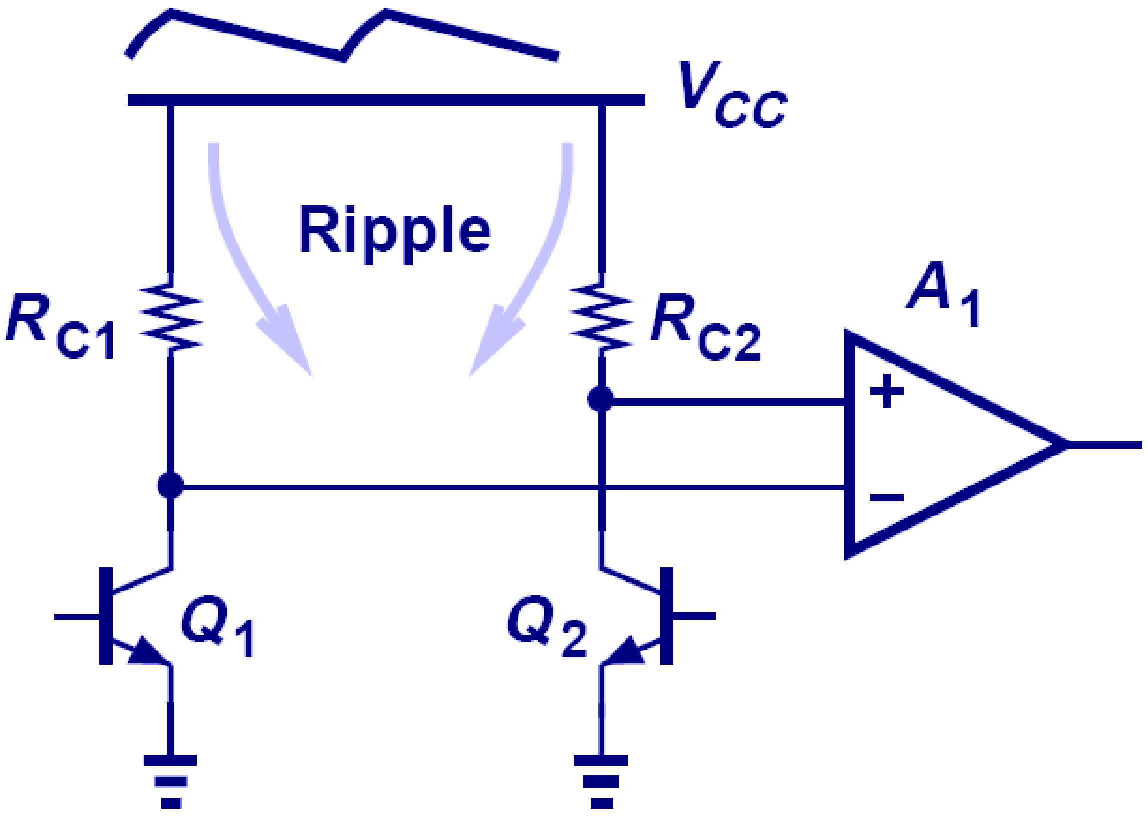
Supply Ripple Rejection

$$v_X = A_v v_{in} + v_r$$
$$v_Y = v_r$$
$$v_X - v_Y = A_v v_{in}$$



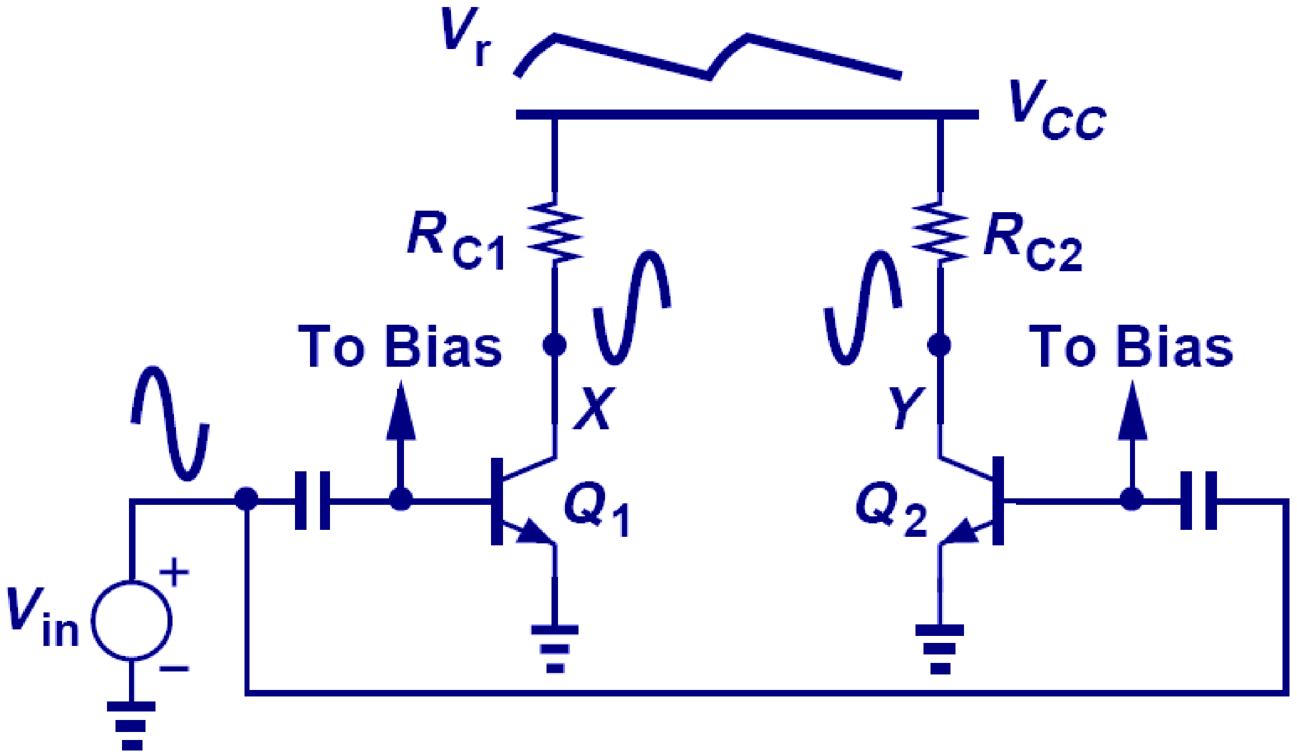
➢ **Since both node X and Y contain the ripple, their difference will be free of ripple. Note that Q_2 carries no signal, simply serving as a constant current source.**

Ripple-Free Differential Output



- Since the signal is taken as a difference between two nodes, an amplifier that senses differential signals is needed.

Common Inputs to Differential Amplifier



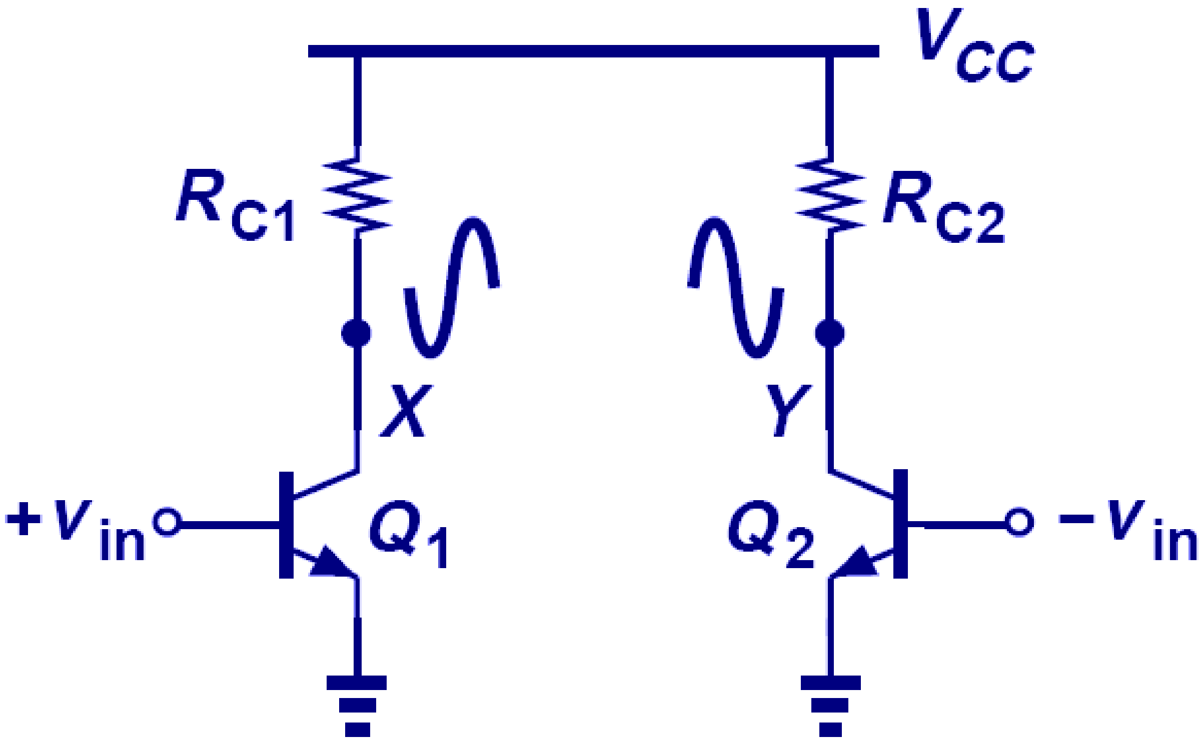
$$v_X = A_v v_{in} + v_r$$

$$v_Y = A_v v_{in} + v_r$$

$$v_X - v_Y = 0$$

- **Signals cannot be applied in phase to the inputs of a differential amplifier, since the outputs will also be in phase, producing zero differential output.**

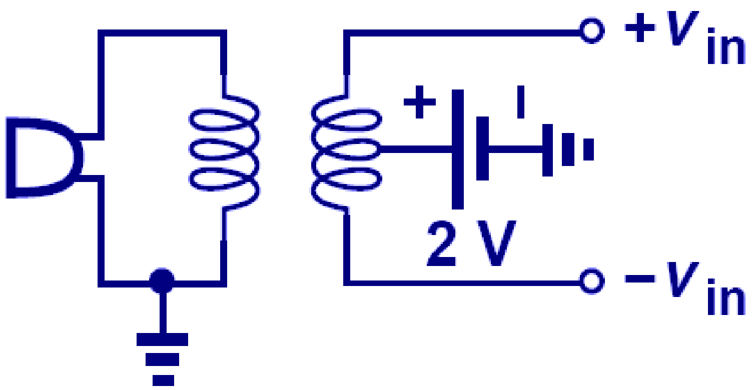
Differential Inputs to Differential Amplifier

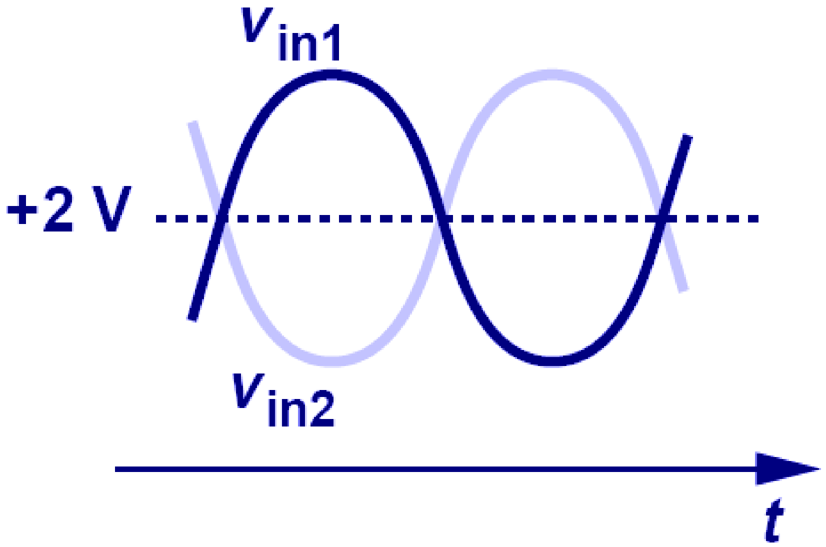


$$v_X = A_v v_{in} + v_r$$
$$v_Y = -A_v v_{in} + v_r$$
$$v_X - v_Y = 2A_v v_{in}$$

- When the inputs are applied differentially, the outputs are 180° out of phase; enhancing each other when sensed differentially.

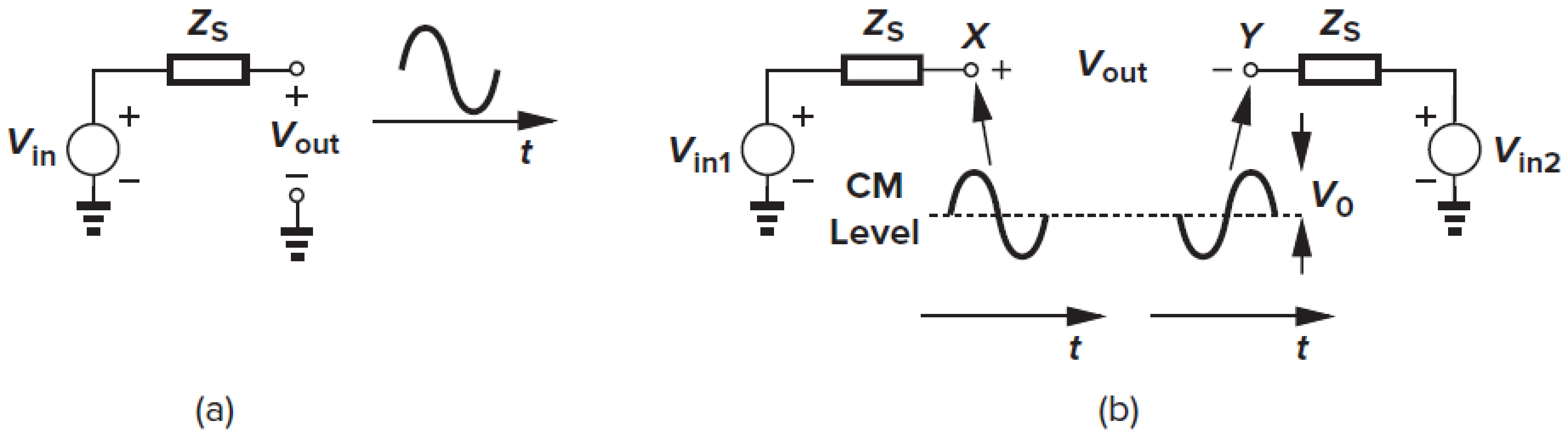
Differential Signals





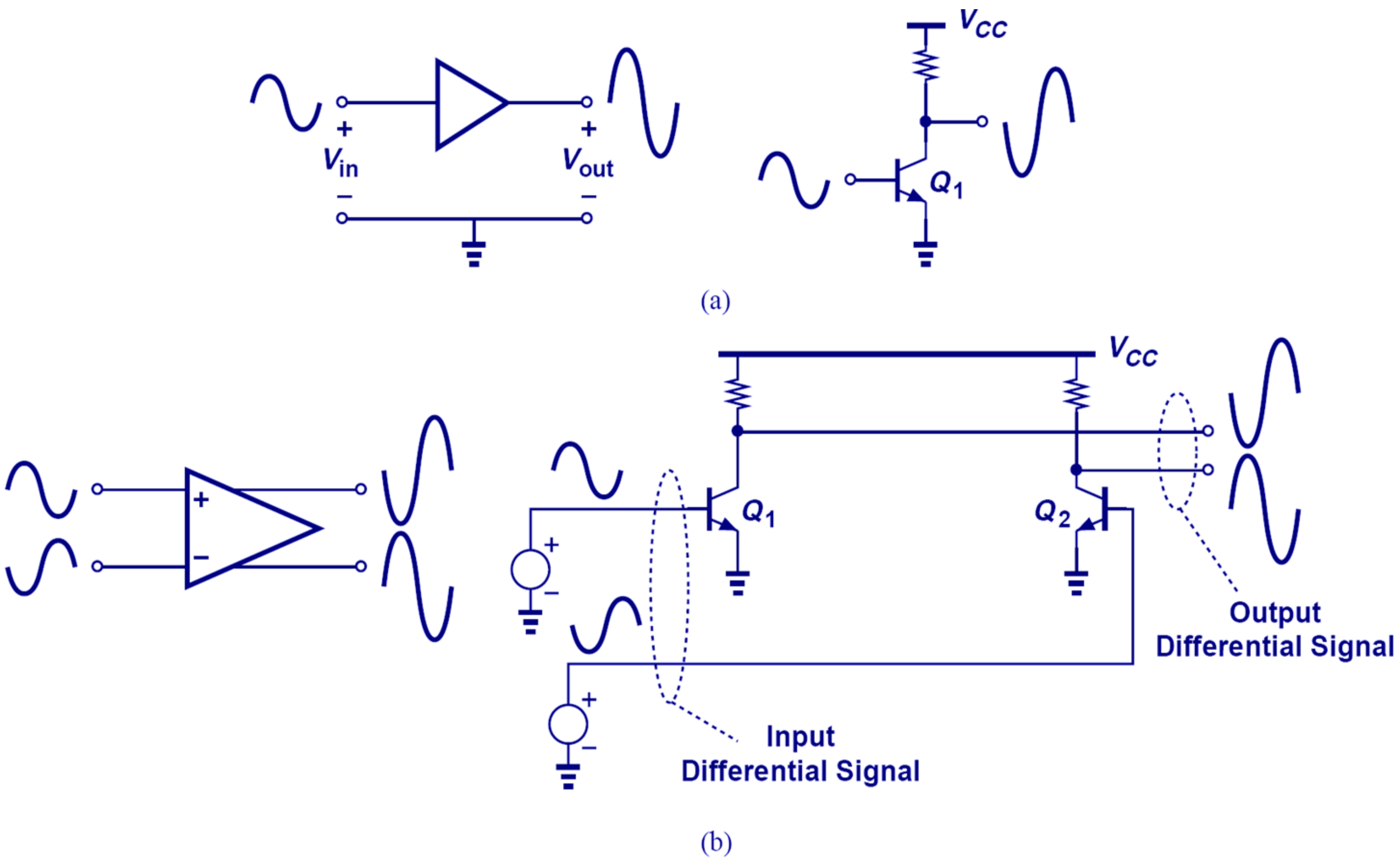
- A pair of differential signals can be generated, among other ways, by a transformer.
- Differential signals have the property that they share the same average value to ground and are equal in magnitude but opposite in phase.

Single-Ended vs Differential Operation

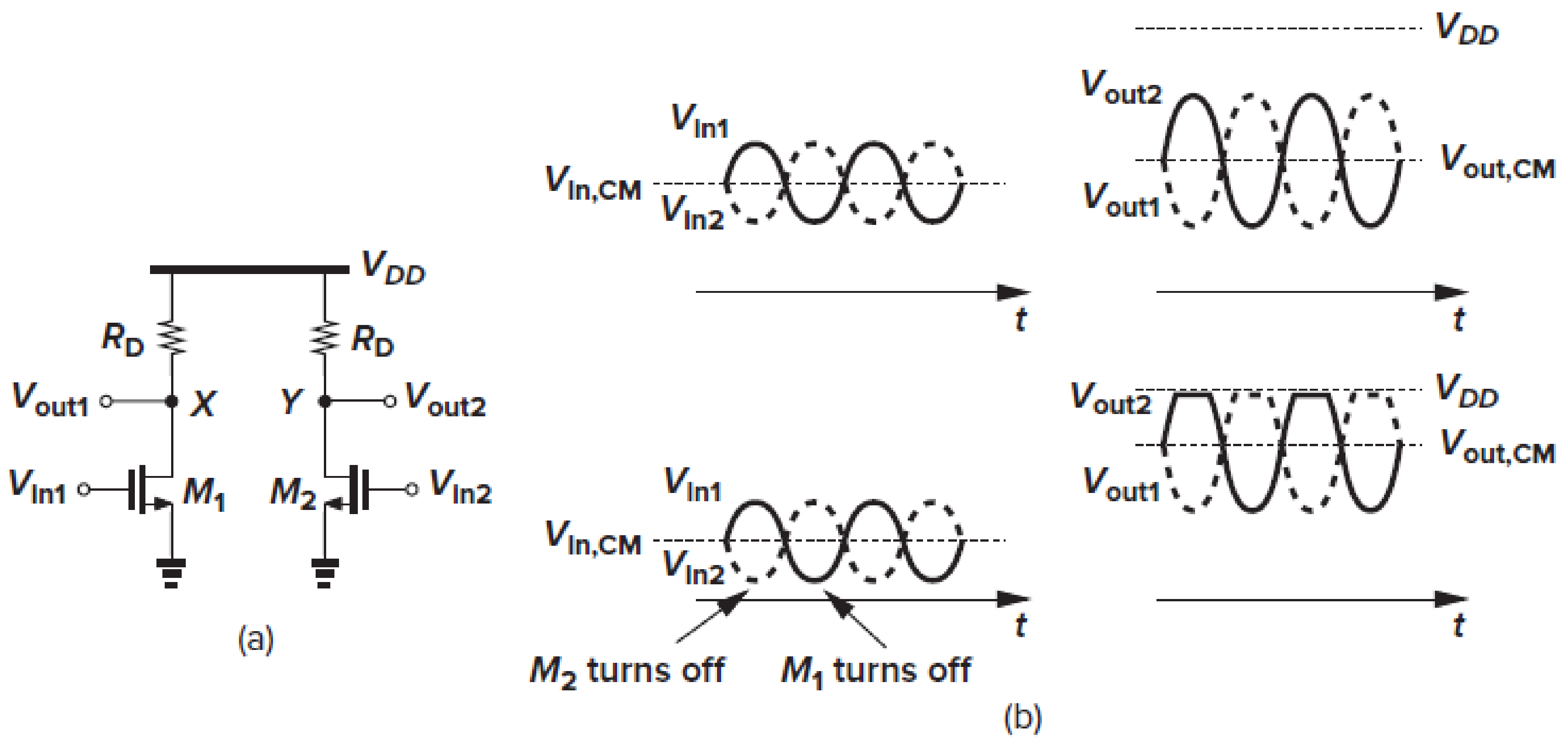


- A "single-ended" signal is defined as one that is measured with respect to a fixed potential, usually the ground.
- A "differential signal" is defined as one that is measured between two nodes that have equal and opposite signal excursions around a fixed potential.

Single-Ended vs Differential Operation

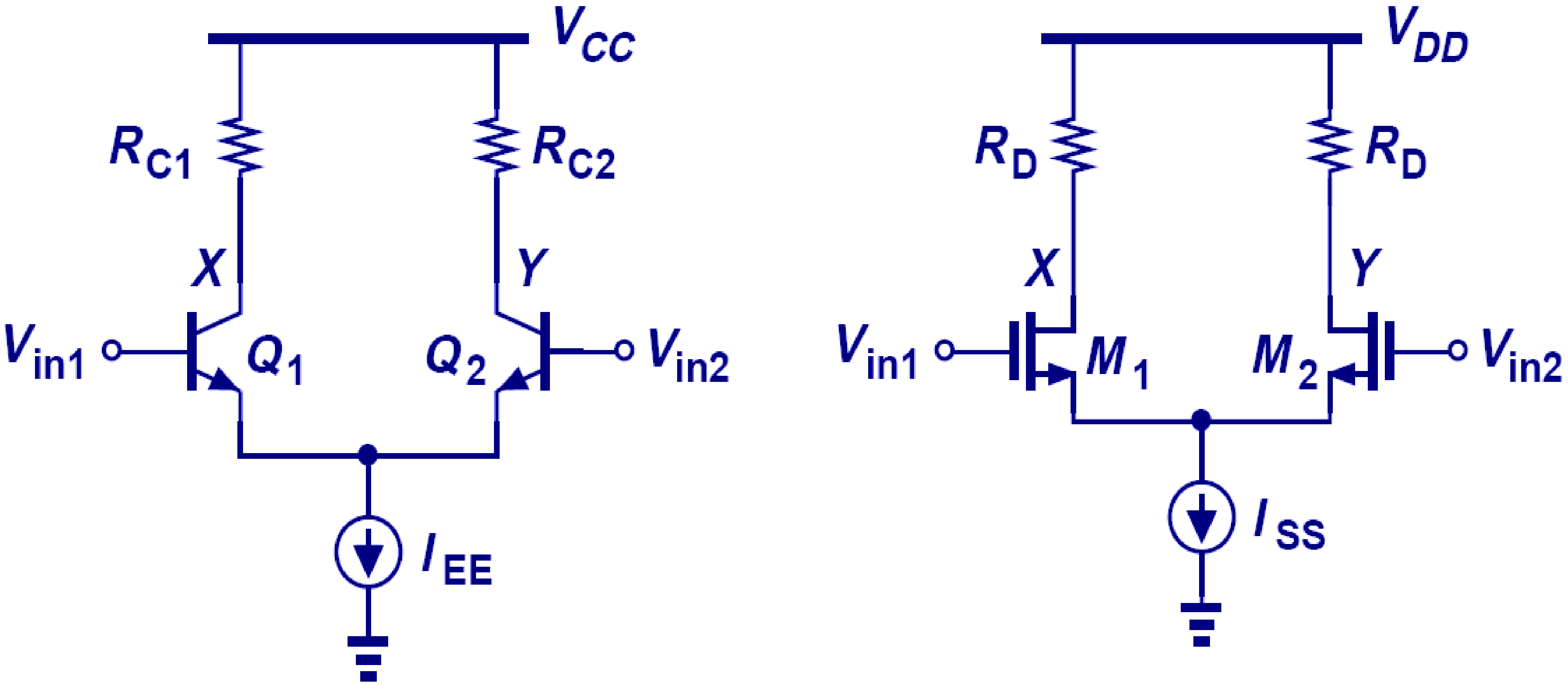


Differential Pair



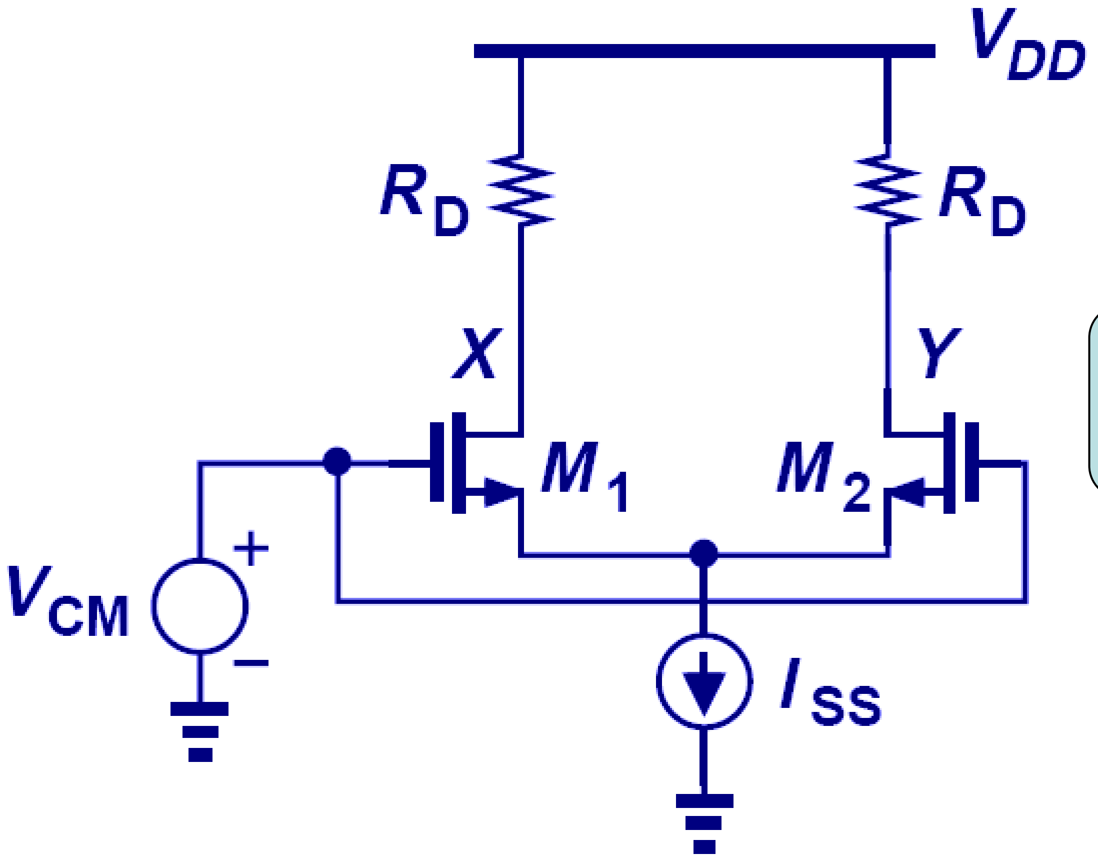
- **Drawback: If V_{in1} and V_{in2} experience a large common-mode disturbance or simply do not have a well-defined common-mode dc level, the bias currents of M_1 and M_2 change, thus varying both the transconductance of the devices and the output CM level.**

Differential Pair



- **With the addition of a tail current, the circuits above operate as an elegant, yet robust differential pair.**
- **The "differential pair" employs a current source I_{SS}/I_{EE} to make $I_{D1} + I_{D2}$ independent of $V_{in,CM}$.**

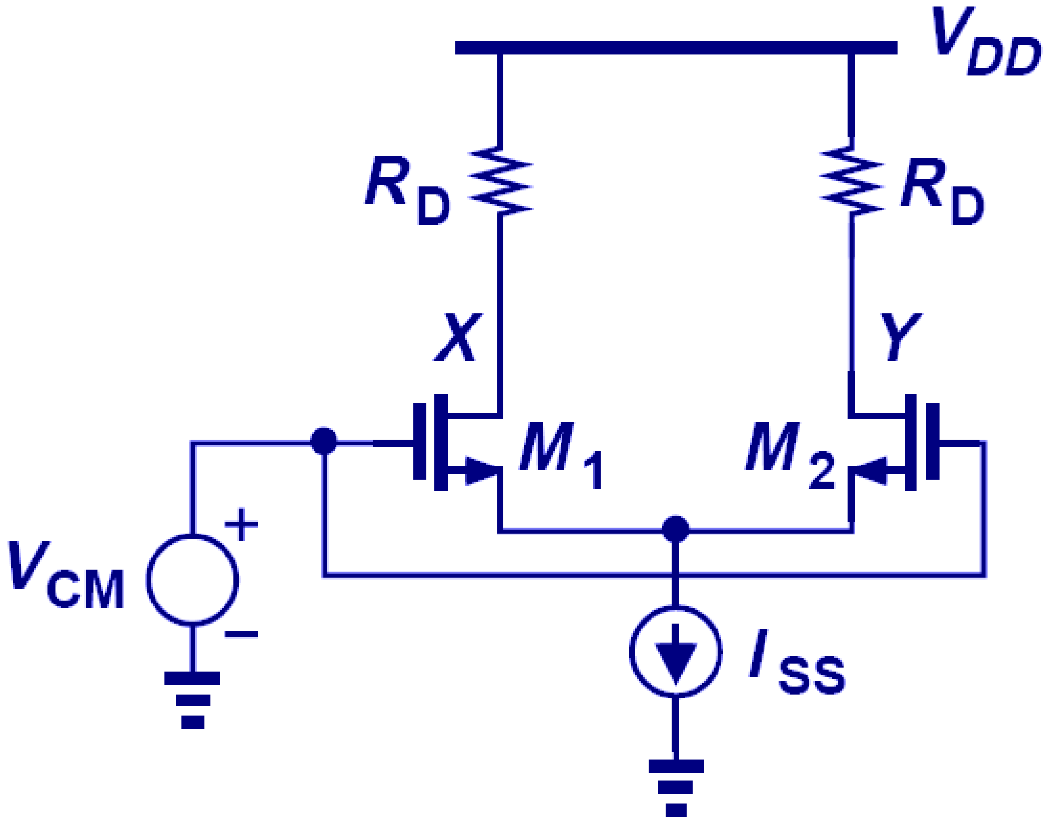
MOS Differential Pair's Common-Mode Response



$$V_X = V_Y = V_{DD} - R_D \frac{I_{SS}}{2}$$

- Similar to its bipolar counterpart, an ideal MOS differential pair produces zero differential output as VCM changes.

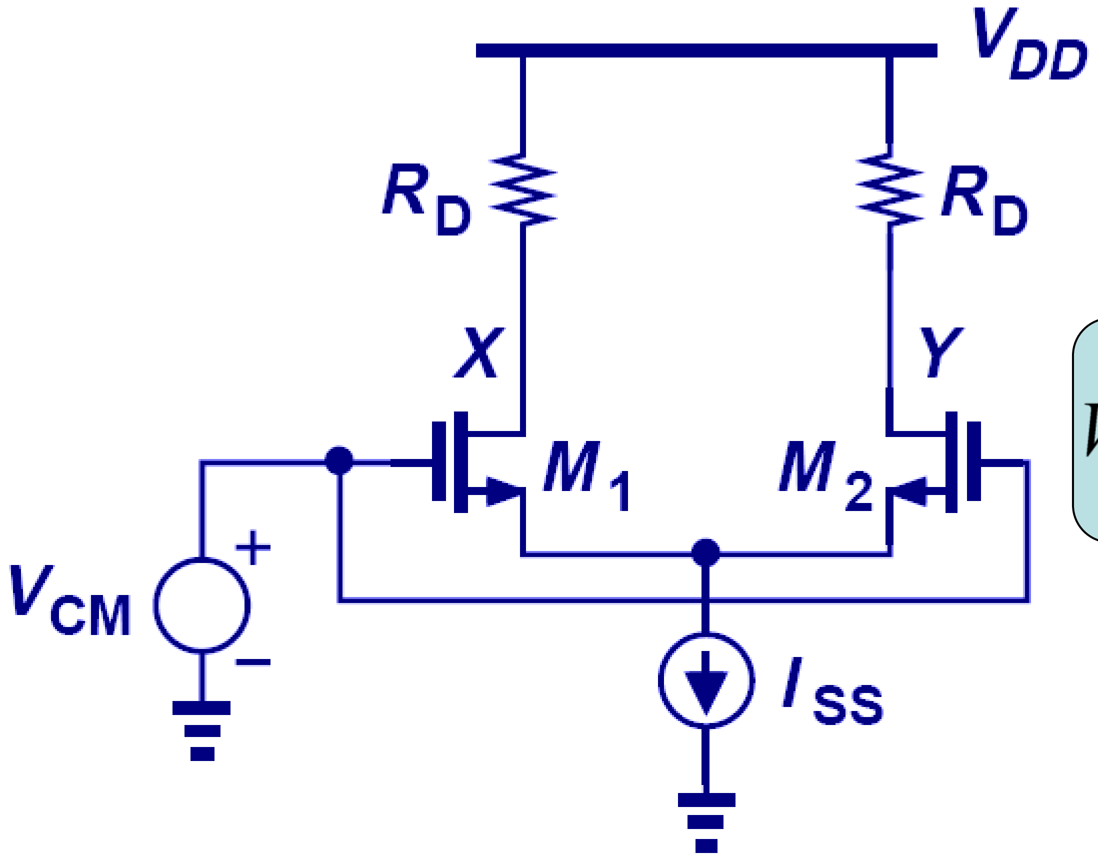
Equilibrium Overdrive Voltage



$$\left(V_{GS}-V_{TH}\right)_{equil}=\sqrt{\frac{I_{SS}}{\mu_n C_{ox}\frac{W}{L}}}$$

➢ **The equilibrium overdrive voltage is defined as the overdrive voltage seen by M_1 and M_2 when both of them carry a current of $I_{SS}/2$.**

Minimum Common-Mode Output Voltage



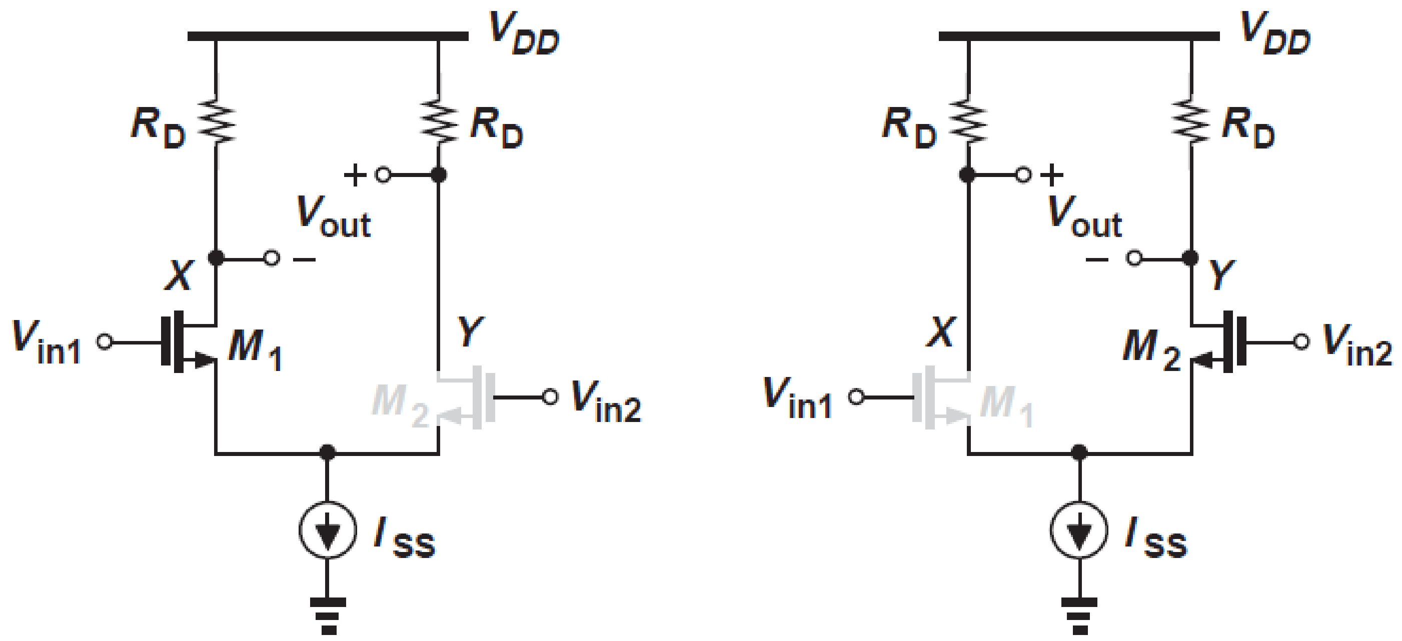
$$V_{DD} - R_D \frac{I_{SS}}{2} > V_{CM} - V_{TH}$$

- In order to maintain M_1 and M_2 in saturation, the common-mode output voltage cannot fall below the value above.
- This value usually limits voltage gain.

Qualitative Analysis

$$V_X = V_{DD} - R_D I_{SS}$$

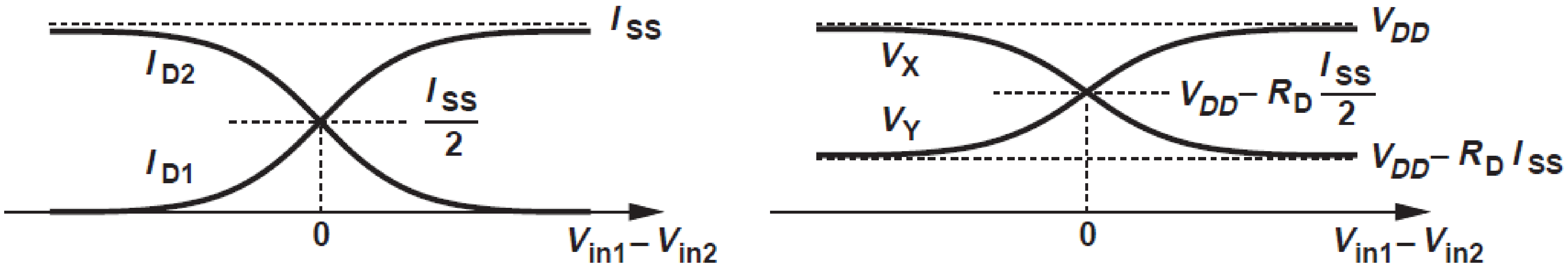
$$V_Y = V_{DD}.$$



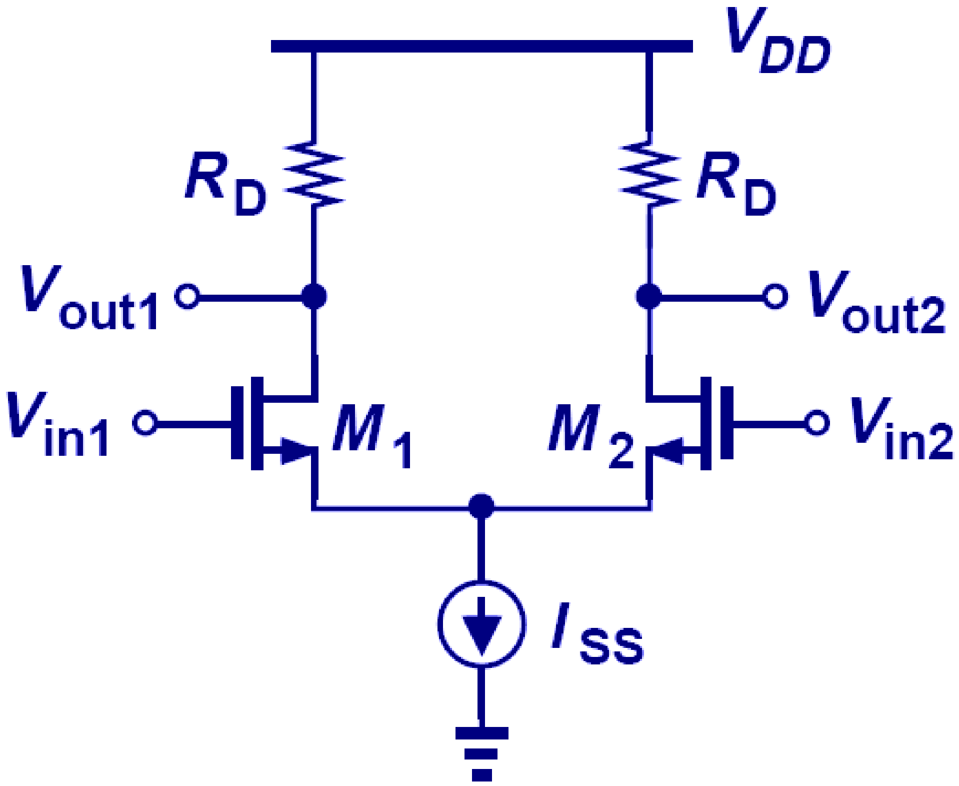
(a) (b)

$$V_X = V_{DD}$$

$$V_Y = V_{DD} - R_D I_{SS}.$$

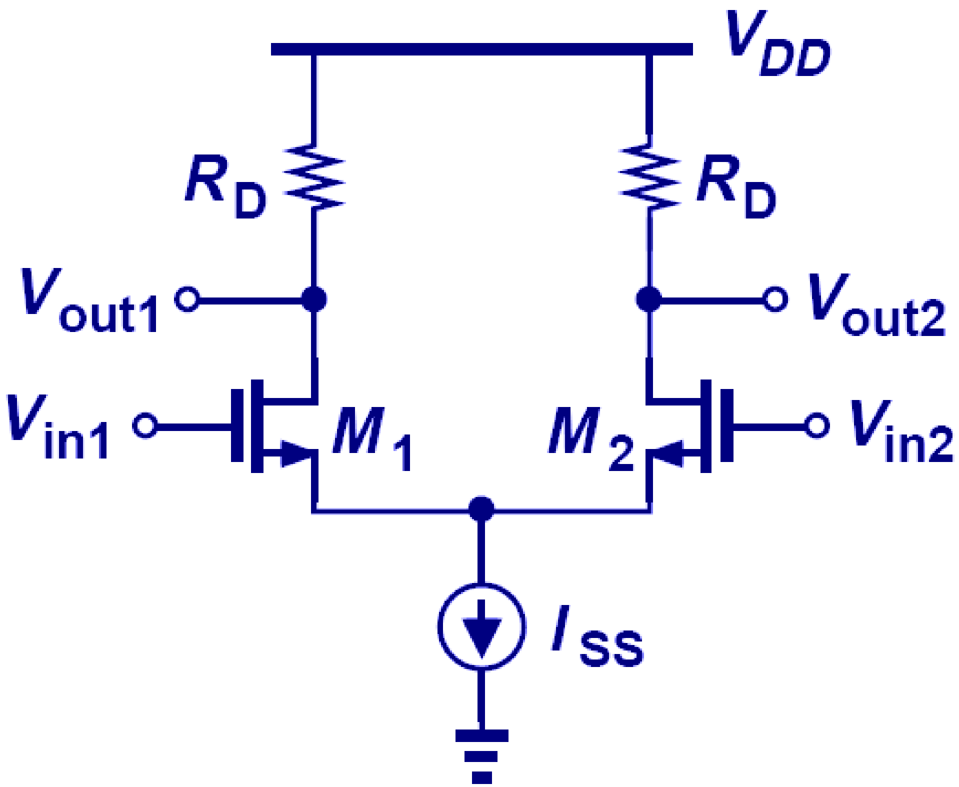


MOS Differential Pair's Large-Signal Response



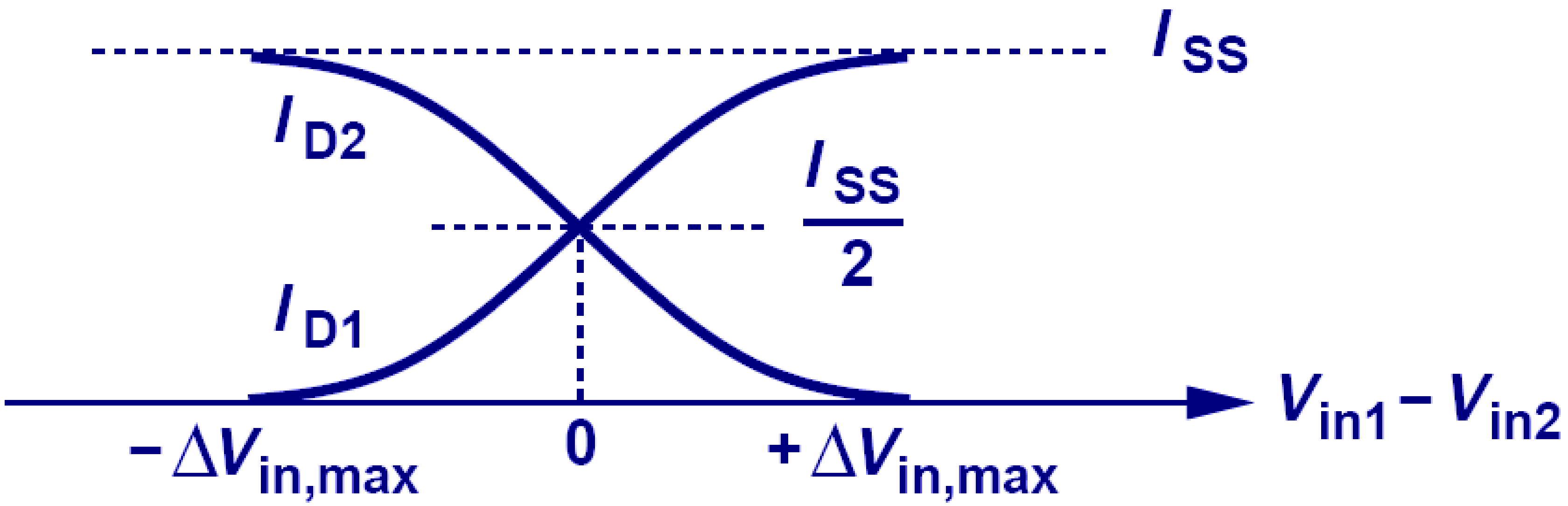
$$I_{D1} - I_{D2} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left(V_{in1} - V_{in2}\right)\sqrt{\frac{4I_{SS}}{\mu_n C_{ox}\frac{W}{L}} - \left(V_{in1} - V_{in2}\right)^2}$$

MOS Differential Pair's Large-Signal Response



$$I_{D1,2} = 0.5 I_{SS}\left(1 \pm x\sqrt{1 - 0.25x^2}\right)$$

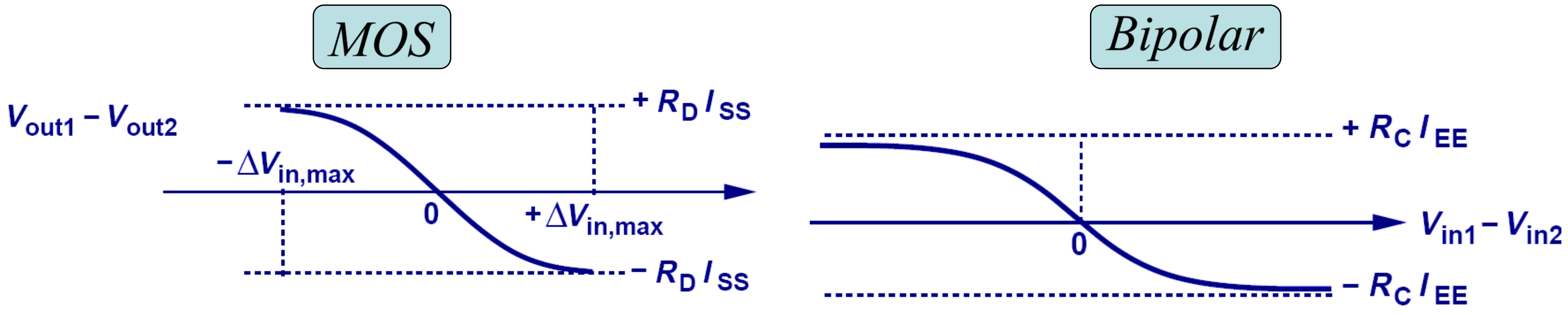
Maximum Differential Input Voltage



$$\left| V_{in1} - V_{in2} \right|_{\max} = \sqrt{2} \left(V_{GS} - V_{TH} \right)_{equil}$$

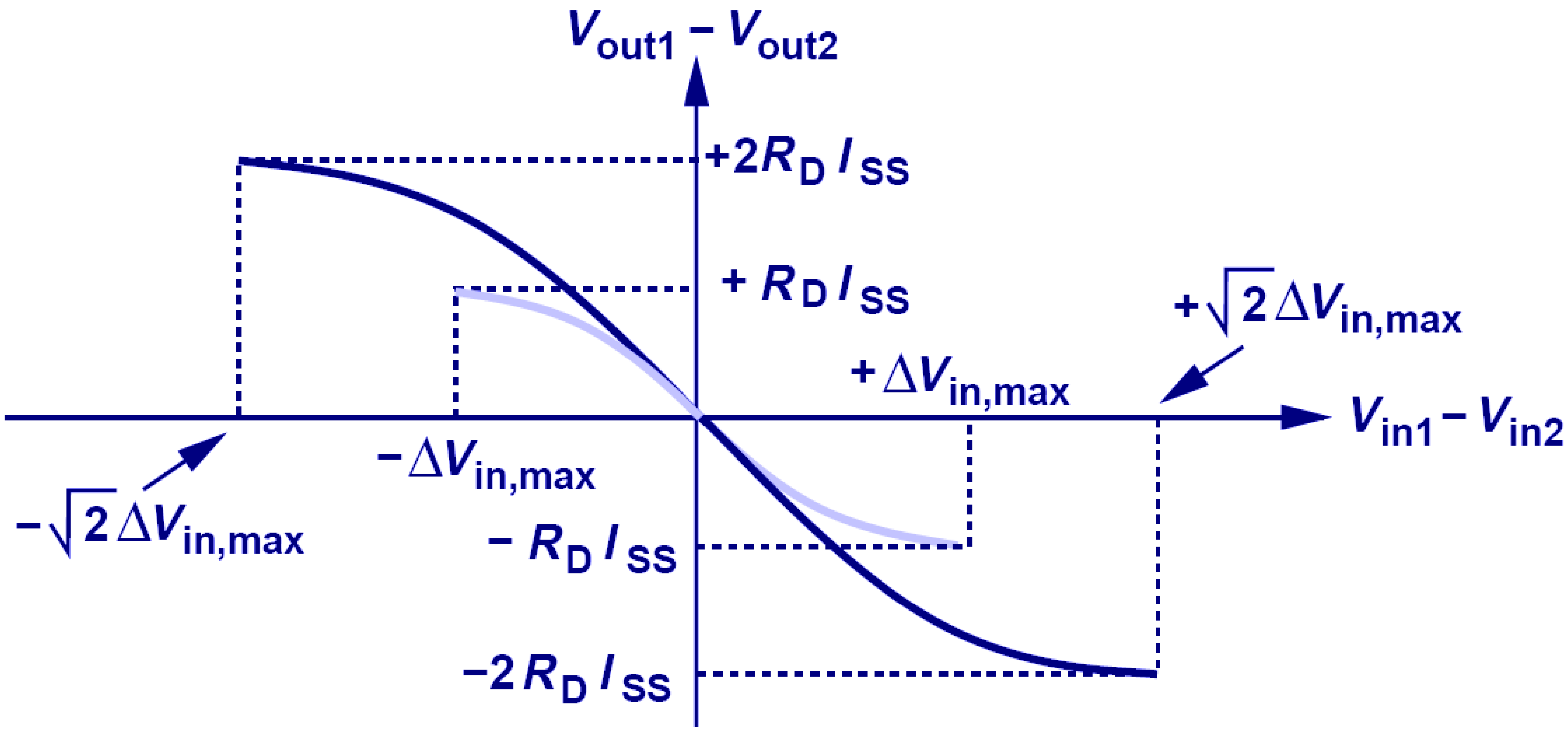
➢ **There exists a finite differential input voltage that completely steers the tail current from one transistor to the other. This value is known as the maximum differential input voltage. In other words, this value serves as an absolute bound on the input signal levels that have any effect on the output.**

Contrast Between MOS and Bipolar Differential Pairs



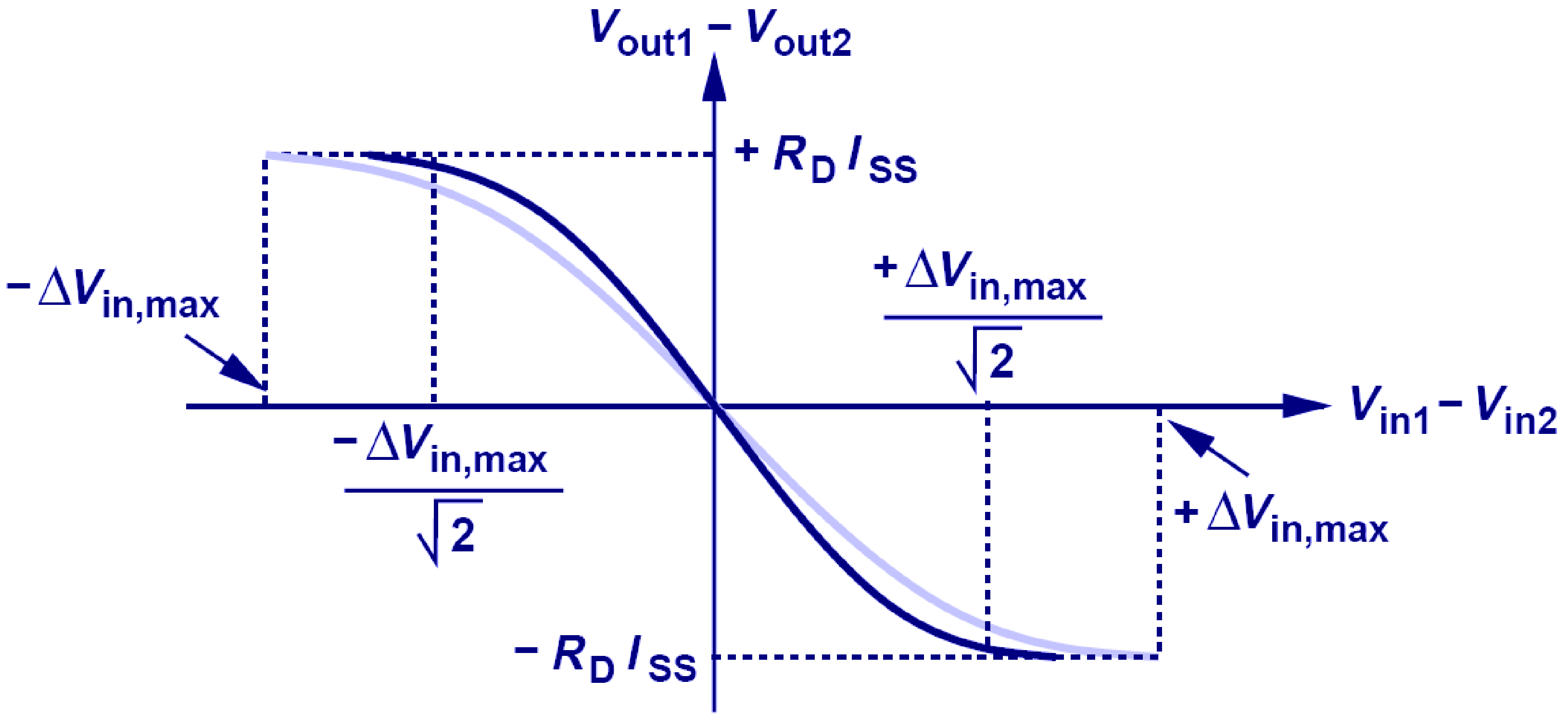
➢ **In a MOS differential pair, there exists a finite differential input voltage to completely switch the current from one transistor to the other, whereas, in a bipolar pair that voltage is infinite.**

The effects of Doubling the Tail Current



- Since I_{SS} is doubled and W/L is unchanged, the equilibrium overdrive voltage for each transistor must increase by $\sqrt{2}$ to accommodate this change, thus $\Delta V_{in,max}$ increases by $\sqrt{2}$ as well. Moreover, since I_{SS} is doubled, the differential output swing will double.

The effects of Doubling W/L



- Since W/L is doubled and the tail current remains unchanged, the equilibrium overdrive voltage will be lowered by $\sqrt{2}$ to accommodate this change, thus $\Delta V_{in,max}$ will be lowered by $\sqrt{2}$ as well. Moreover, the differential output swing will remain unchanged since neither I_{SS} nor R_D has changed

Thanks

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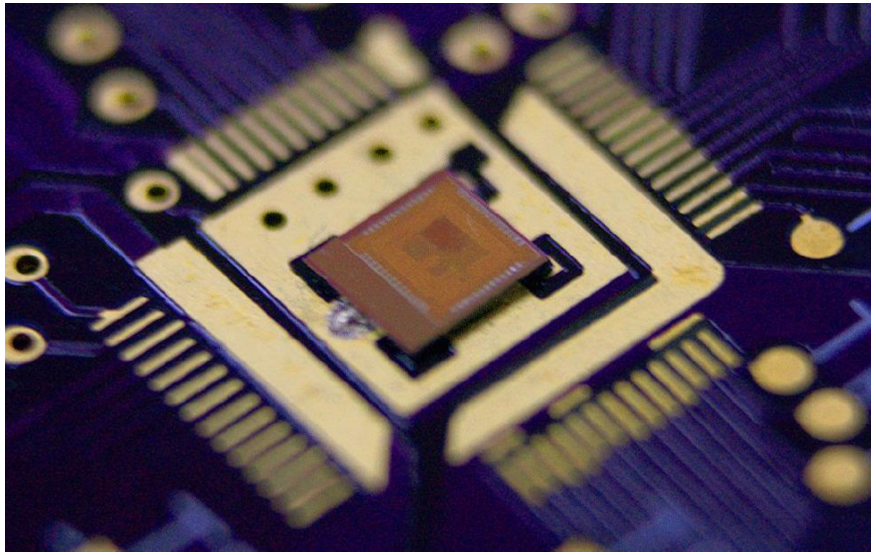

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