EECE488: Analog CMOS Integrated Circuit Design

Set 3

Differential Amplifiers

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Overview

- Reading: Chapter 4 of the Textbook   nost 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).
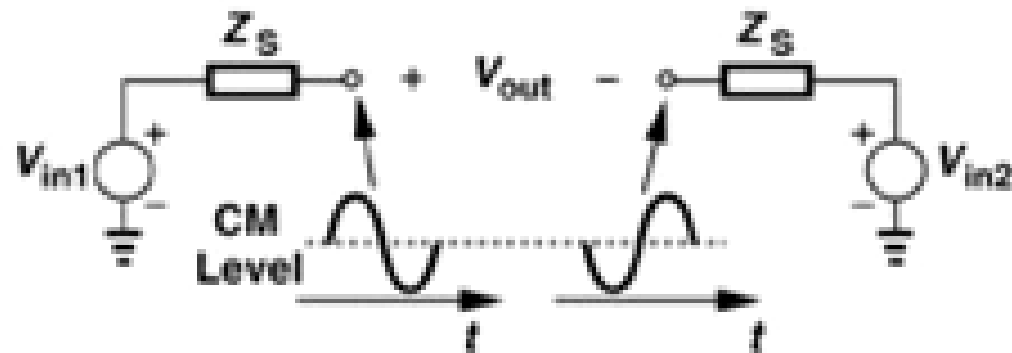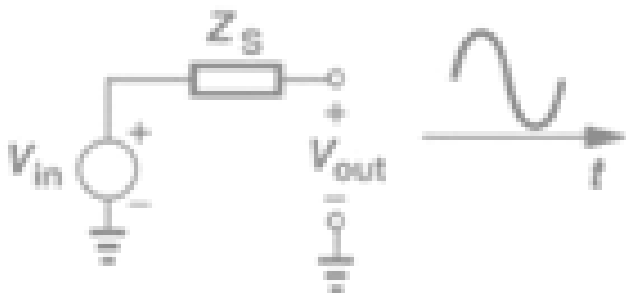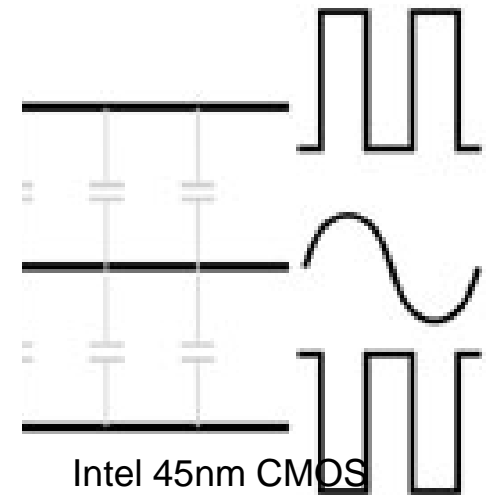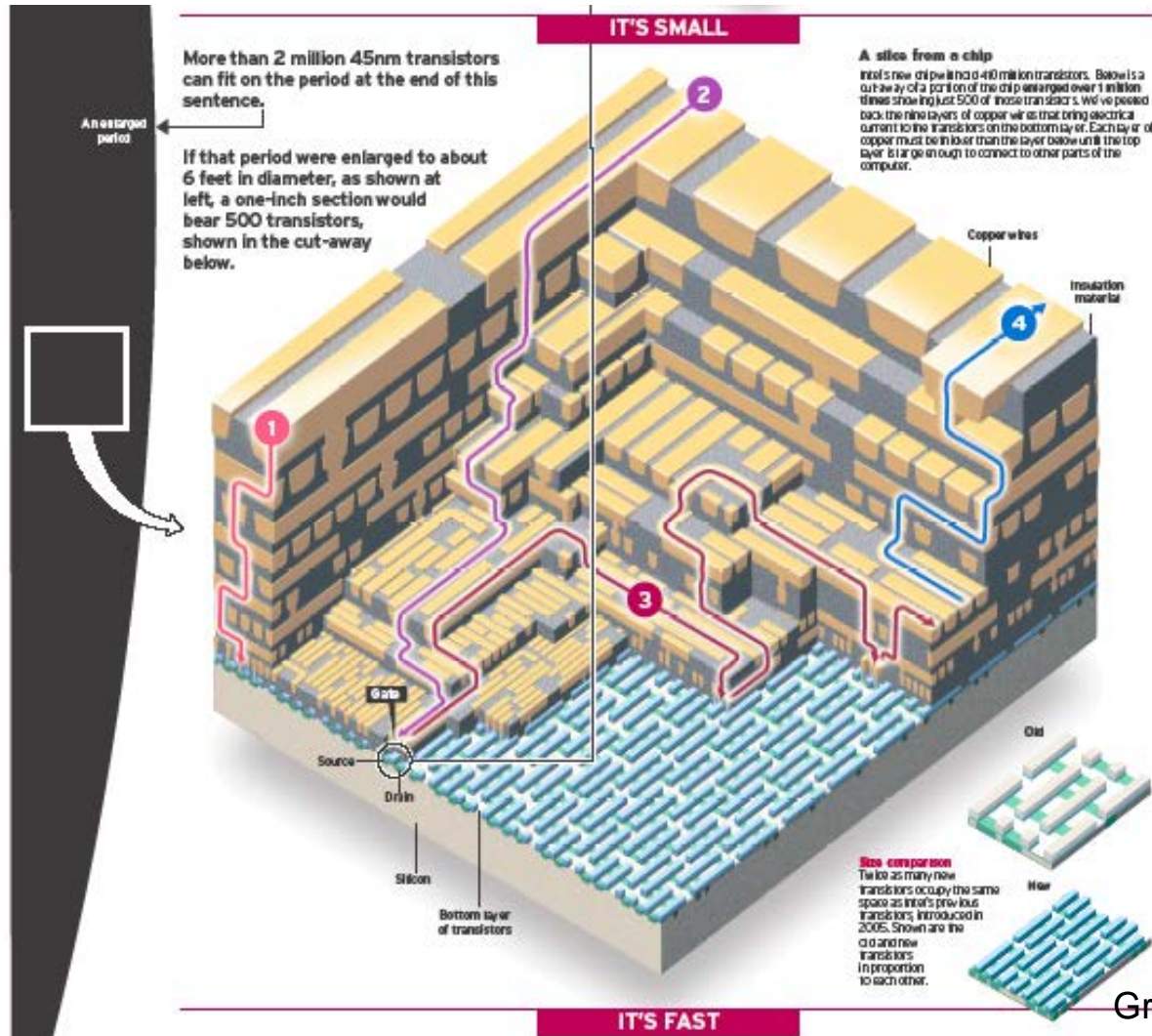
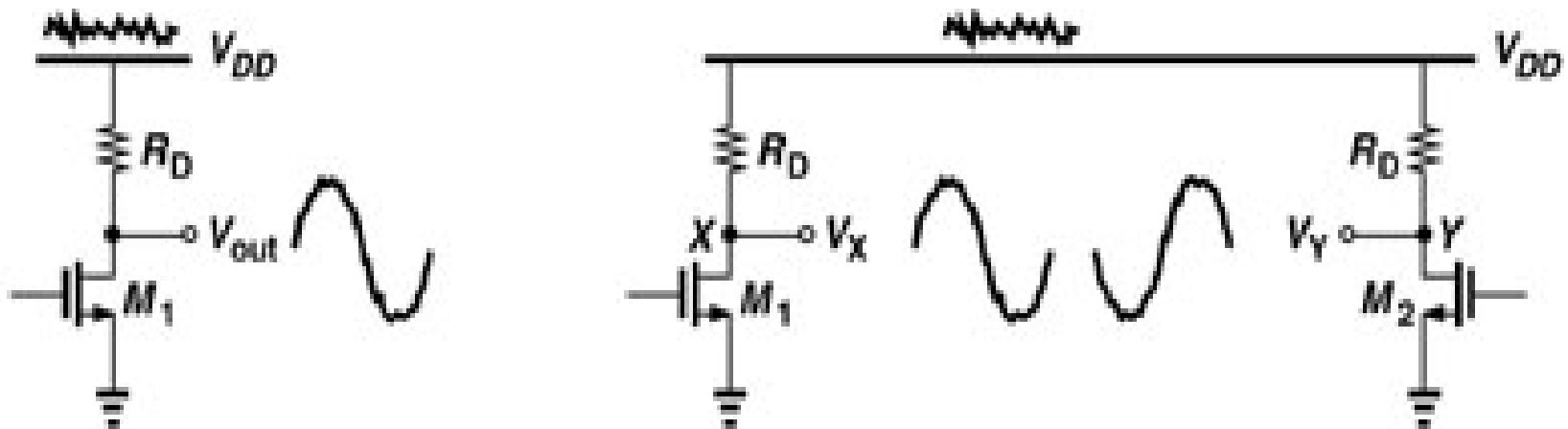# Board Notes (Differential Amplifiers)

Why Differential?

- Better immunity to environmental noise

- Improved linearity

- Higher signal swing compared to single-ended

Higher Immunity to Noise Coupling

IT'S SMALL

More than 2 million 45nm transistors can fit on the period at the end of this sentence.

An enlarged period

If that period were enlarged to about 6 feet in diameter, as shown at left, a one-inch section would bear 500 transistors, shown in the cut-away below.

A slice from a chip

Intel's new chip with 410 million transistors. Below is a cut away of a portion of the chip enlarged over 1 million times showing just 500 of those transistors. We've peeled back the nine layers of copper wires that bring electrical current to the transistors on the bottom layer. Each layer of copper must be thicker than the layer below until the top layer is large enough to connect to other parts of the computer.

Copper wires

Insulation material

Gate

Source

Drain

Silicon

Bottom layer of transistors

Size comparison
Twice as many new transistors occupy the same space as Intel's previous transistors, introduced in 2005. Shown are the old and new transistors in proportion to each other.

Old

New

IT'S FAST

Intel 45nm CMOS

Graphics: Steve Cowden, Oregonian, 2007

Supply Noise Reduction

ELEC401 Set 3 - Differential Amplifiers

Board Notes (Improved Linearity)

Basic Differential Pair

(a)

$V_{in,CM}$ ······································

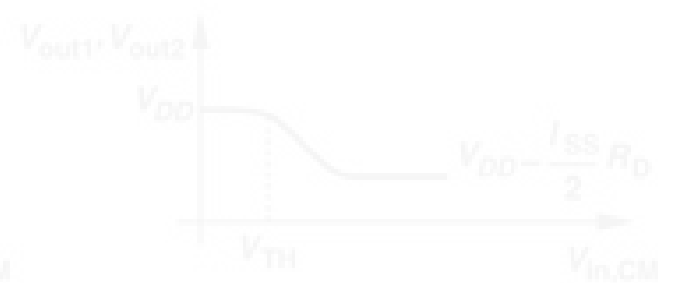································ $V_{out,CM}$
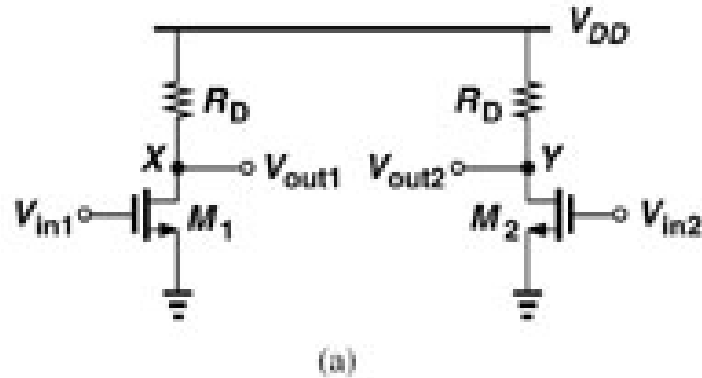
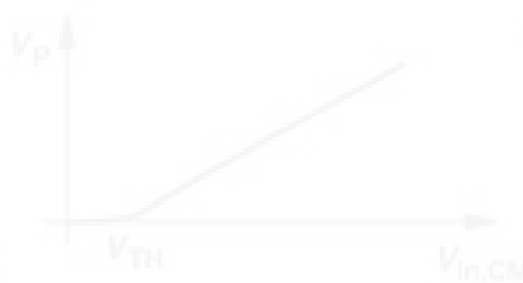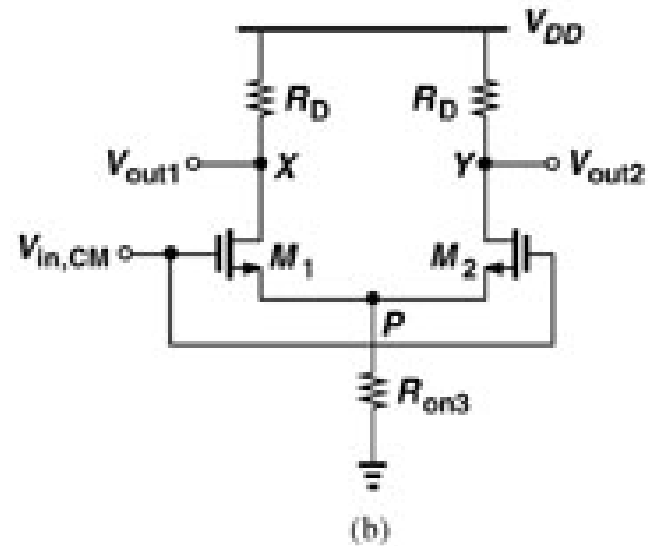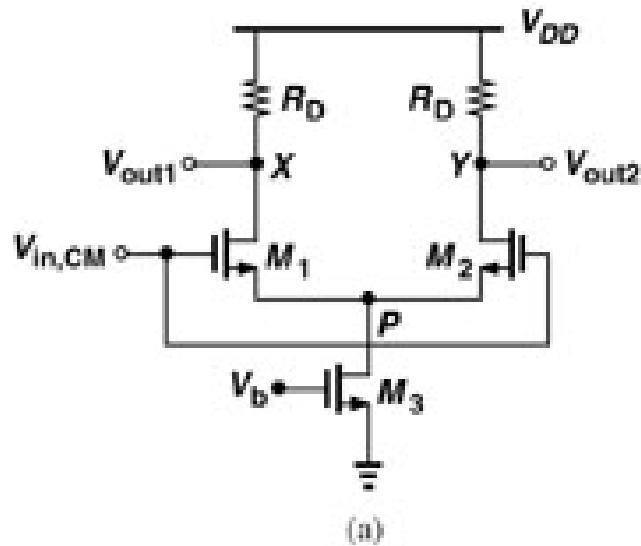# Basic Differential Pair
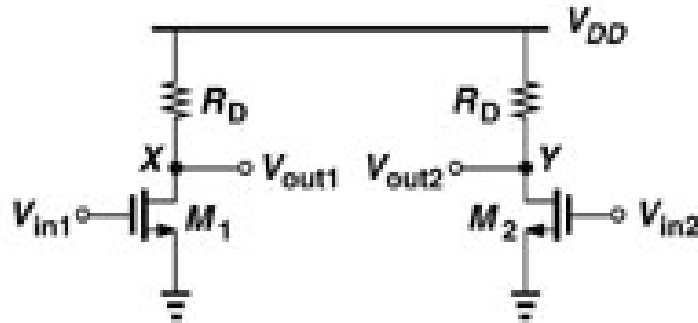
- Problem: Sensitive to input common-mode (CM) level

  - Bias currents of the transistors M_1 and M_2 changes as the input CM level changes

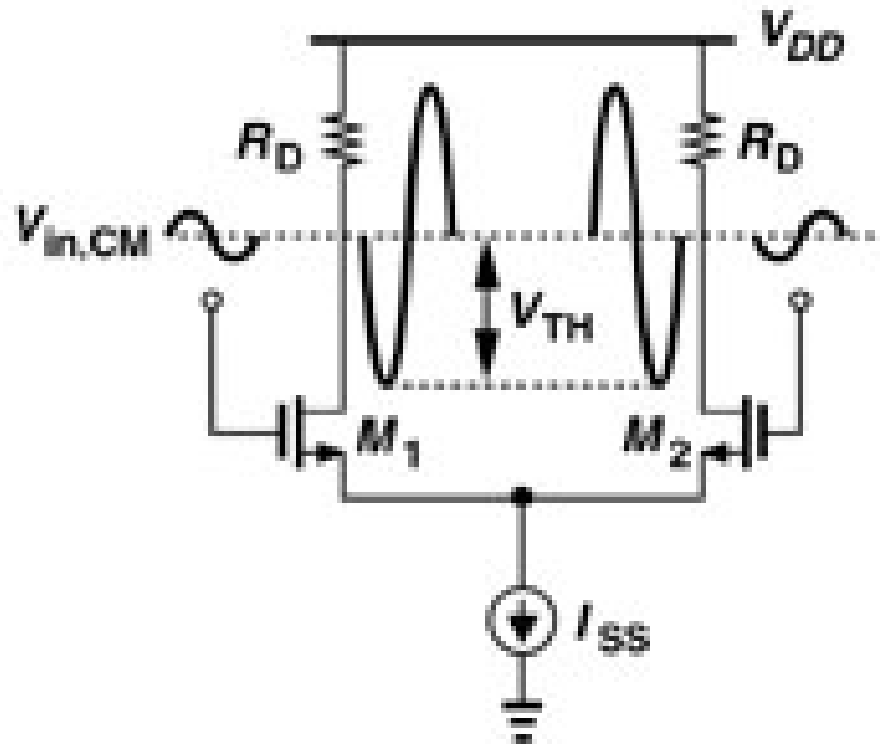 - g_m of the devices as well as output CM level change

- Can we think of a solution?

Differential Pair

V_{DD}

R_{D1} R_{D2}

V_{out1} — X   Y — V_{out2}

V_{in1} — M_1 M_2 — V_{in2}

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

ELEC401 Set 3 - Differential Amplifiers

Common-Mode Response

(a)

(b)
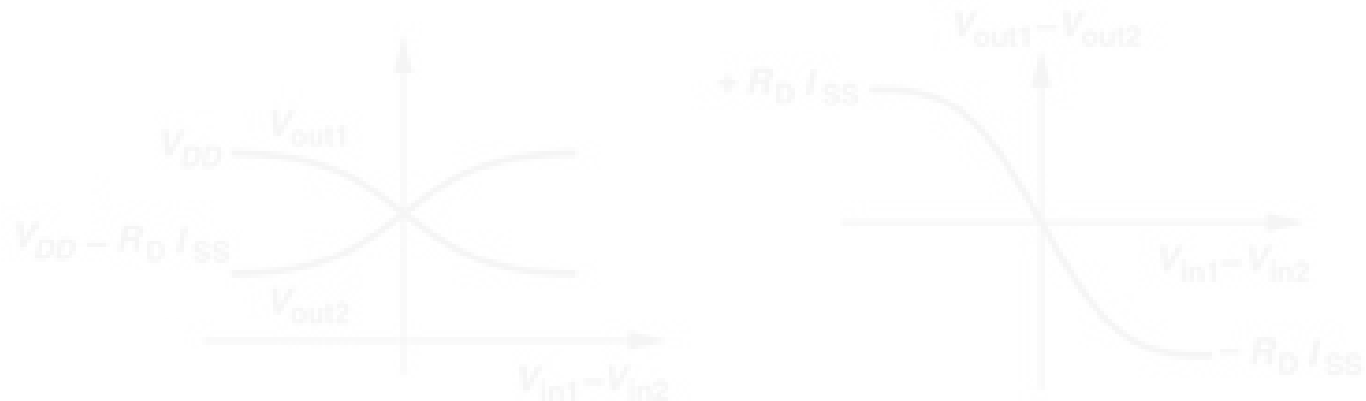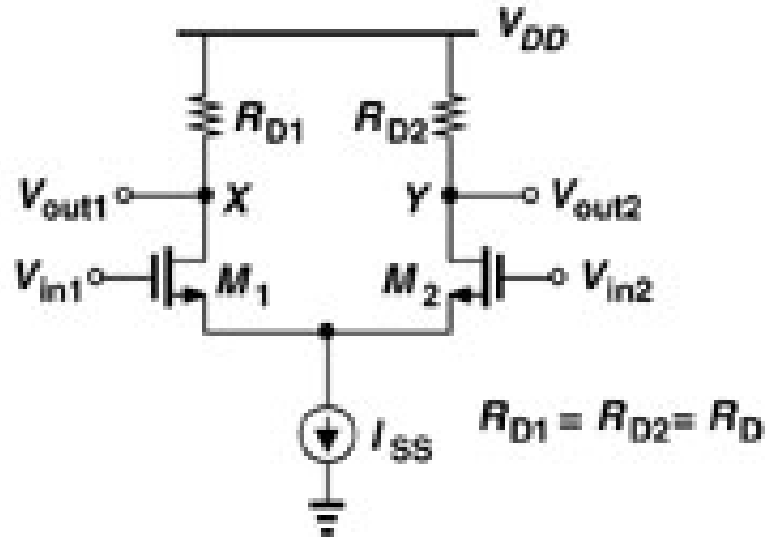
Common-Mode Input versus Output Swing

Board Notes ("Half-Circuit" Concept)

Board Notes ("Half-Circuit" Concept)

ELEC401 Set 3 - Differential Amplifiers

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).
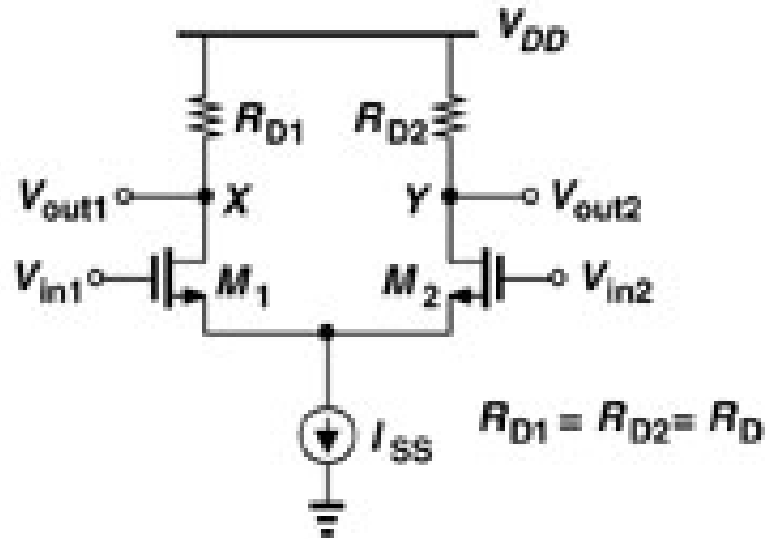
Example

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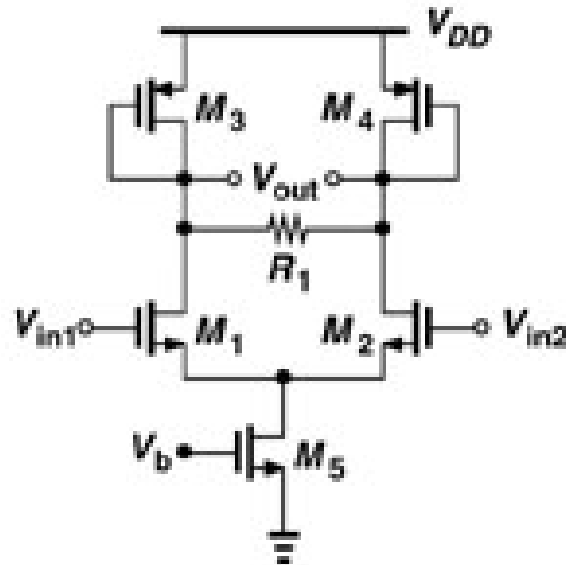
Example

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

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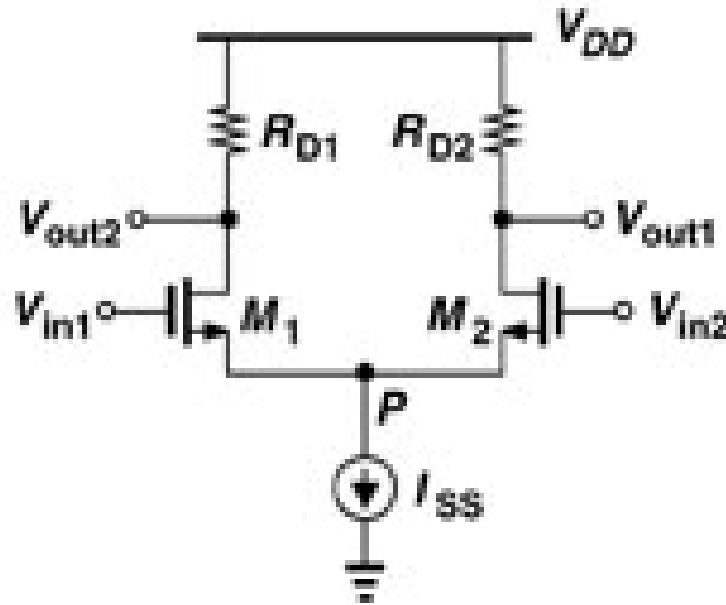
$$V_{in1} - V_{in2} = V_{GS1} - V_{GS2}, \qquad V_{GS} = \sqrt{\dfrac{2I_D}{\mu_n C_{ox} \dfrac{W}{L}}} + V_{TH}$$

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

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

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

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

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

(a)

(b)
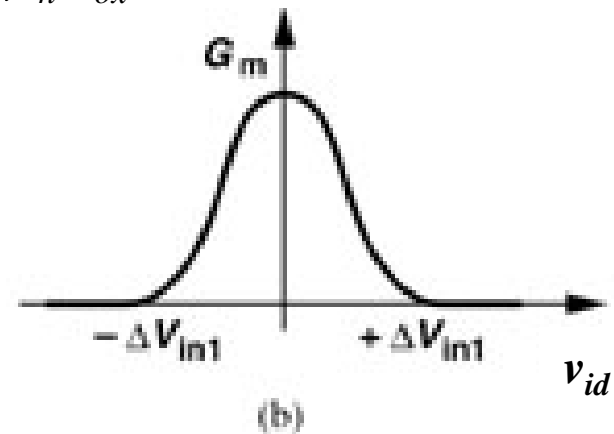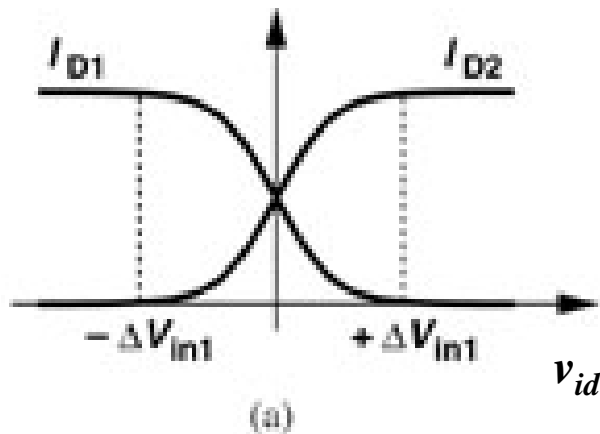
Analysis of Differential Amplifier

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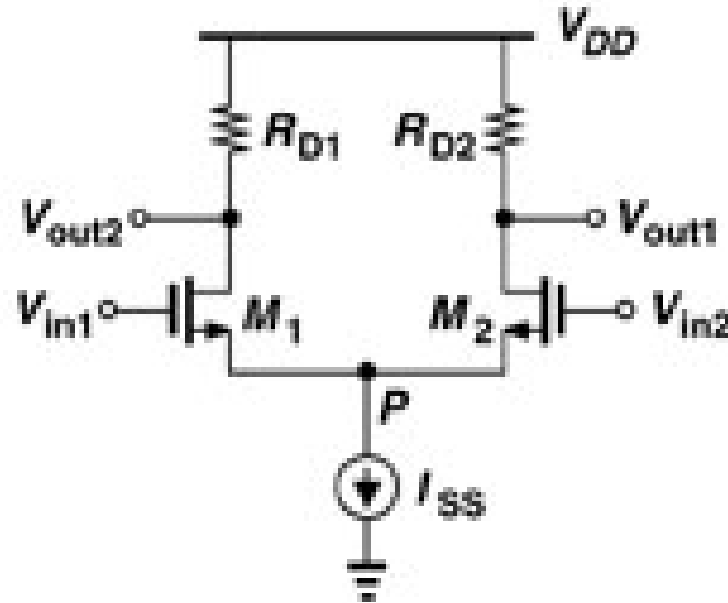
$$A_v(diff) = \frac{V_{out1} - V_{out2}}{V_{in1} - V_{in2}} = g_m R_D$$

$$A_v(Single - Ended) = \frac{g_m}{2} R_D$$

Differential Pair as a CS and CD-CG Amplifier

(a)

(b)

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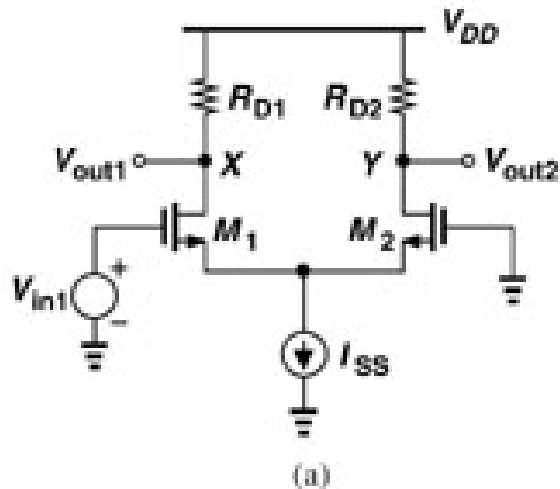
$$A_v = -\frac{g_m R_D}{1 + g_m R_S}$$

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

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

Common-Mode Response

(a)

(b)

(c)
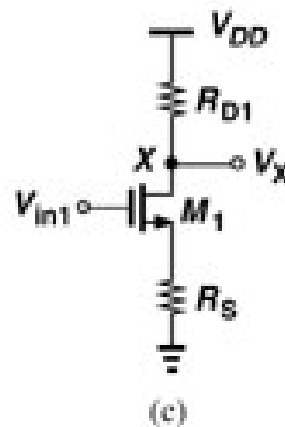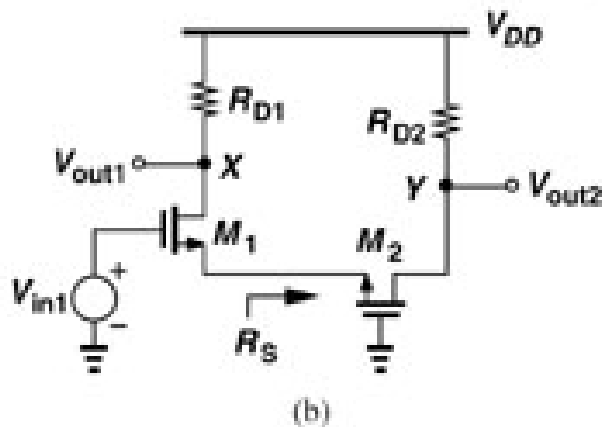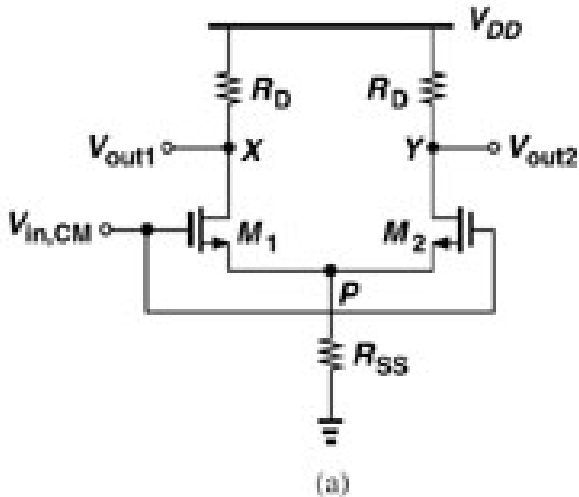
$$A_v = \frac{V_{out}}{V_{in,CM}}$$

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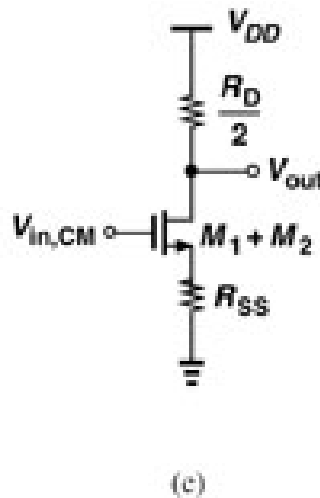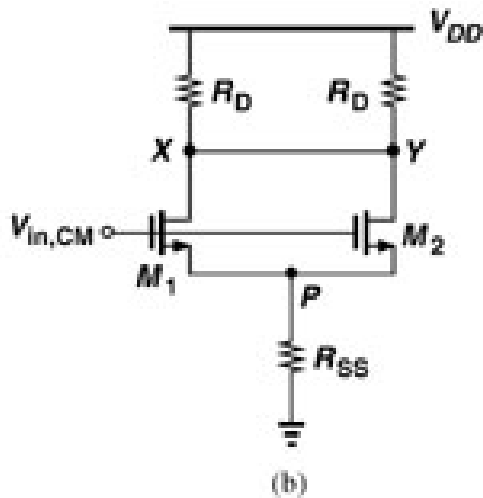
Board Notes

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 $V_{DD}=3V$.
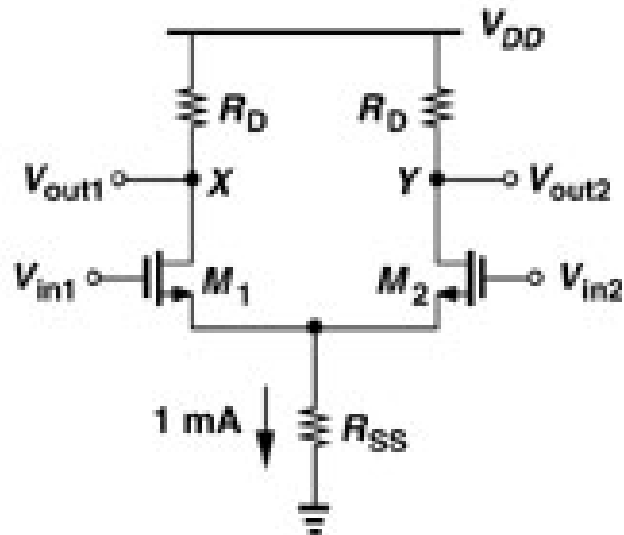
a) What is the required input CM for which R_{SS} sustains 0.5V?

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

ELEC401 Set 3 - Differential Amplifiers

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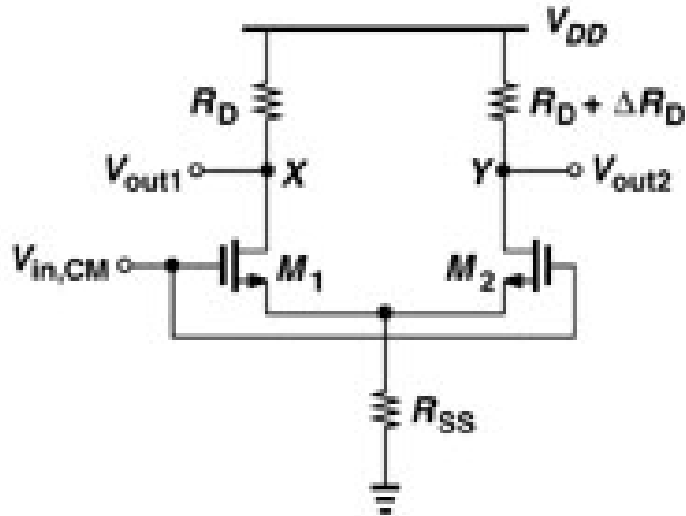
$$\frac{\Delta V_X}{\Delta V_{in,CM}} = -\frac{g_m}{1+2g_m R_{SS}} R_D$$

$$\frac{\Delta V_Y}{\Delta V_{in,CM}} = -\frac{g_m}{1+2g_m R_{SS}}(R_D + \Delta R_D)$$
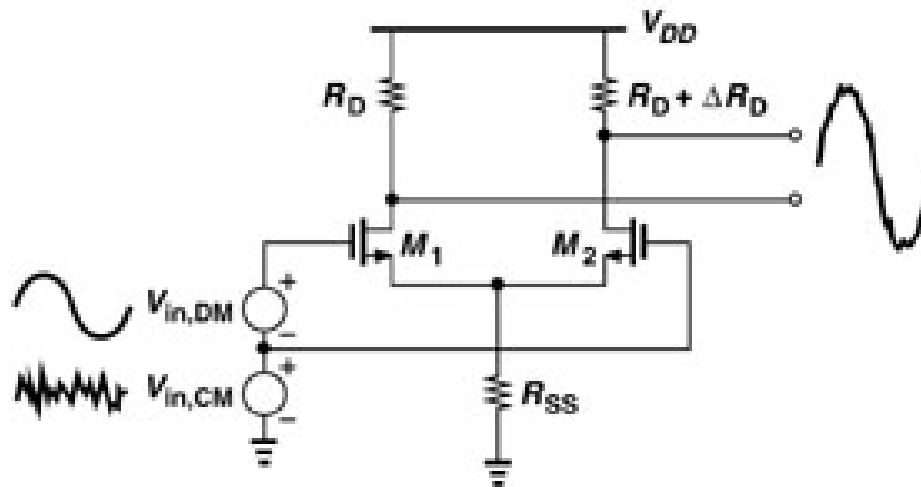
Common-Mode Response
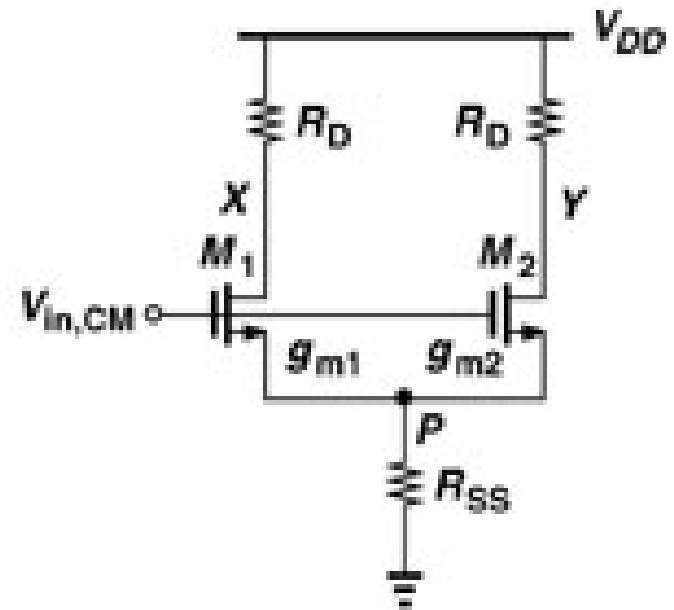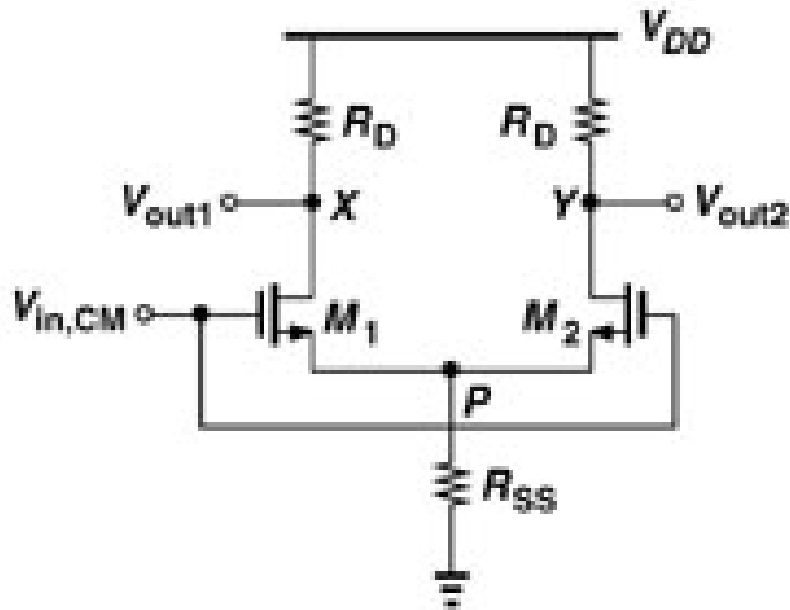
$$\frac{V_X - V_Y}{V_{in,CM}} = -\frac{g_{m1} - g_{m2}}{(g_{m1} + g_{m2})R_{SS} + 1}R_D$$

Common-Mode Response
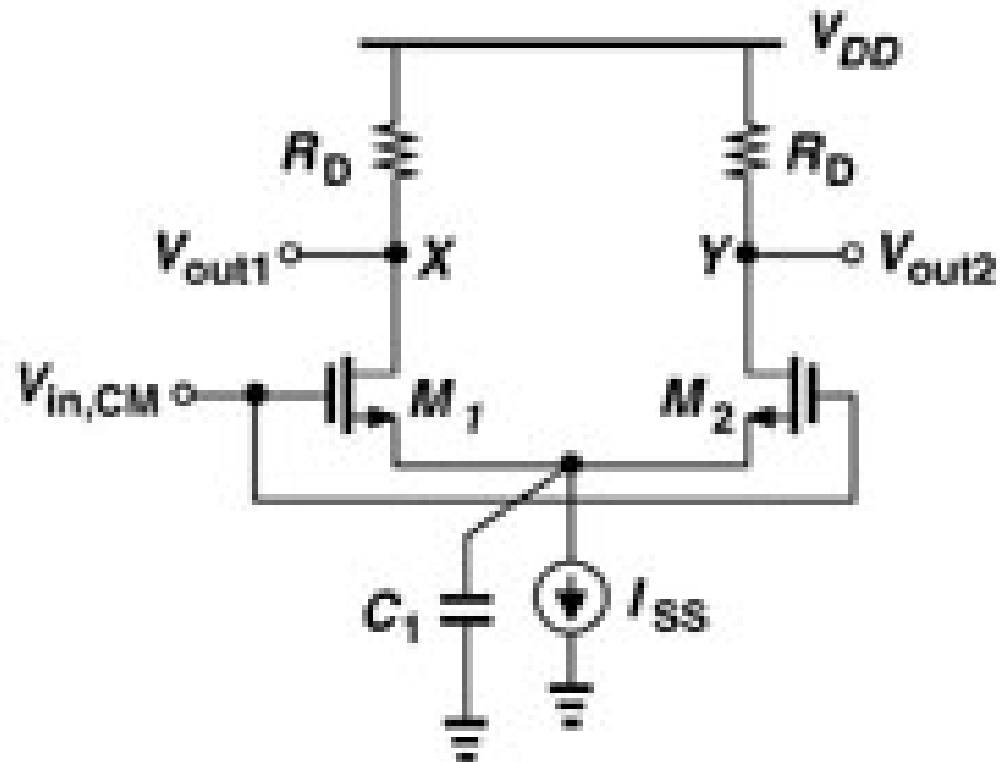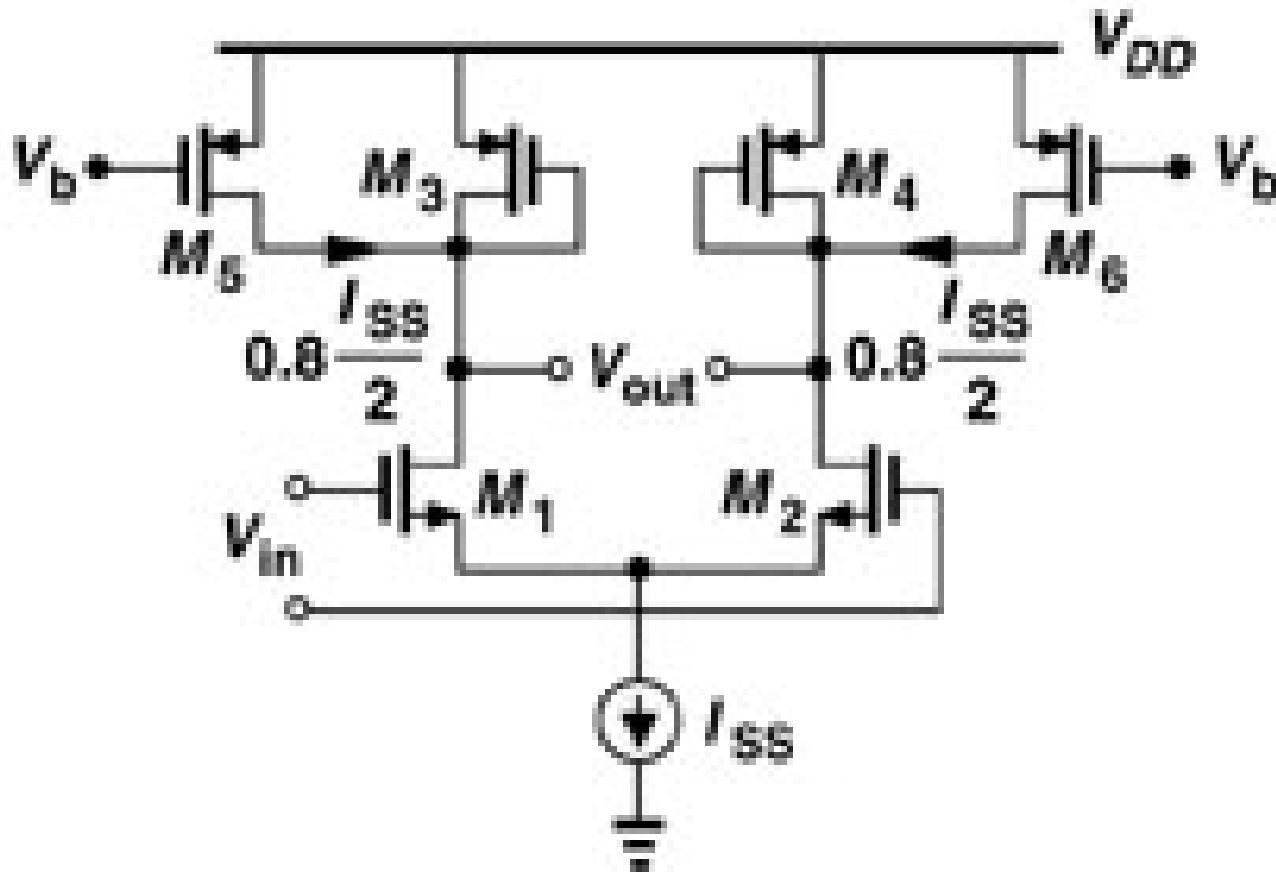
Differential Pair with MOS Loads

(b)
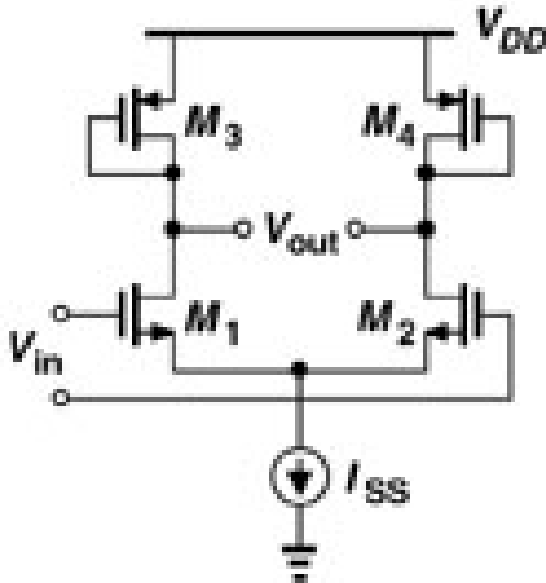
$$A_v = -g_{mN}(g_{mP}^{-1} \parallel r_{oN} \parallel r_{oP})$$

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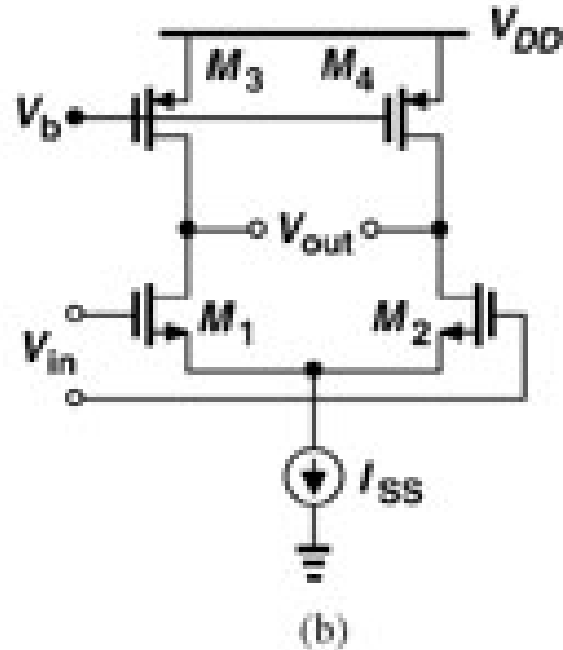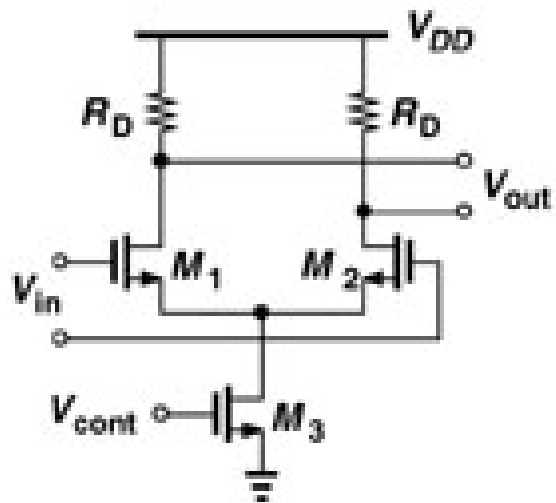
$$A_v = -g_{mN}(r_{oN} \parallel r_{oP})$$
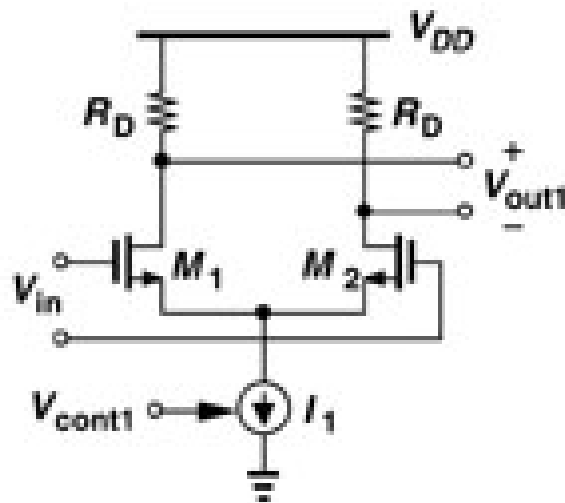
MOS Loads

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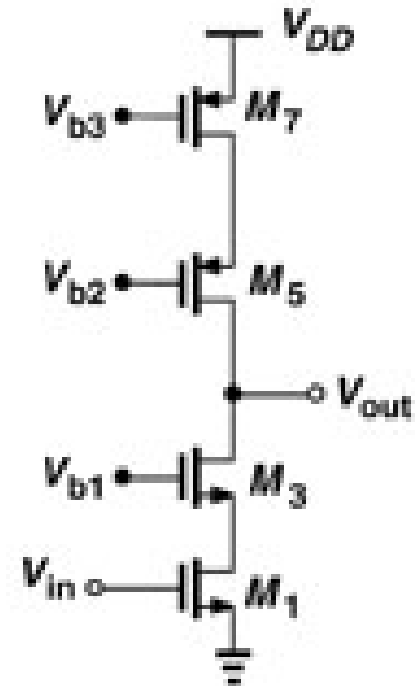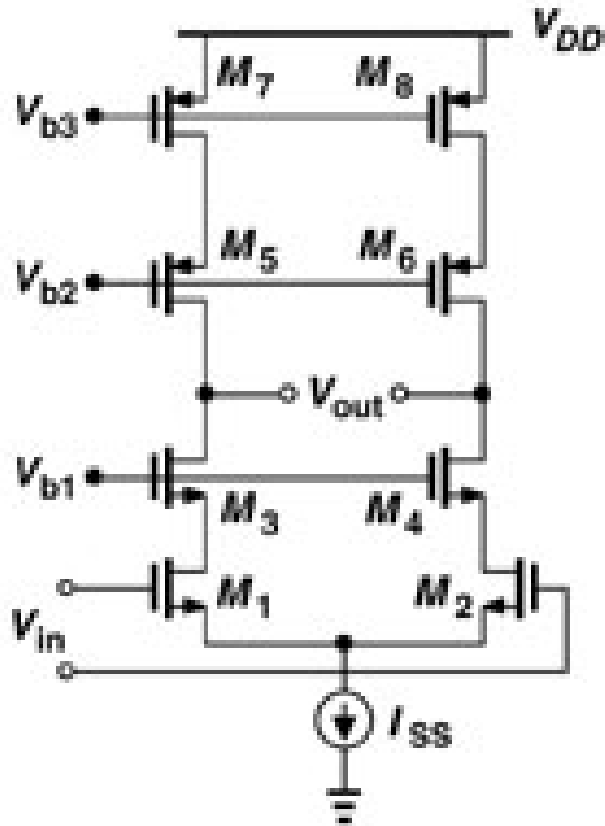
$$A_v \approx g_{m1}[(g_{m3}r_{o3}r_{o1}) \| (g_{m5}r_{o5}r_{o7})]$$

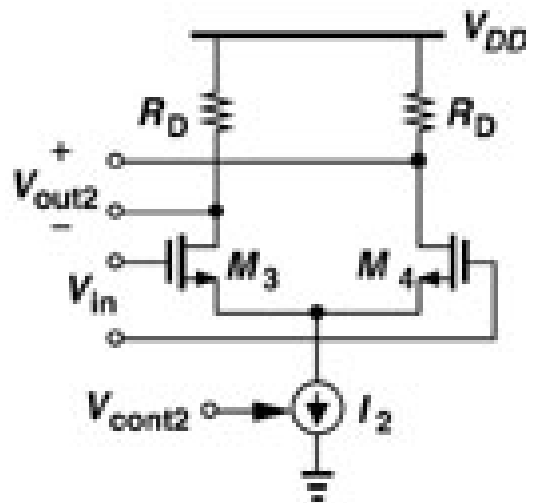ELEC401 Set 3 - Differential Amplifiers

Gilbert Cell

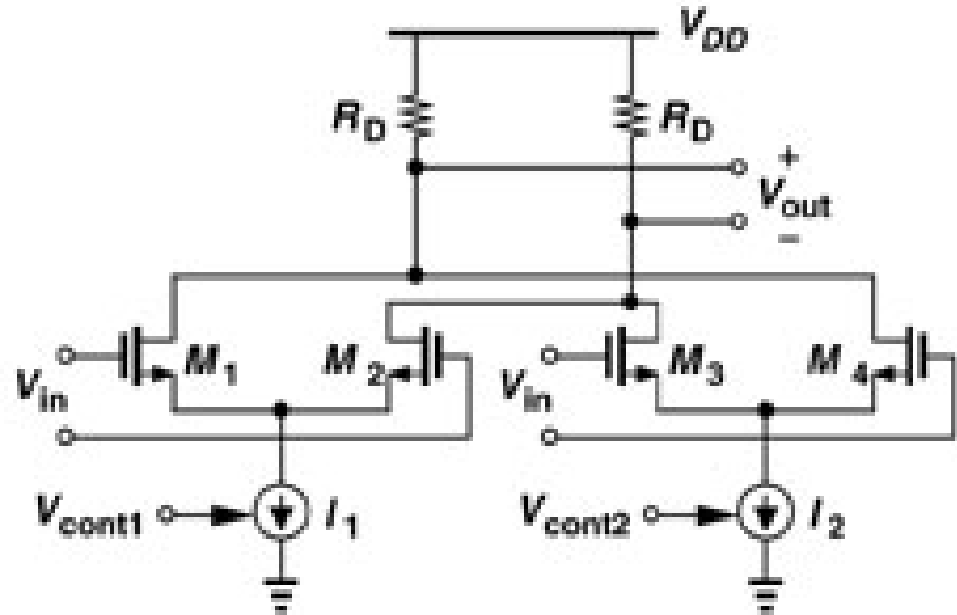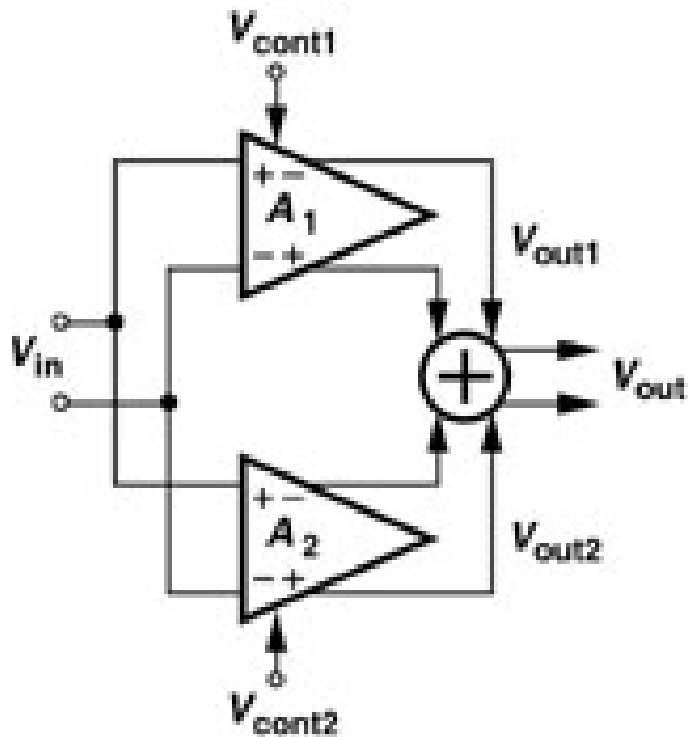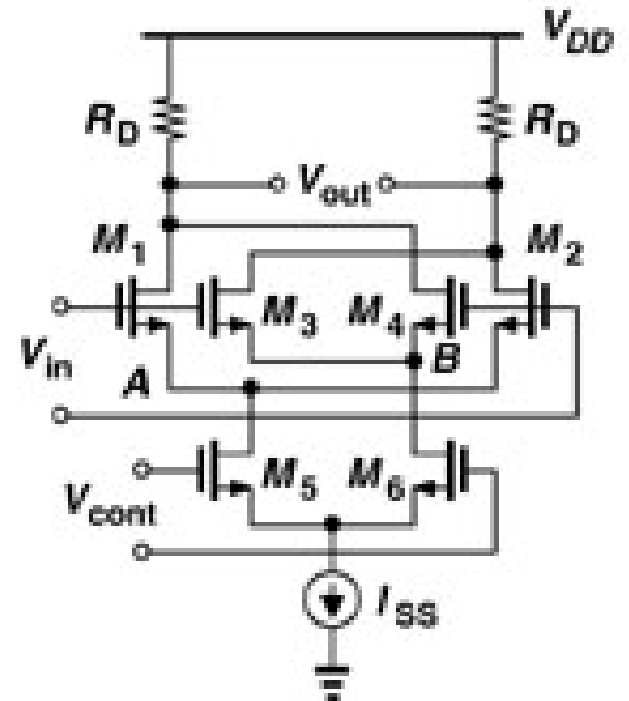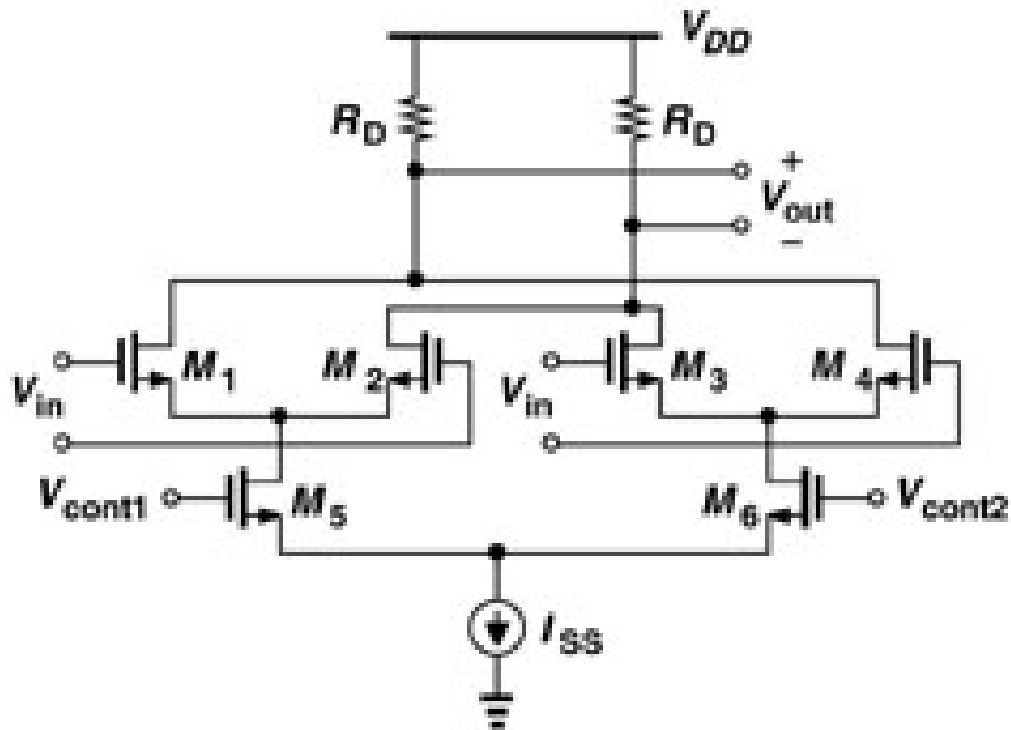(a)   (b)

Gilbert Cell

Gilbert Cell

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