EE105
Microelectronic Devices and Circuits
Module 4-5: Differential Amplifiers

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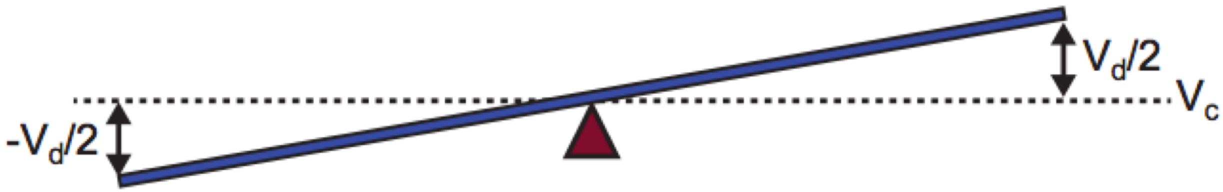
Differential & Common Mode Signals



- Consider positive and negative input terminal signals V_i^+ and V_i^-
- Define differential signal as: $V_{id} = V_{in}^+ - V_{in}^-$
- Define common mode signal as: $V_{ic} = (V_{in}^+ + V_{in}^-)/2$
- We can create arbitrary V_i^+ and V_i^- signals from differential and common mode components:

$$V_{in}^+ = V_{ic} + \frac{1}{2}V_{id} \qquad V_{in}^- = V_{ic} - \frac{1}{2}V_{id}$$

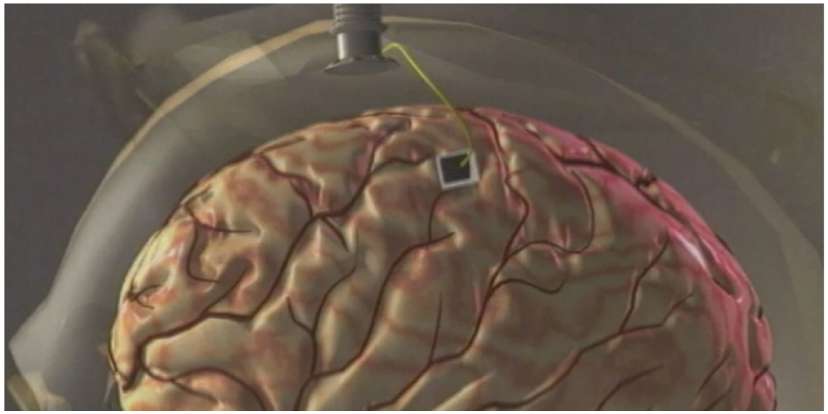
- This also applies to differential output signals:

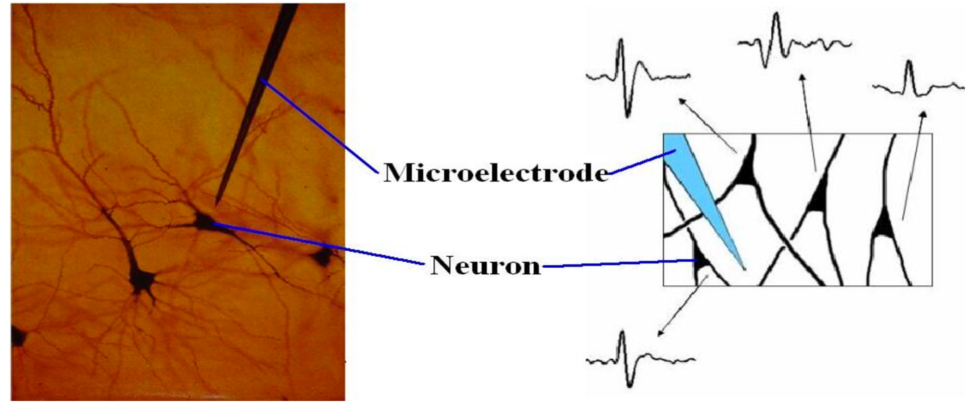
$$V_o^+ = V_{oc} + \frac{1}{2}V_{od} \qquad V_o^- = V_{oc} - \frac{1}{2}V_{od}$$

Why Differential?

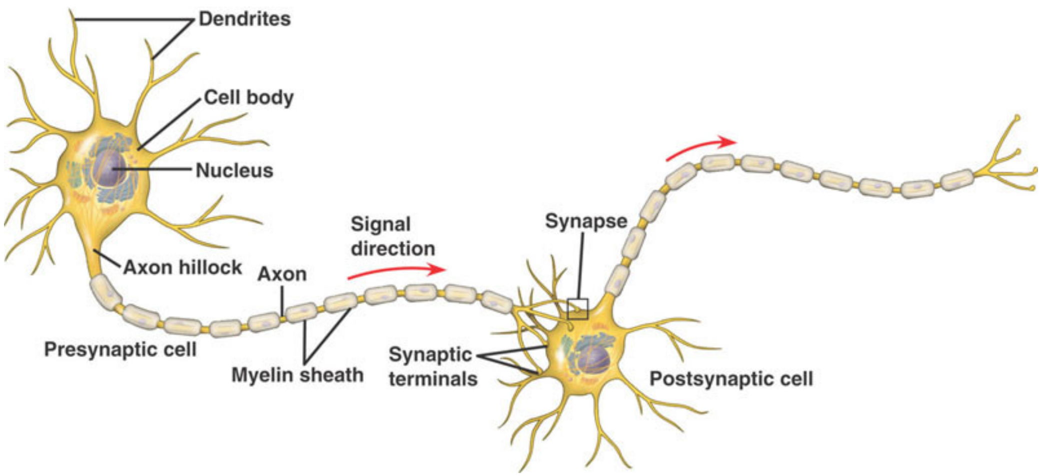
- Differential circuits are much less sensitive to noises and interferences
- Differential configuration enables us to bias amplifiers and connect multiple stages without using coupling or bypass capacitors
- Differential amplifiers are widely used in IC's
  - Excellent matching of transistors, which is critical for differential circuits
  - Differential circuits require more transistors → not an issue for IC

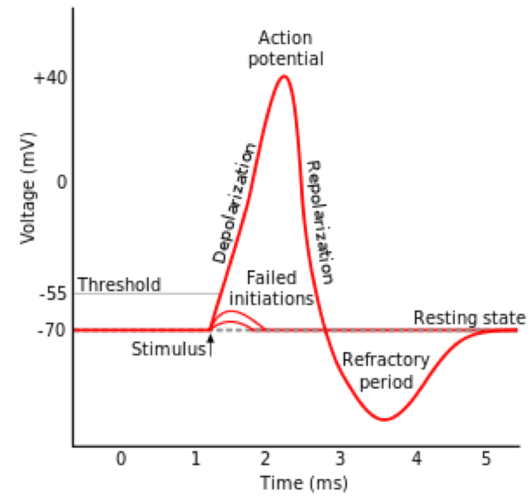
Neural Recording





An array of electrodes is implanted in the motor cortex and senses extracellular signals that include firing from nearby neurons

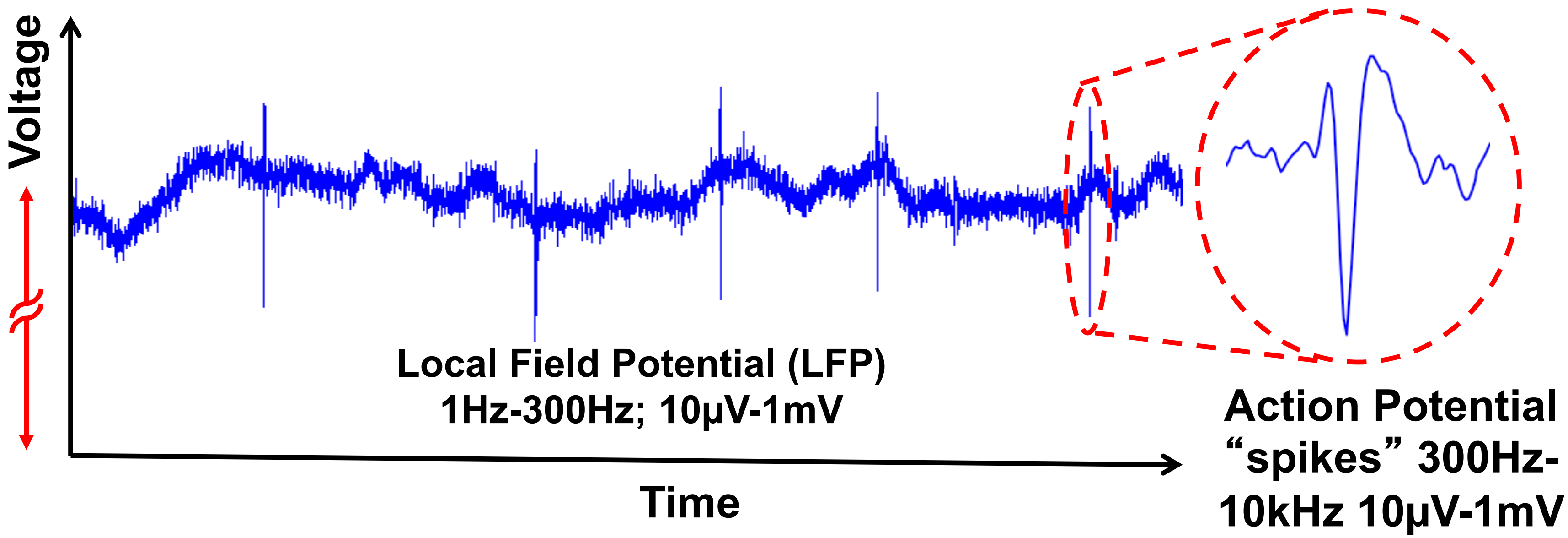




The propagation of signals from neuron to neuron is called an Action Potential, which is analogous to a digital "pulse"

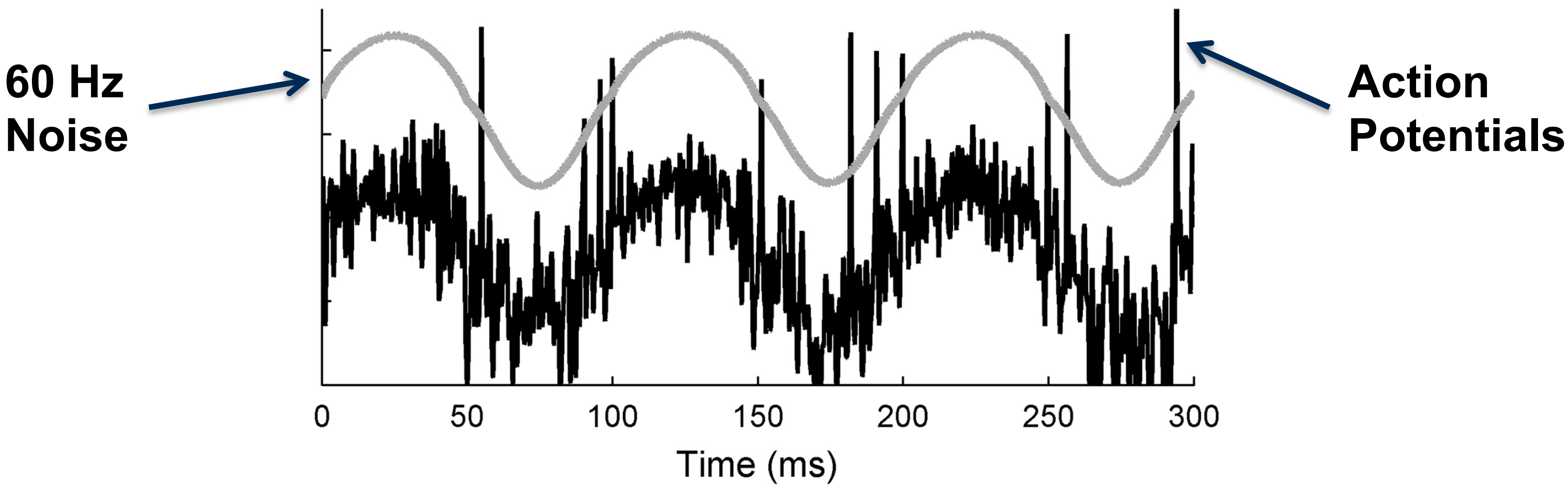
BSAC

Extracellular Neuronal Signals



- The goal of a neural recording device is to record the small-amplitude neural signals and pick out the meaningful signals from the “noise”.
- These signals are then decoded to create trajectories, movements, and speeds for controlling prostheses, computers, etc.

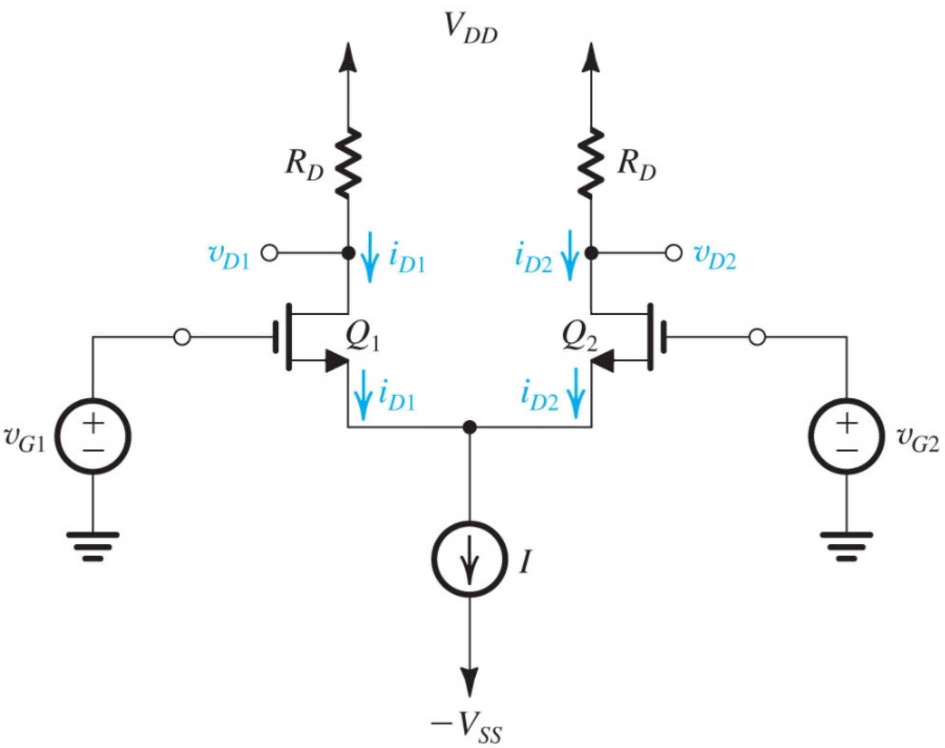
60Hz and Other Interferers



- In reality, the tiny signals recorded from the brain can get corrupted by numerous interferers.
- Ambient 60Hz noise couples into electrical signals in and on the body
- Motion can cause voltage artifacts from the movement of the electrodes relative to the neurons

MOS Differential-Pair

Basic Configuration



Two matched MOS transistors

Common current bias

"Differential signls" applied to v_{G1} and v_{G2}

(equal amplitude but opposite sign)

"Differential outputs" are produced

at v_{D1} and v_{D2}

Note in differential configuration,

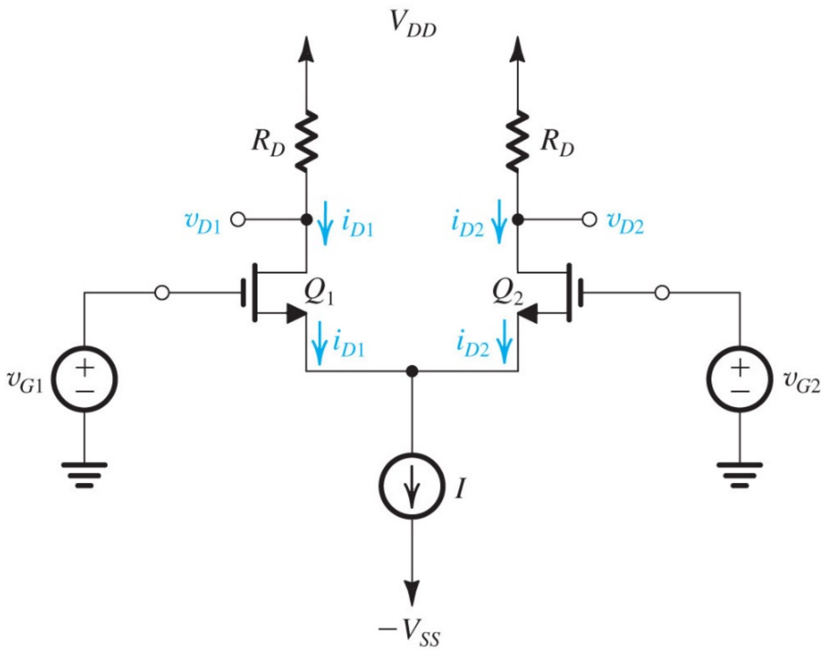
V_{GS} is fixed for both Q_1 and Q_2

$$I_{D1} = I_{D2} = \frac{I}{2}$$

$$\frac{I}{2} = \frac{k_n}{2}\left(V_{GS} - V_{tn}\right)^2$$

$$V_{GS} = V_{tn} + \sqrt{\frac{I}{k_n}}$$

Large Signal Behavior of Diff Mode Operation



$$v_{id} = v_{in+} - v_{in-} = \left(V_{Tn} + \sqrt{\frac{I_1}{k_n}}\right) - \left(V_{Tn} + \sqrt{\frac{I_2}{k_n}}\right)$$

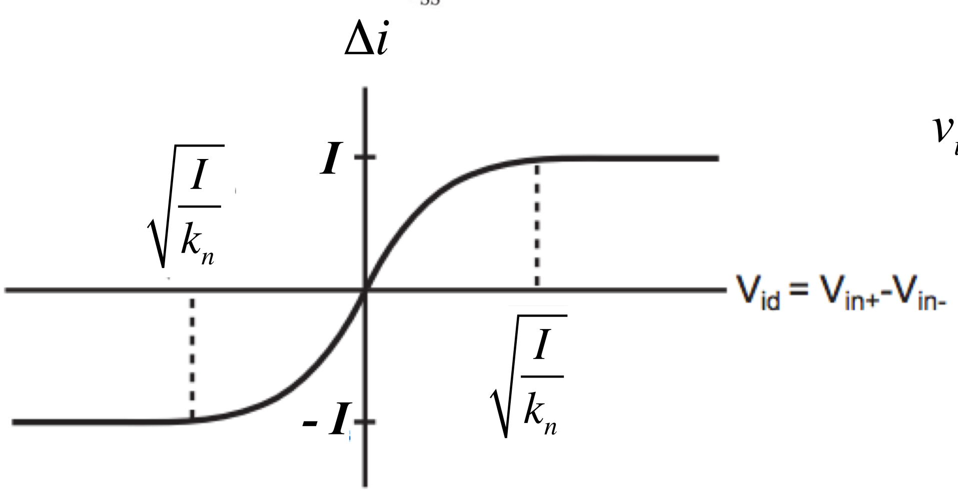
$$v_{id} = \sqrt{\frac{I_1}{k_n}} - \sqrt{\frac{I_2}{k_n}} = \sqrt{\frac{I + \Delta i/2}{k_n}} - \sqrt{\frac{I_2 - \Delta i/2}{k_n}}$$

$$\Delta i = i_{D1} - i_{D2}$$

solve

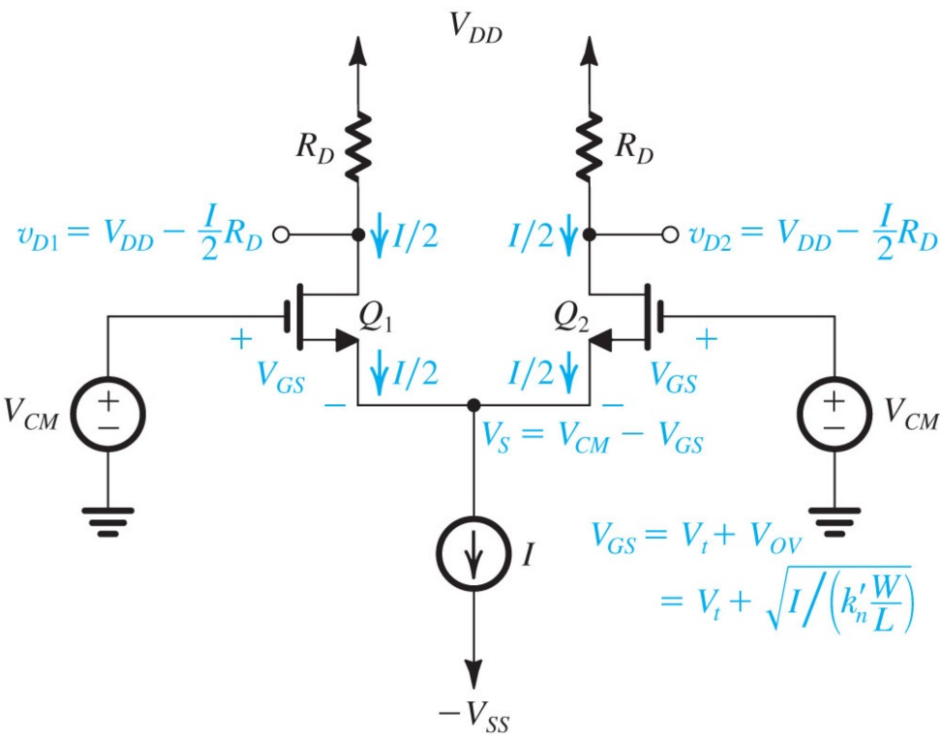
$$\Delta i = k_n v_{id}\sqrt{\frac{2I}{k_n} - v_{id}^2}$$

$$v_{id} \leq \sqrt{\frac{I}{k_n}}$$



Common Mode Rejection

Differential Pair
Rejects Common-Mode Inputs



The common voltages applied to both Q_1 and Q_2 are referred to as common mode, V_{CM}.

Common mode inputs usually come from noises or interferences.

Differential pair should reject V_{CM} :

Since $V_{GS1} = V_{GS2} = V_{tn} + \sqrt{\frac{I}{k_n}}$

is fixed in differential pair,

V_{CM} simply changes the voltage at Source, V_S.

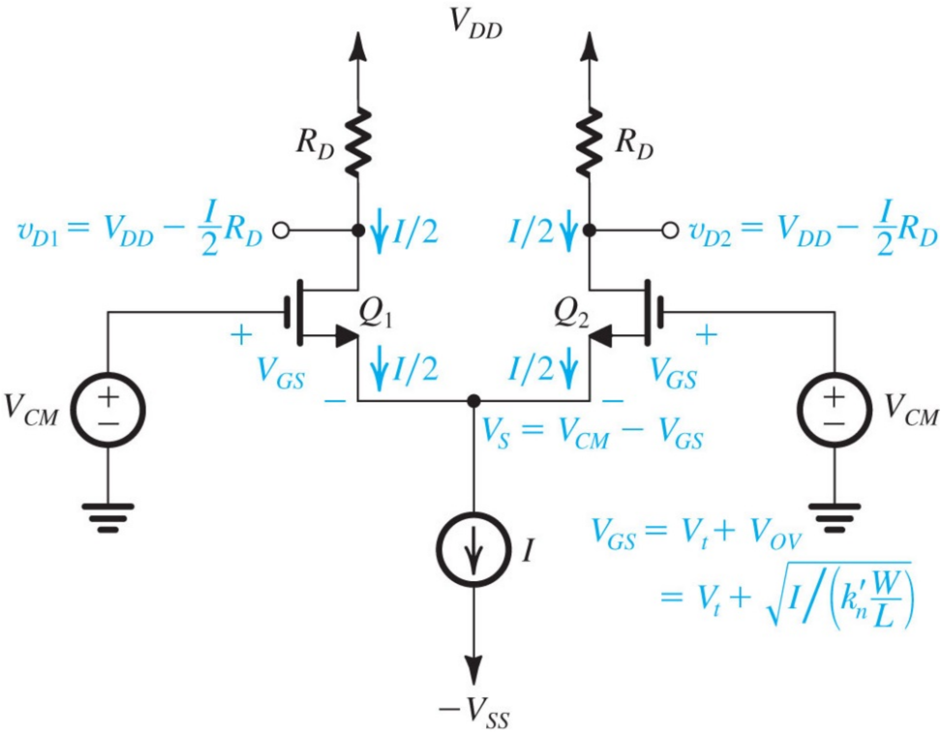
The drain currents remain fixed:

$$I_1 = I_2 = \frac{I}{2}$$

$$v_{D1} = V_{DD} - \frac{I}{2}R_D = v_{D2}$$

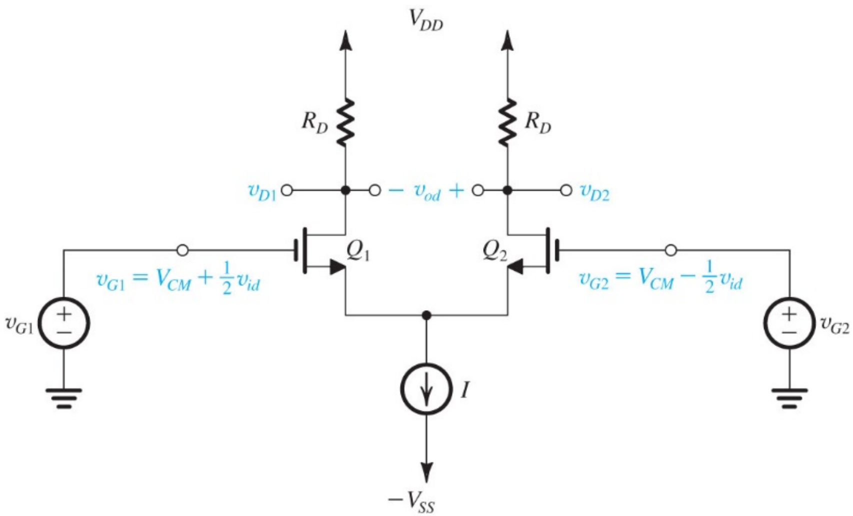
Differential output $v_{D1} - v_{D2} = 0$

Common Mode Input Range

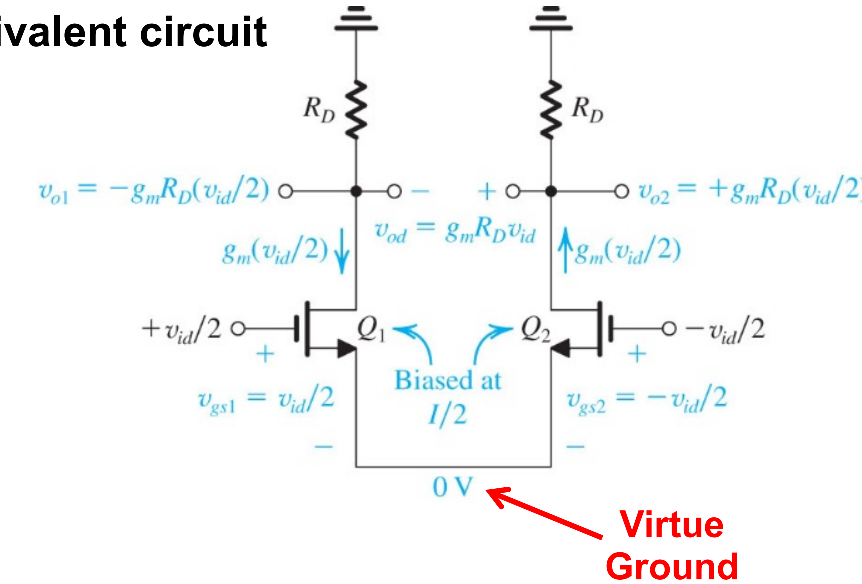


What is the maximum and minimum common-mode input voltage?

Small Signal Operation



AC equivalent circuit

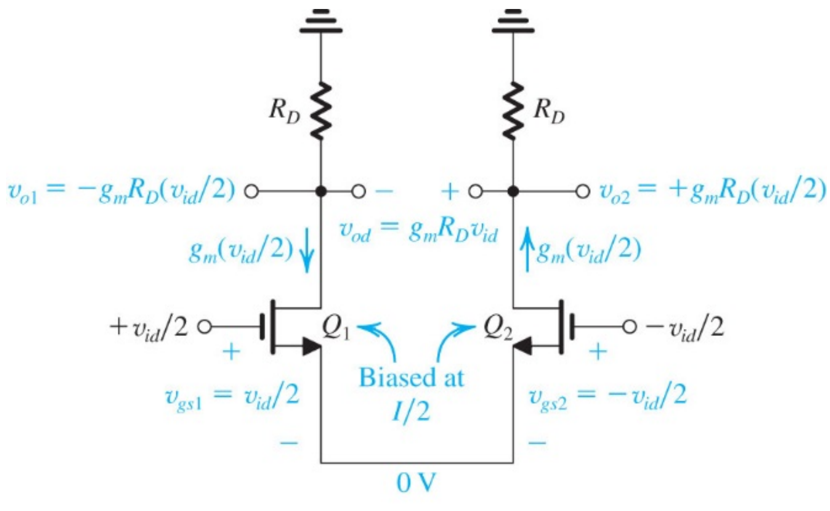


$$v_{G1} = V_{CM} + \frac{1}{2} v_{id}; \quad v_{G2} = V_{CM} - \frac{1}{2} v_{id}$$

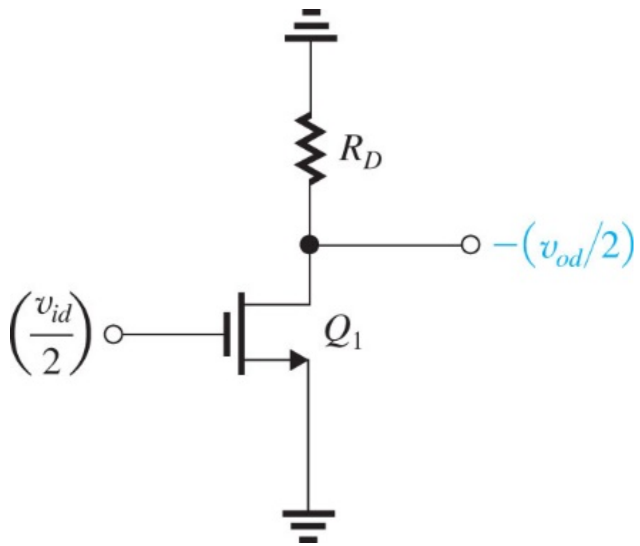
For differential AC small signal, the differential pair is "anti-symmetric". The potential at the mid point (Source) is zero. This is called "Virtual Ground"

This virtual ground is obtained without using a large bypass capacitor
→ much smaller area and better frequency response

Differential "Half Circuit"



(b)

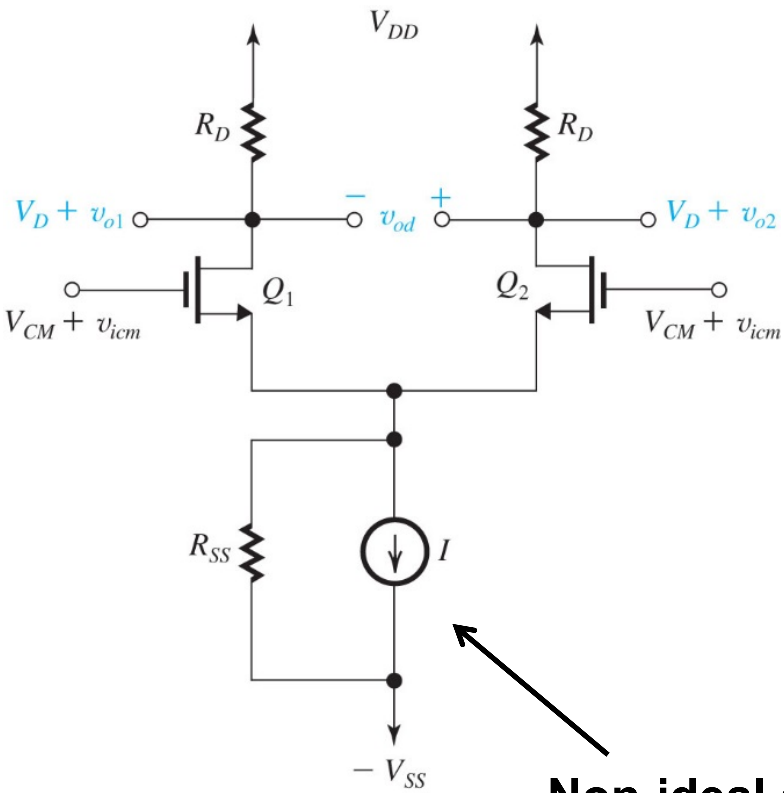


Because the two halves of the circuits are anti-symmetric, and Source is at virtual ground, we can simplifed and just analyze the "half circuit"

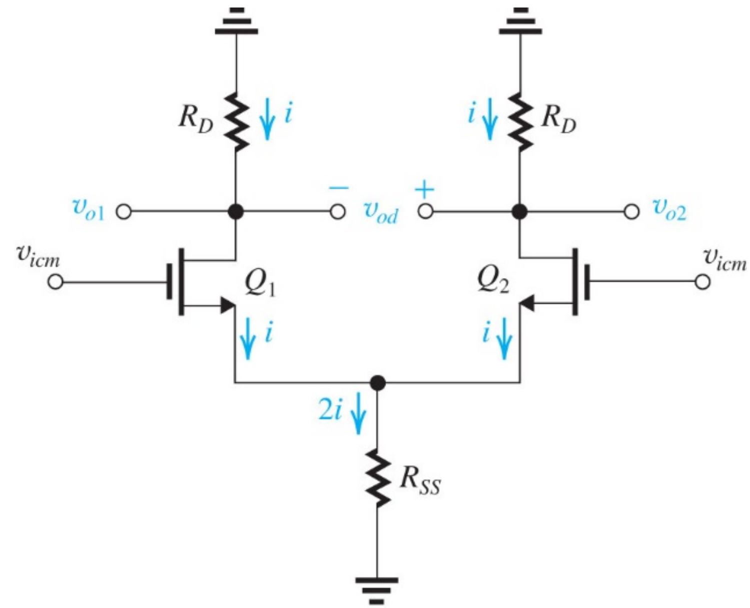
Q_1 biased at $\frac{I}{2}$

$$A_d = \frac{\frac{v_{od}}{2}}{\frac{v_{id}}{2}} = \frac{v_{od}}{v_{id}} = g_m \left(R_D \parallel r_o \right)$$

AC Equivalent Circuit for Common Mode Input



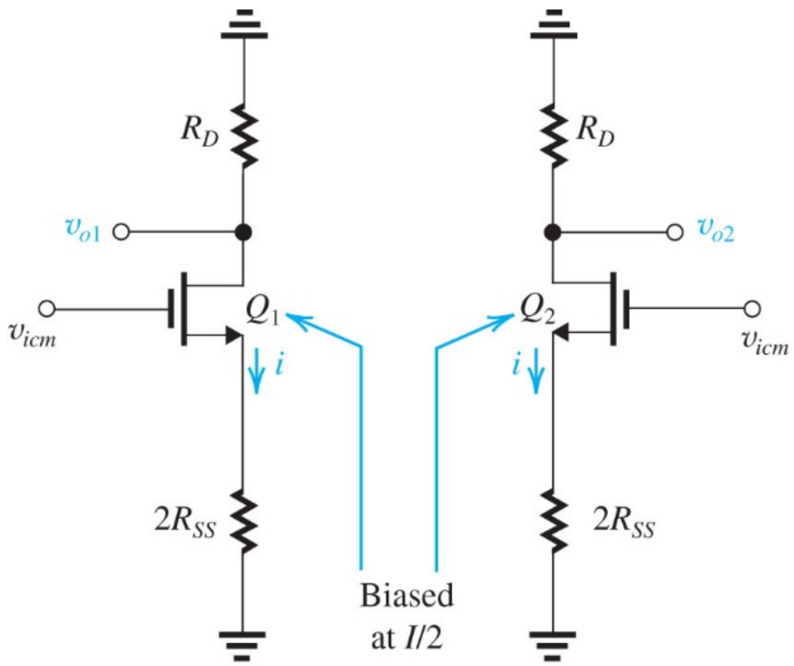
(a)



(b)

Non-ideal current source consists of an ideal current source shunted by a large resistance, R_{SS}

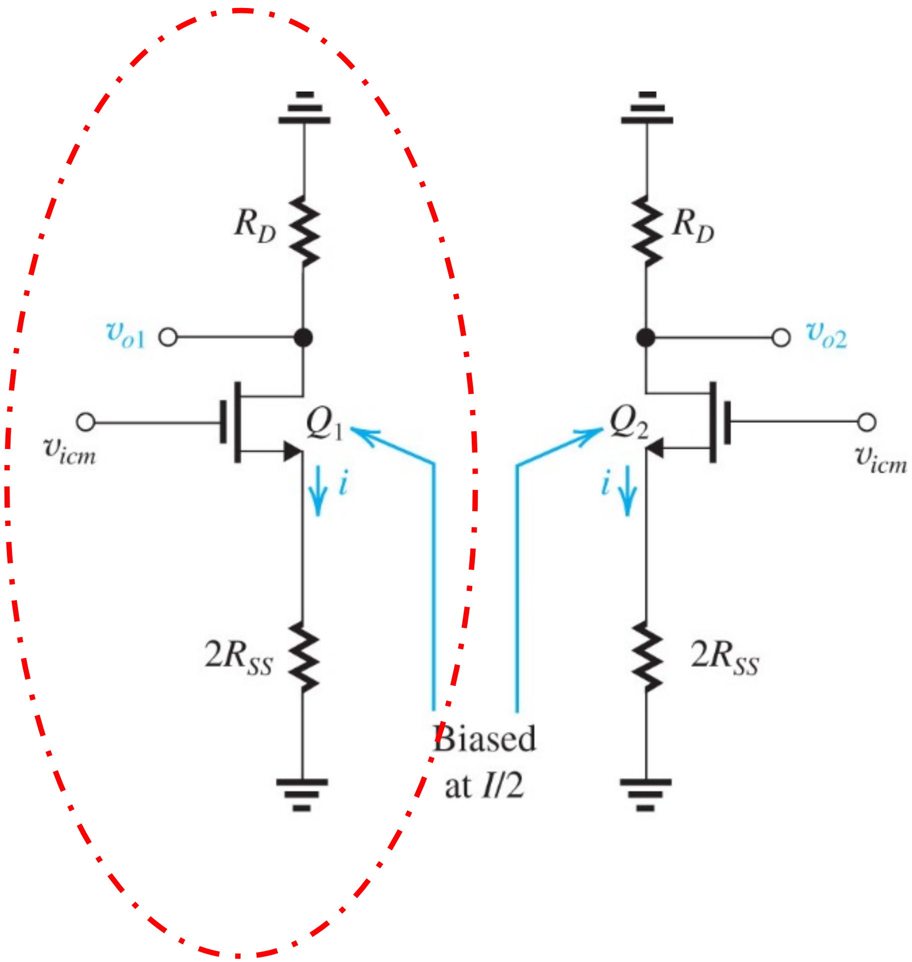
Common Mode "Half Circuit"



- **For common-mode inputs, the two half circuits are symmetric. The Source is not virtual ground any more.**

- **R_{SS} can be considered as two parallel combination of $2R_{SS}$.**
- **Each CM half circuit has $2R_{SS}$ connected to the source**

Ideal CM Output Voltage



Common-Source with degeneration

The common-mode half-circuit is basically a common-source amplifier with source degeneration.

The gain is

$$\frac{v_{o1}}{v_{icm}} = \frac{v_{o2}}{v_{icm}} = \frac{-R_D}{1/g_m + 2R_{SS}}$$

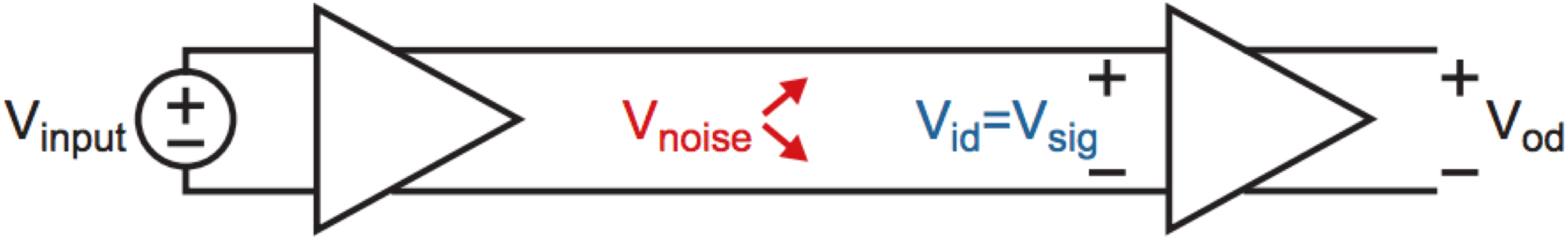
Since $2R_{SS} >> 1/g_m$,

$$\frac{v_{o1}}{v_{icm}} = \frac{v_{o2}}{v_{icm}} \approx \frac{-R_D}{2R_{SS}}$$

$$v_{od} = v_{o2} - v_{o1} = 0$$

Output voltage is zero for ideal differential pair with perfectly matched transistors and resistors, and the CM voltage is small enough that Q_1 and Q_2 remains in Saturation

Useful Metric for Diff Amps: CMRR



- **Common Mode Rejection Ratio (CMRR)**
  - **Define: a_{vd}: differential gain, a_{vc}: common mode gain**

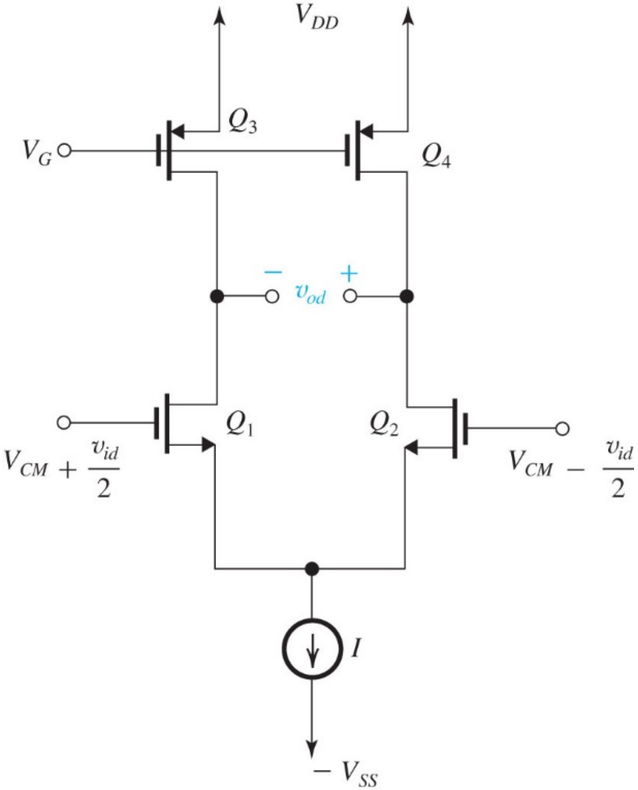
$$\mathrm{CMRR} = \left(\frac{a_{vd}}{a_{vc}}\right)$$

  - **CMRR corresponds to ratio of differential to common mode gain and is related to received signal-to-noise ratio**

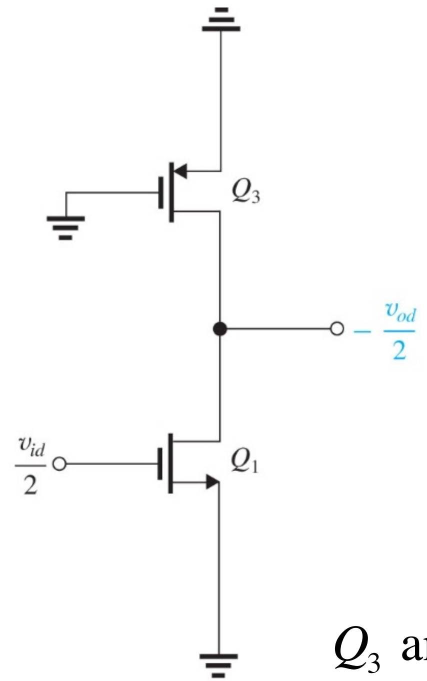
$$V_{od} = a_{vd} V_{sig} + a_{vc} V_{noise}$$

$$\Rightarrow \frac{Signal}{Noise} = \left(\frac{a_{vd}}{a_{vc}}\right)\left(\frac{V_{sig}}{V_{noise}}\right) = \mathrm{CMRR}\left(\frac{V_{sig}}{V_{noise}}\right)$$

Differential Amplifier with Current-Source Loads



(a)



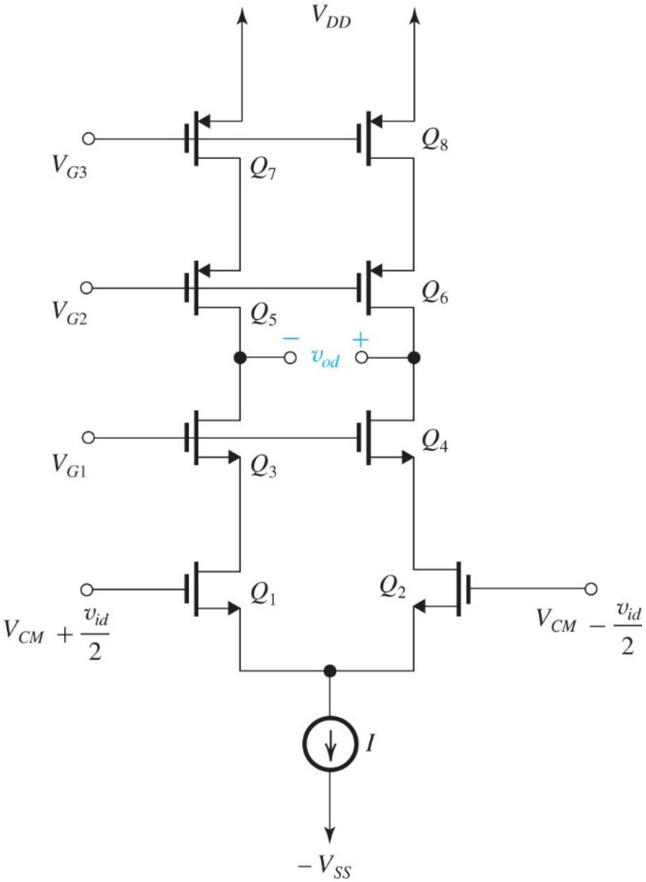
(b)

Q_3 and Q_4 are PMOS current sources (active loads)

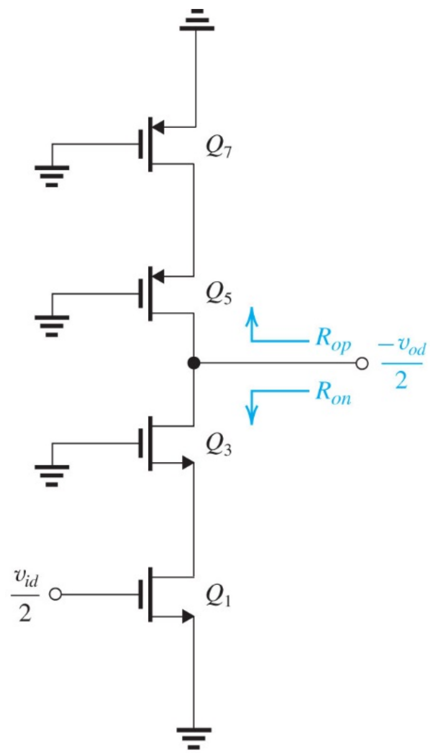
From half-circuit

$$A_d = \frac{v_{od}}{v_{id}} = g_{m1}\left(r_{o1} \parallel r_{o3}\right)$$

Cascode Differential Amplifier



(a)



(b)

Cascode configurations for both amplifying transistors and current source loads.

From half-circuit

$$A_d = \frac{v_{od}}{v_{id}} = g_{m1}\left(R_{on} \parallel R_{op}\right)$$

$$R_{on} = \left(g_{m3} r_{o3}\right) r_{o1}$$

$$R_{op} = \left(g_{m5} r_{o5}\right) r_{o7}$$

If all transistors are identical,

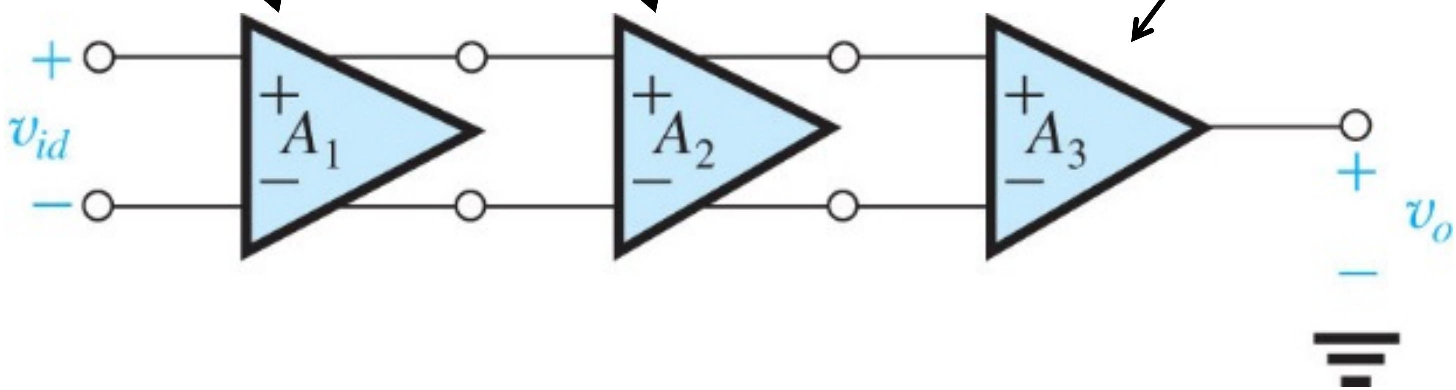
$$R_{on} = R_{op} = g_m r_o^2$$

$$A_d = \frac{1}{2} g_m^2 r_o^2$$

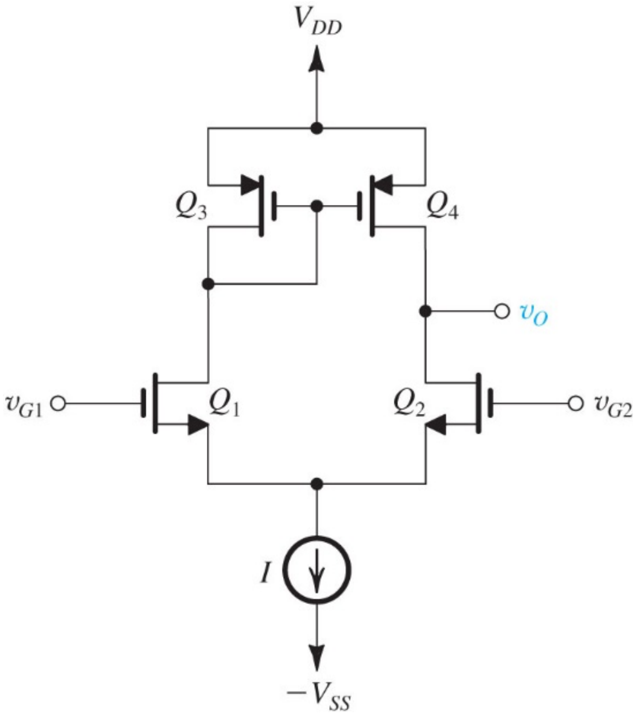
Differential Input, Single-End Output

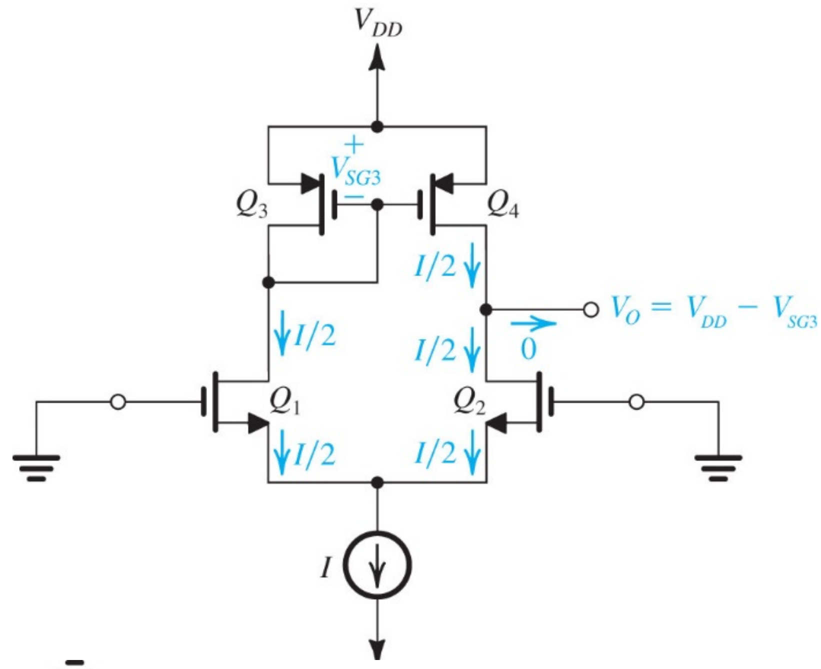
Differential-in, Differential-out

Differential input, Single-ended Output

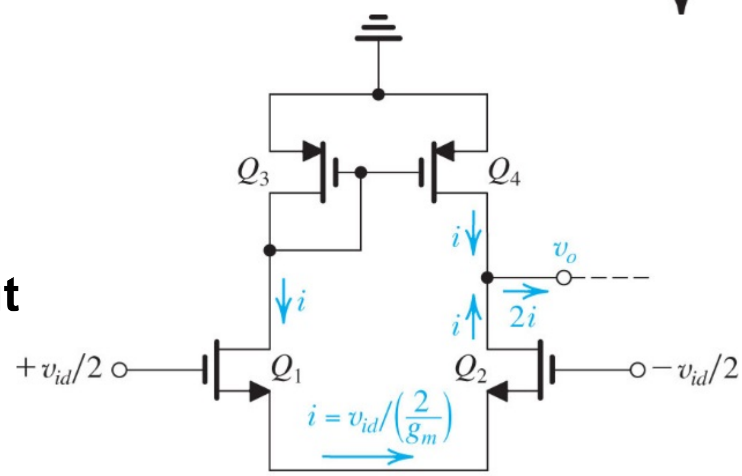


MOS Differential Pair with Current Mirror Load





AC equivalent circuit for differential input



Current mirror forces small-signal currents through Q_3 and Q_4 to be the same

→ output currents = 2x that of half circuit