EECE488: Analog CMOS Integrated Circuit Design

Set 4

Differential Amplifiers

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Overview

- The "differential amplifier" is one of the most important circuit inventions.

- Their invention dates back to vacuum tube era (1930s).

- Alan Dower Blumlein (a British Electronics Engineer, 1903-1942) is regarded as the inventor of the vacuum-tube version of differential pair.

- Differential operation offers many useful properties and is widely used in analog and mixed-signal integrated circuits

Single-ended and Differential Signals

• A "single-ended" signal is a signal that is measured with respect to a fixed potential (typically ground).

• "Differential signal" is generally referred to a signal that is measured as a difference between two nodes that have equal but opposite-phase signal excursions around a fixed potential (the fixed potential is called common-mode (CM) level).
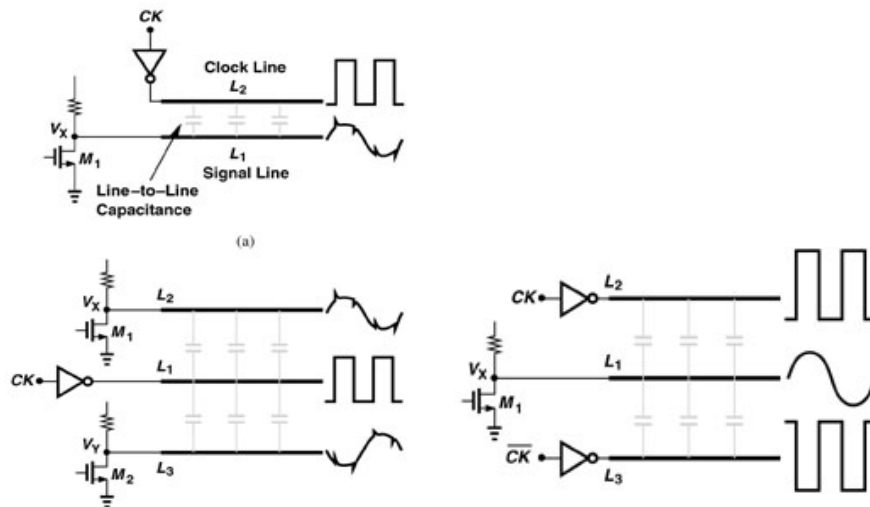
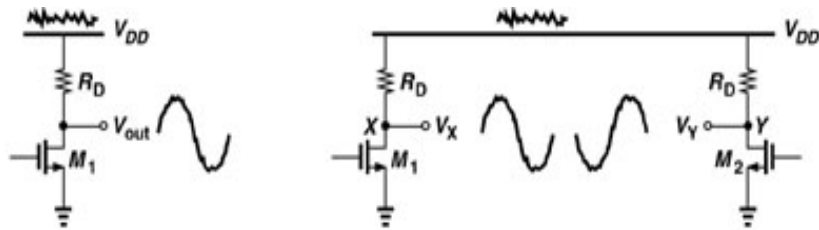## Board Notes (Differential Amplifiers)

Why Differential?

- Better immunity to environmental noise

- Improved linearity

- Higher signal swing compared to single-ended
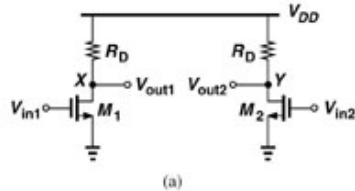
Higher Immunity to Noise Coupling
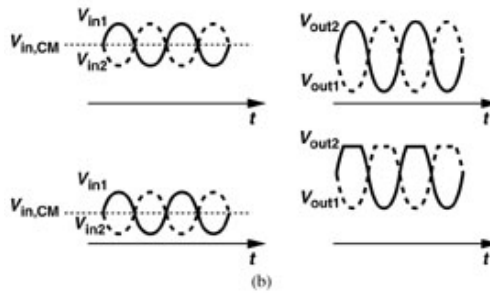
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Supply Noise Reduction

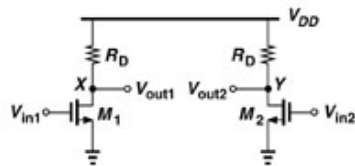# Board Notes (Improved Linearity)
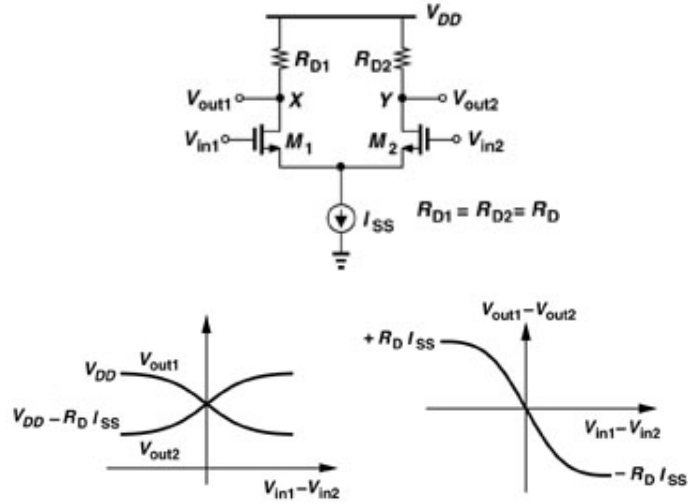
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Basic Differential Pair

Basic Differential Pair

- Problem: Sensitive to input common-mode (CM) level
  - Bias current of the transistors M_1 and M_2 changes as the input CM level changes

  - g_m of the devices as well as output CM level change
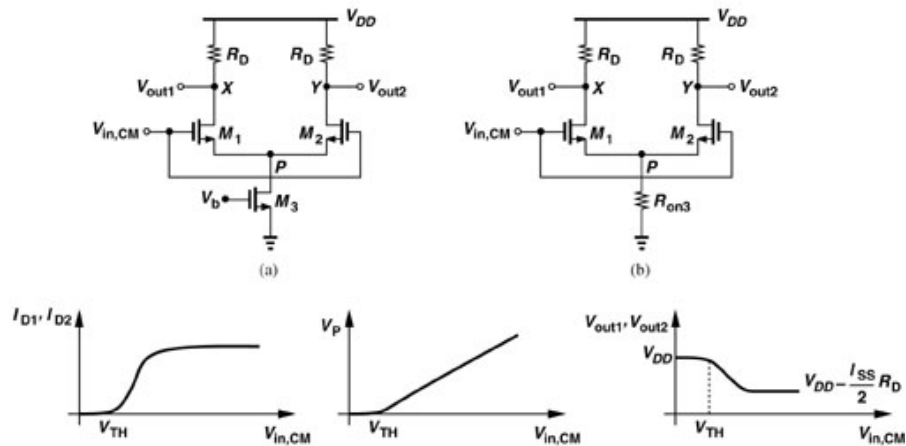
- Can we think of a solution?

Differential Pair

$$R_{D1} = R_{D2} = R_D$$

Common-Mode Response

(a)

(b)
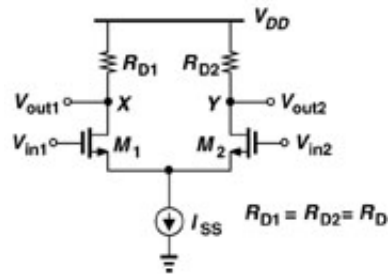
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Common-Mode Input versus Output Swing
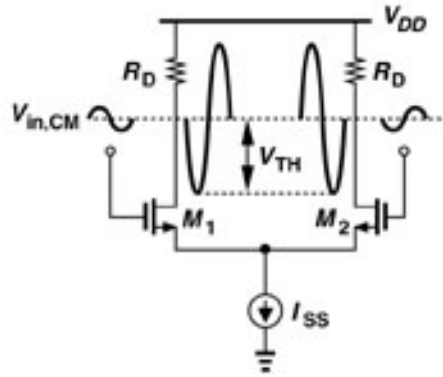
Board Notes ("Half-Circuit" Concept)
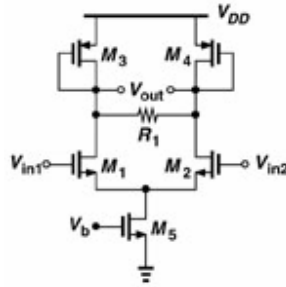
Board Notes ("Half-Circuit" Concept)

Example

- Using the half-circuit concept, calculate the small-signal differential gain of the following circuit (for two cases of $\lambda=0$ and $\lambda\neq0$).

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Example

- Using the half-circuit concept, calculate the small-signal differential gain of the following circuit (for two cases of λ=0 and λ≠0).

Example

- Sketch the small-signal gain of a differential pair as a function of its input common-mode level.

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Analysis of Differential Amplifier
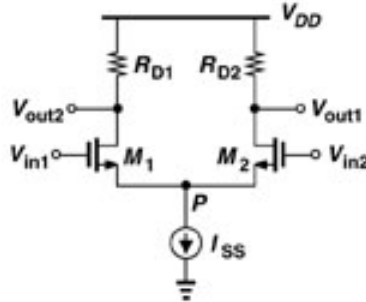
$$V_{in1} - V_{in2} = V_{GS1} - V_{GS2}, \qquad V_{GS} = \sqrt{\frac{2I_D}{\mu_n C_{ox} \frac{W}{L}}} + V_{TH}$$

Analysis of Differential Amplifier

$$V_{in1} - V_{in2} = \sqrt{\frac{2I_{D1}}{\mu_n C_{ox} \frac{W}{L}}} - \sqrt{\frac{2I_{D2}}{\mu_n C_{ox} \frac{W}{L}}}$$

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

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

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

Analysis of Differential Amplifier

Using:

$$4I_{D1}I_{D2} = (I_{D1} + I_{D2})^2 - (I_{D1} - I_{D2})^2 = I_{SS}^2 - (I_{D1} - I_{D2})^2$$

and

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

We have:

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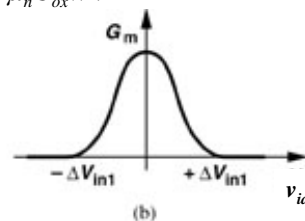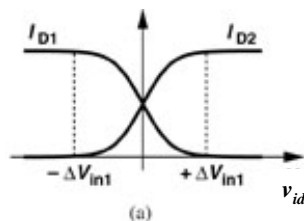

Analysis of Differential Amplifier

$$i_d = \frac{1}{2}\mu_n C_{ox}\frac{W}{L} v_{id}\sqrt{\frac{4I_{SS}}{\mu_n C_{ox}\frac{W}{L}} - v_{id}^2}$$

$$\frac{\partial i_d}{\partial v_{id}} = G_m = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}\frac{\frac{4I_{SS}}{\mu_n C_{ox}W/L} - v_{id}^2}{\sqrt{\frac{4I_{SS}}{\mu_n C_{ox}W/L} - v_{id}^2}}$$

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Analysis of Differential Amplifier
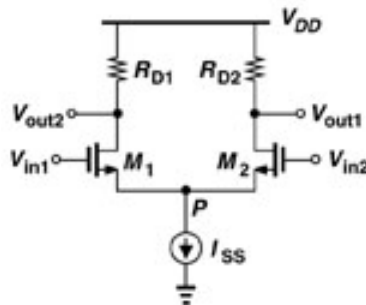
- For small v_{id}:

$$G_m = \frac{\partial i_d}{\partial v_{id}} = \sqrt{\mu_n C_{ox} \frac{W}{L} I_{SS}} = g_{m1} = g_{m1}$$

- We have:

$$V_{out1} - V_{out2} = R_D(I_{D1} - I_{D2}) = R_D G_m(V_{in1} - V_{in2})$$

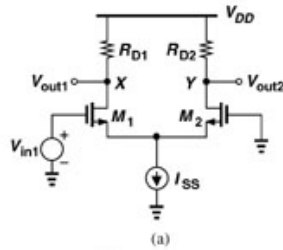$$\frac{V_{out1} - V_{out2}}{V_{in1} - V_{in2}} = g_{m1}R_D$$

Differential Gain

$$A_v(diff) = \frac{V_{out1} - V_{out2}}{V_{in1} - V_{in2}} = g_m R_D$$
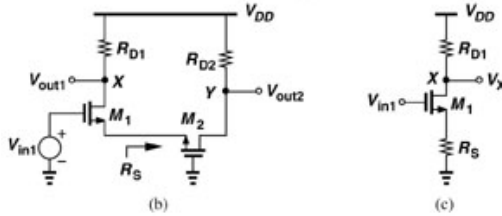
$$A_v(Single - Ended) = \frac{g_m}{2} R_D$$

Differential Pair as a CS and CD-CG Amplifier

$$A_v = -\frac{g_m R_D}{1 + g_m R_S}$$

$$= -\frac{g_m}{2} R_D \ , \ \ (S.E.)$$

$$= g_m R_D \ , \ \ (diff)$$

Common-Mode Response
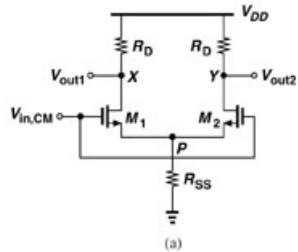
$$A_v = \frac{V_{out}}{V_{in,CM}}$$

$$= -\frac{R_D / 2}{1/(2 g_m) + R_{SS}}$$

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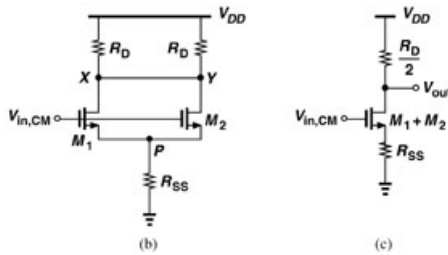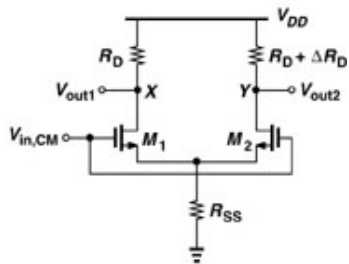
Board Notes

Example

- In the following circuit assume that $R_{SS}=500\Omega$ and W/L=25/0.5, $\mu_n C_{ox}=50\mu A/V^2$, $V_{TH}=0.6$, $\lambda=\gamma=0$ and $V_{DD}=3V$.
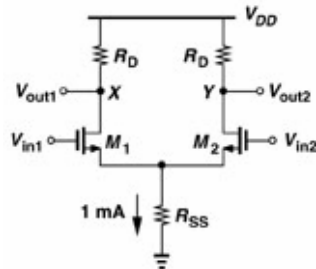
a) What is the required input CM for which R_{SS} sustains 0.5V?

b) Calculate R_D for a differential gain of 5V/V.

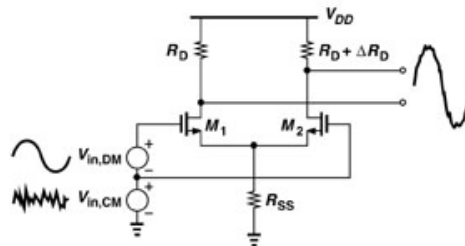c) What happens at the output if the input CM level is 50mV higher than the value calculated in part (a)?
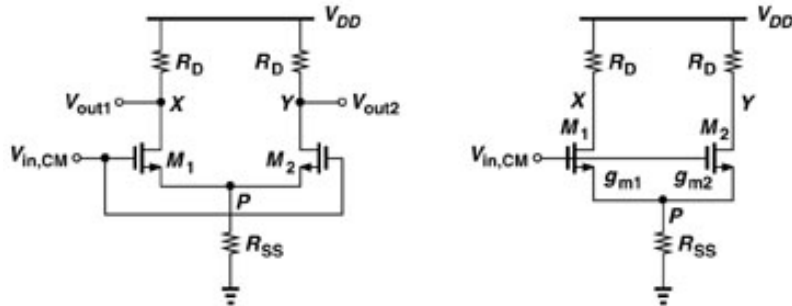
Board Notes

Common-Mode Response

$$\frac{\Delta V_X}{\Delta V_{in,CM}} = -\frac{g_m}{1+2g_m R_{SS}} R_D$$

$$\frac{\Delta V_Y}{\Delta V_{in,CM}} = -\frac{g_m}{1+2g_m R_{SS}} (R_D + \Delta R_D)$$
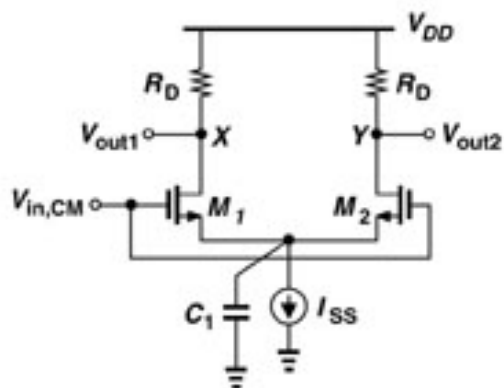
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Common-Mode Response

$$\frac{V_X - V_Y}{V_{in,CM}} = -\frac{g_{m1} - g_{m2}}{(g_{m1} + g_{m2})R_{SS} + 1} R_D$$

Common-Mode Response

Differential Pair with MOS Loads
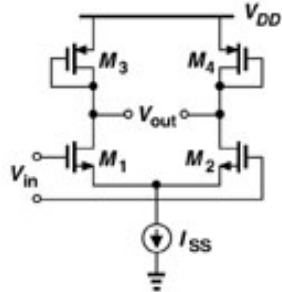
$$A_v = -g_{mN}(g_{mP}^{-1} \| r_{oN} \| r_{oP})$$

$$\approx -\frac{g_{mN}}{g_{mP}}$$
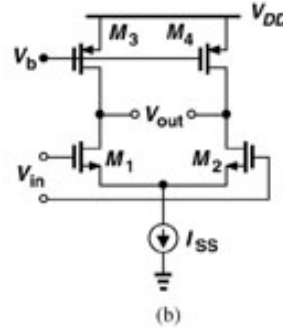
$$A_v = -g_{mN}(r_{oN} \| r_{oP})$$
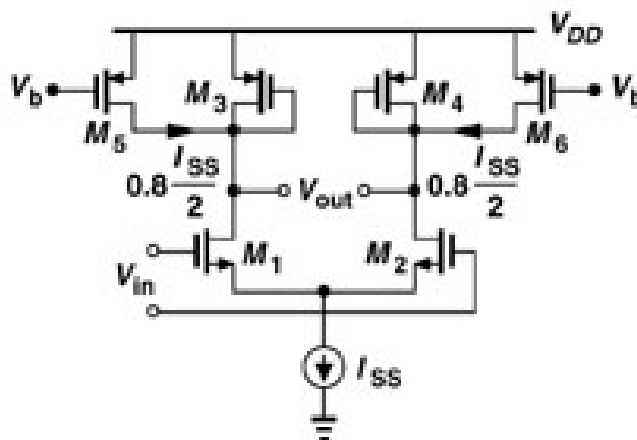
MOS Loads

MOS Loads
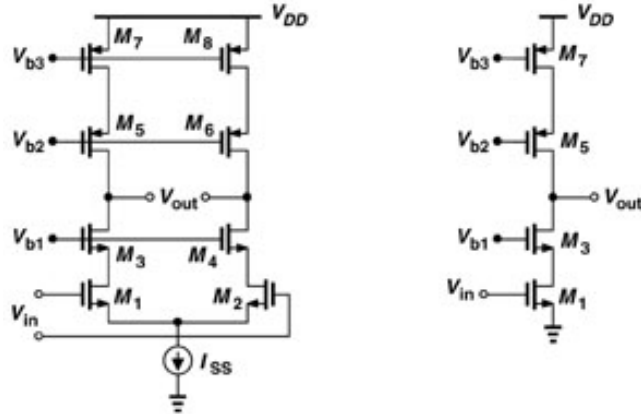
$$A_v \approx g_{m1}[(g_{m3}r_{o3}r_{o1}) \| (g_{m5}r_{o5}r_{o7})]$$
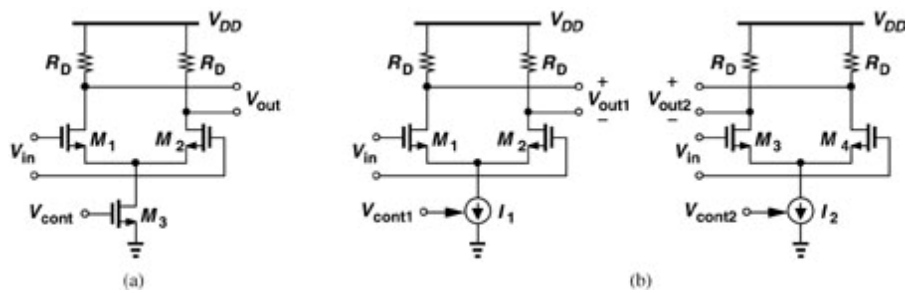
Gilbert Cell

(a)

(b)

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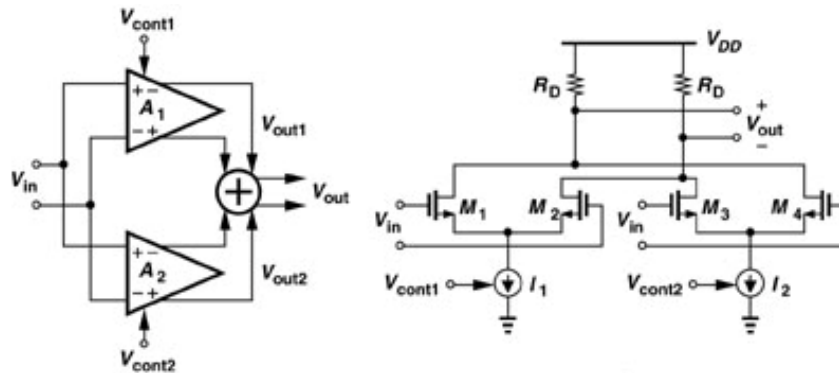
Gilbert Cell

Gilbert Cell

$$V_{OUT} = kV_{in}V_{cont}$$

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