Spring 2019 Purdue University

ECE 255: L28

MOS Differential Pair

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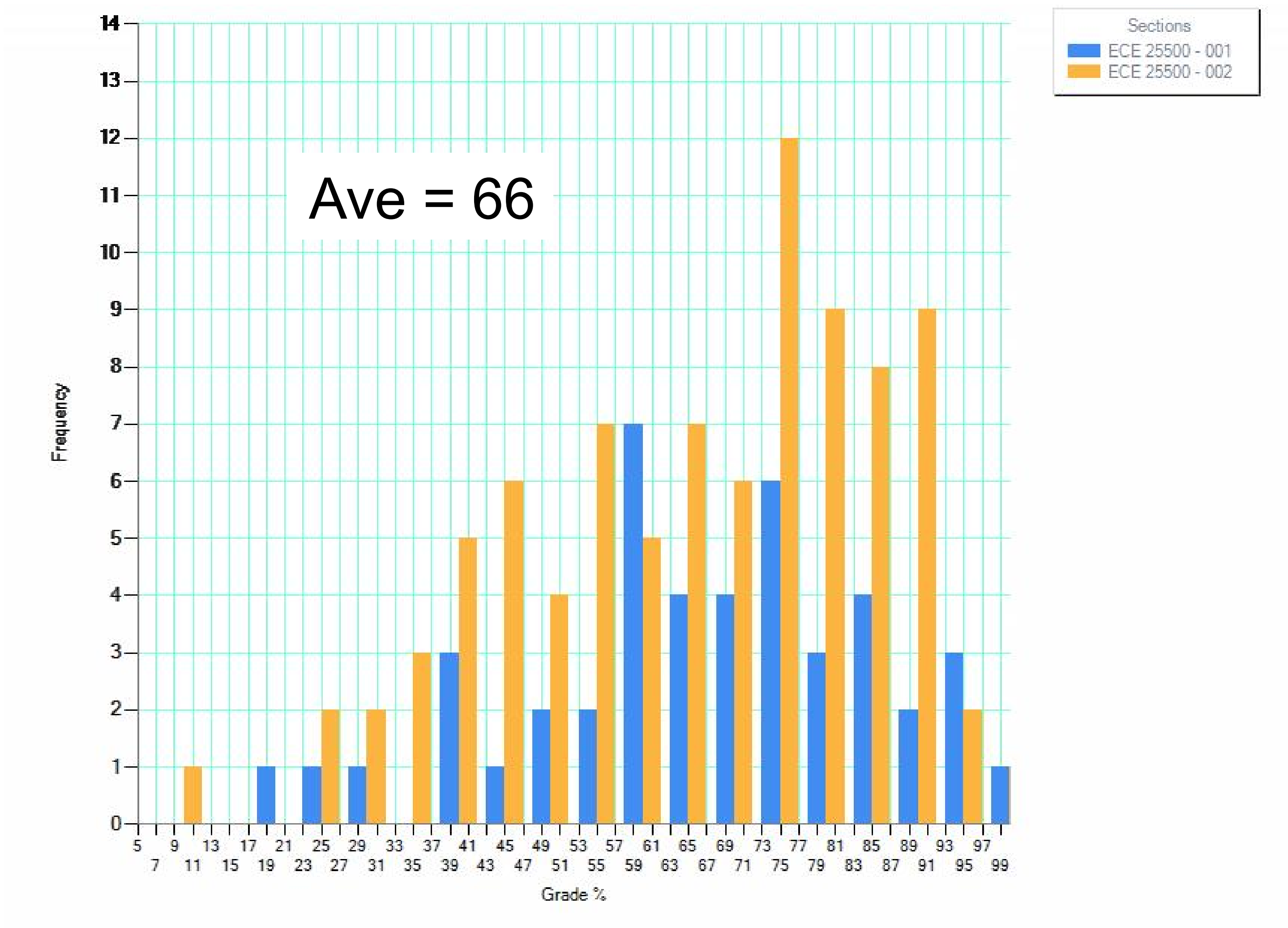
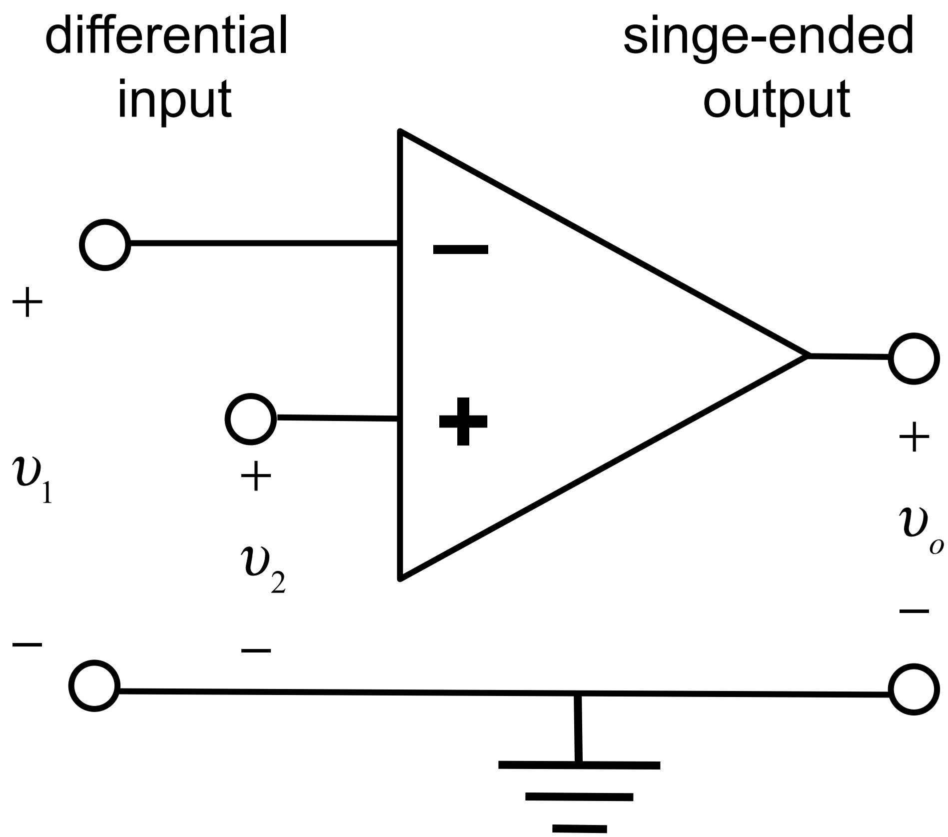
Announcements



Outline

1) Quick Op Amp Review
2) MOS differential pair
3) Large signal: common mode
4) Large signal: differential mode
5) Small signal

OP Amp fundamentals



If:

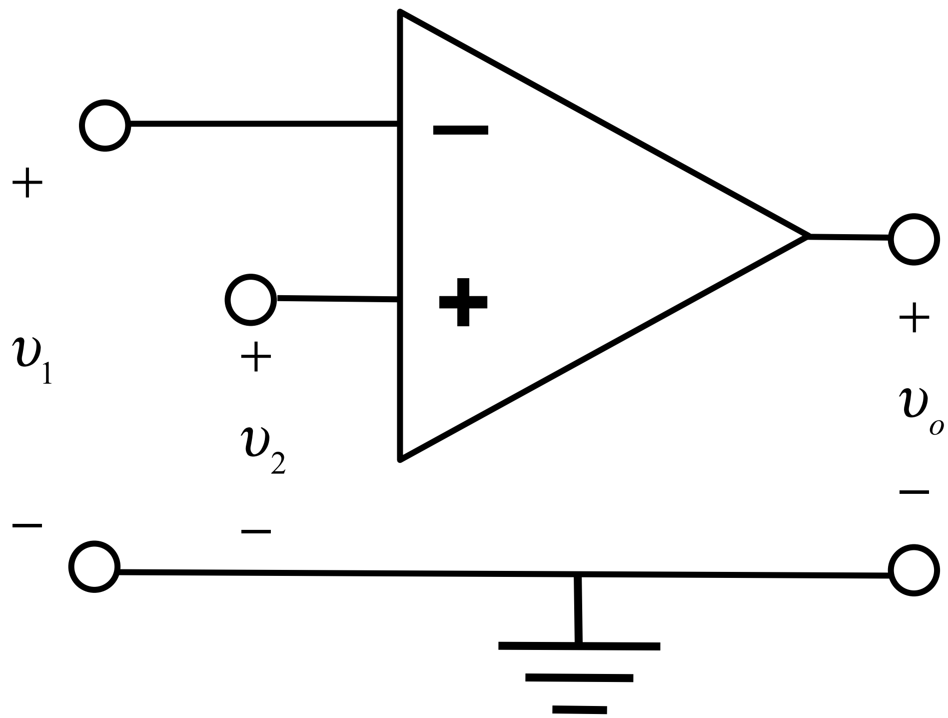
$$v_1 = v_2 = v_{ic}$$

Then

$$v_o = A_{cm} v_{ic}$$

"Common mode gain"

OP Amp fundamentals



If:

$$v_1 = -\frac{v_{id}}{2}$$

$$v_2 = +\frac{v_{id}}{2}$$

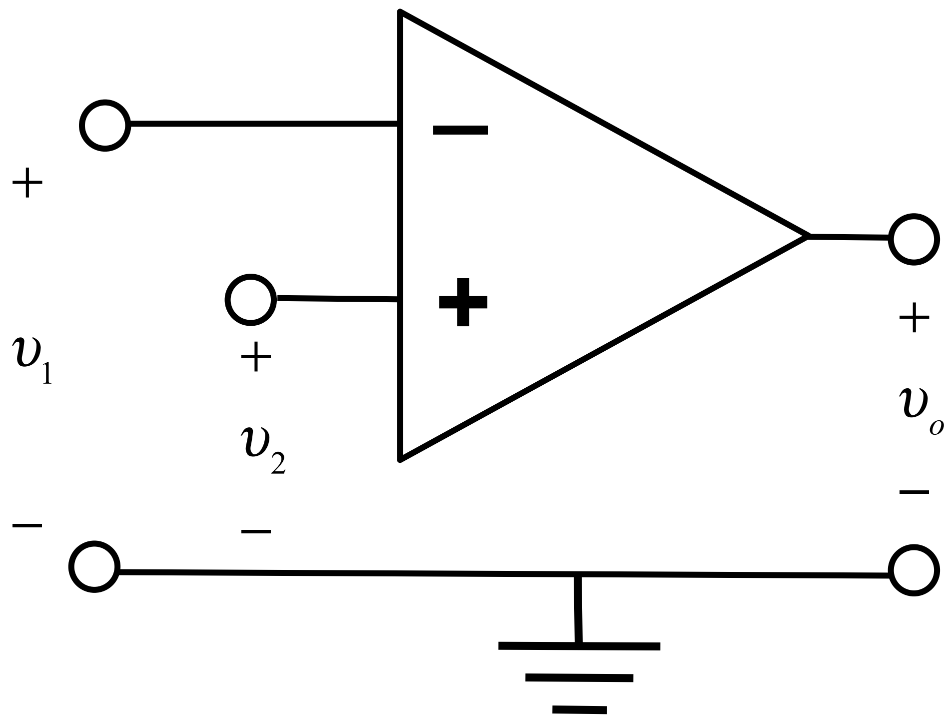
$$v_{id} = v_2 - v_1$$

Then

$$v_o = A_{dm} v_{id}$$

"Differential mode gain"

Common Mode Rejection Ratio



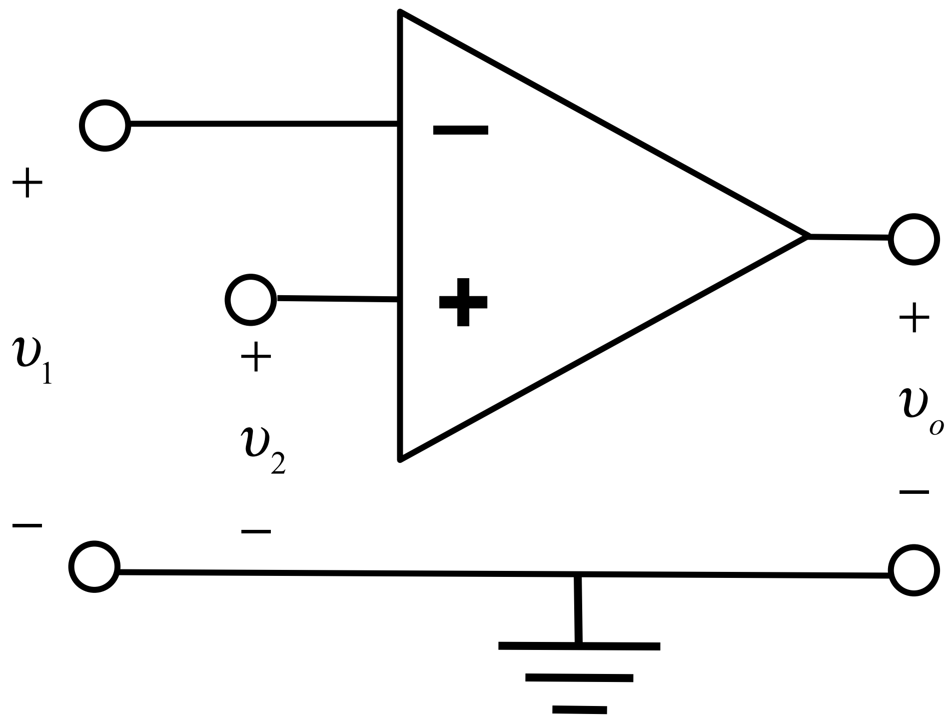
$$\upsilon_{id} = \upsilon_2 - \upsilon_1 \qquad \upsilon_{ic} = (\upsilon_1 + \upsilon_2)/2$$

$$A_{dm} = \frac{\upsilon_o}{\upsilon_{id}}$$

$$A_{cm} = \frac{\upsilon_o}{\upsilon_{ic}}$$

$$CMRR = \frac{A_{dm}}{A_{cm}}$$

Ideal Op Amp



$$A_{dm} = \frac{v_o}{v_{id}} \to \infty$$

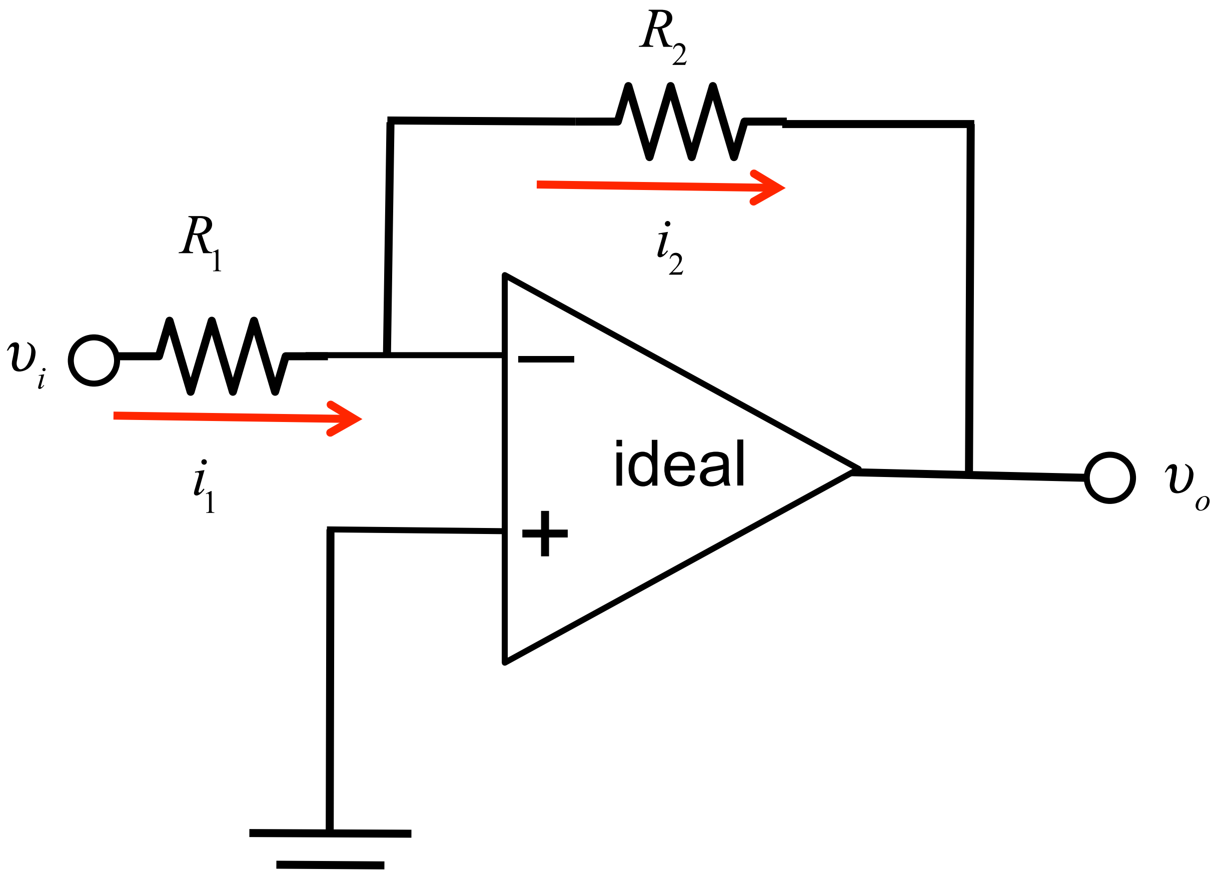
$$A_{cm} = \frac{v_o}{v_{ic}} \to 0$$

$$CMRR = \frac{A_{dm}}{A_{cm}} \to \infty$$

$$R_{in} \to \infty$$

$$R_o \to 0$$

Basic inverting amplifier



$$i_1 = \frac{\upsilon_i - 0}{R_1} = \frac{\upsilon_i}{R_1}$$

(virtual ground)

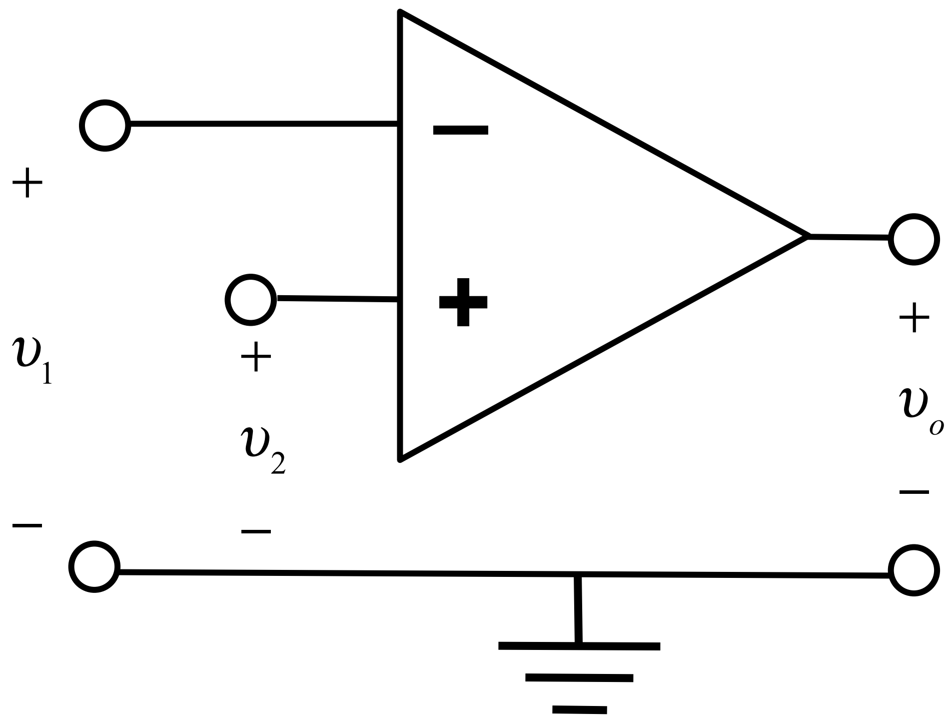
$$i_2 = i_1$$

(inf. Input R)

$$\upsilon_o = -i_2 R_2 = -\frac{R_2}{R_1}\upsilon_i$$

$$A_\upsilon = -\frac{R_2}{R_1}$$

Practical Op Amp



See Sec. 2.1-2.5 of S&S

A_{dm} very large

A_{cm} very small

$CMRR$ very large

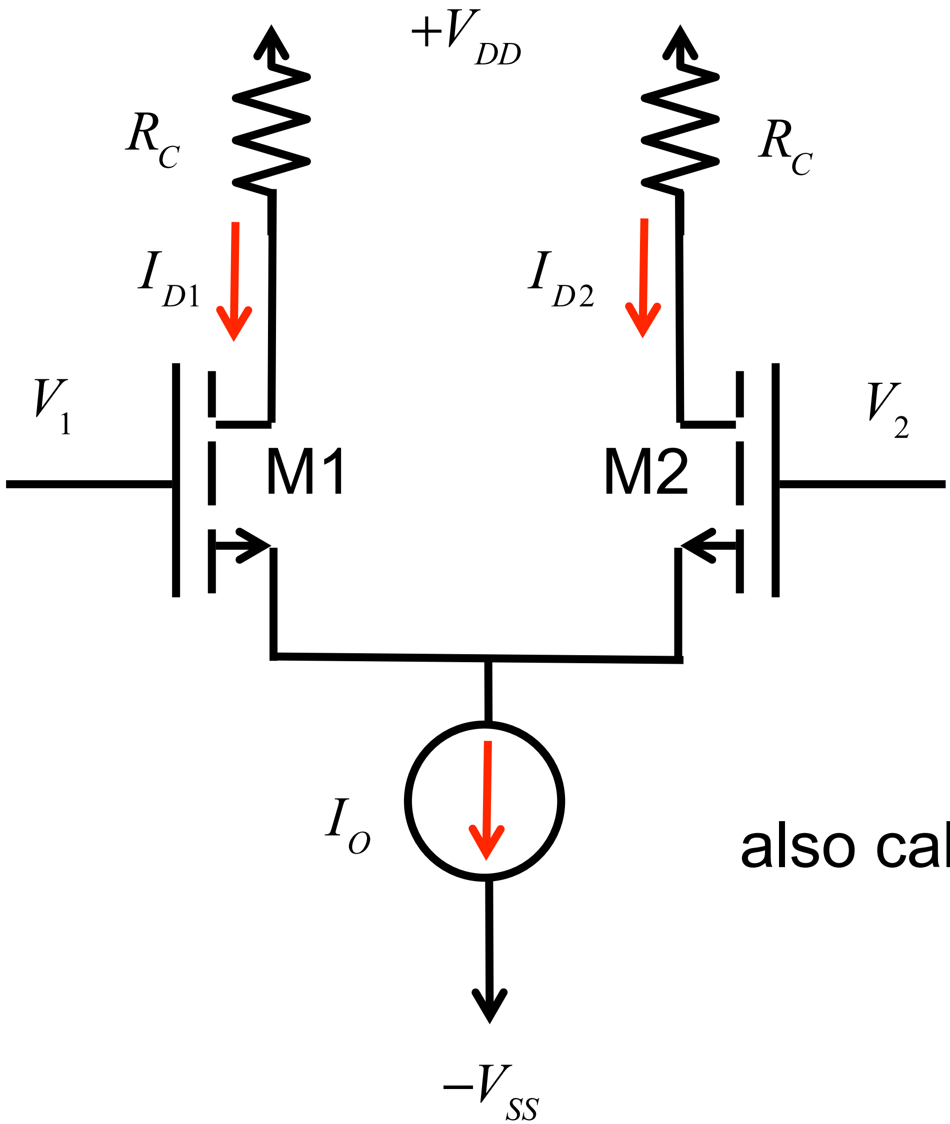
R_{in} very large

R_o very small

Outline

1) Quick Op Amp Review
2) **MOS differential pair**
3) Large signal: common mode
4) Large signal: differential mode
5) Small signal

Basic circuit: source coupled pair



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

also called a “differential pair”

Outline

1) Quick Op Amp Review
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3) **Large signal: common mode**
4) Large signal: differential mode
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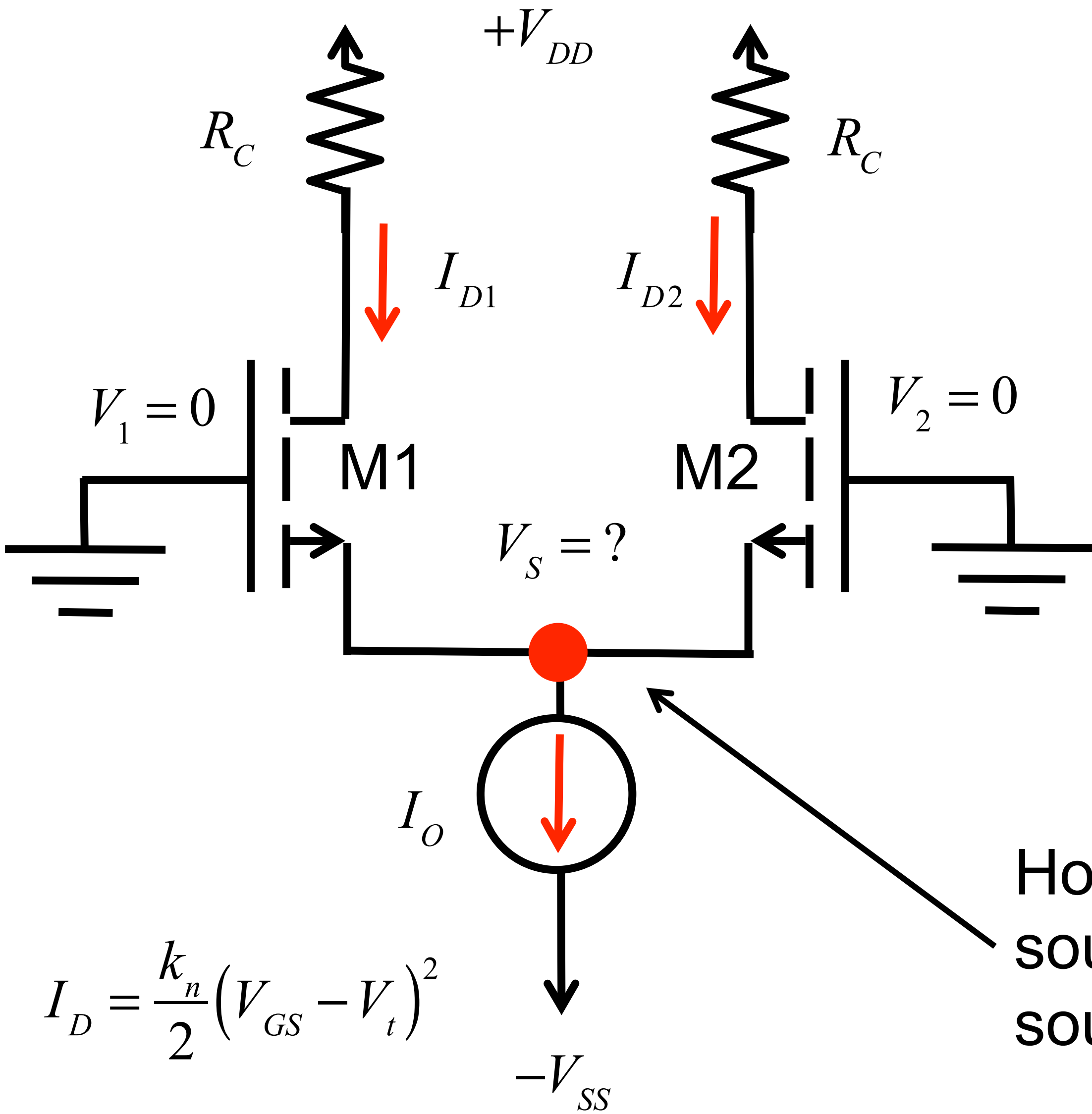
1) Starting point: $V_1 = V_2 = 0$



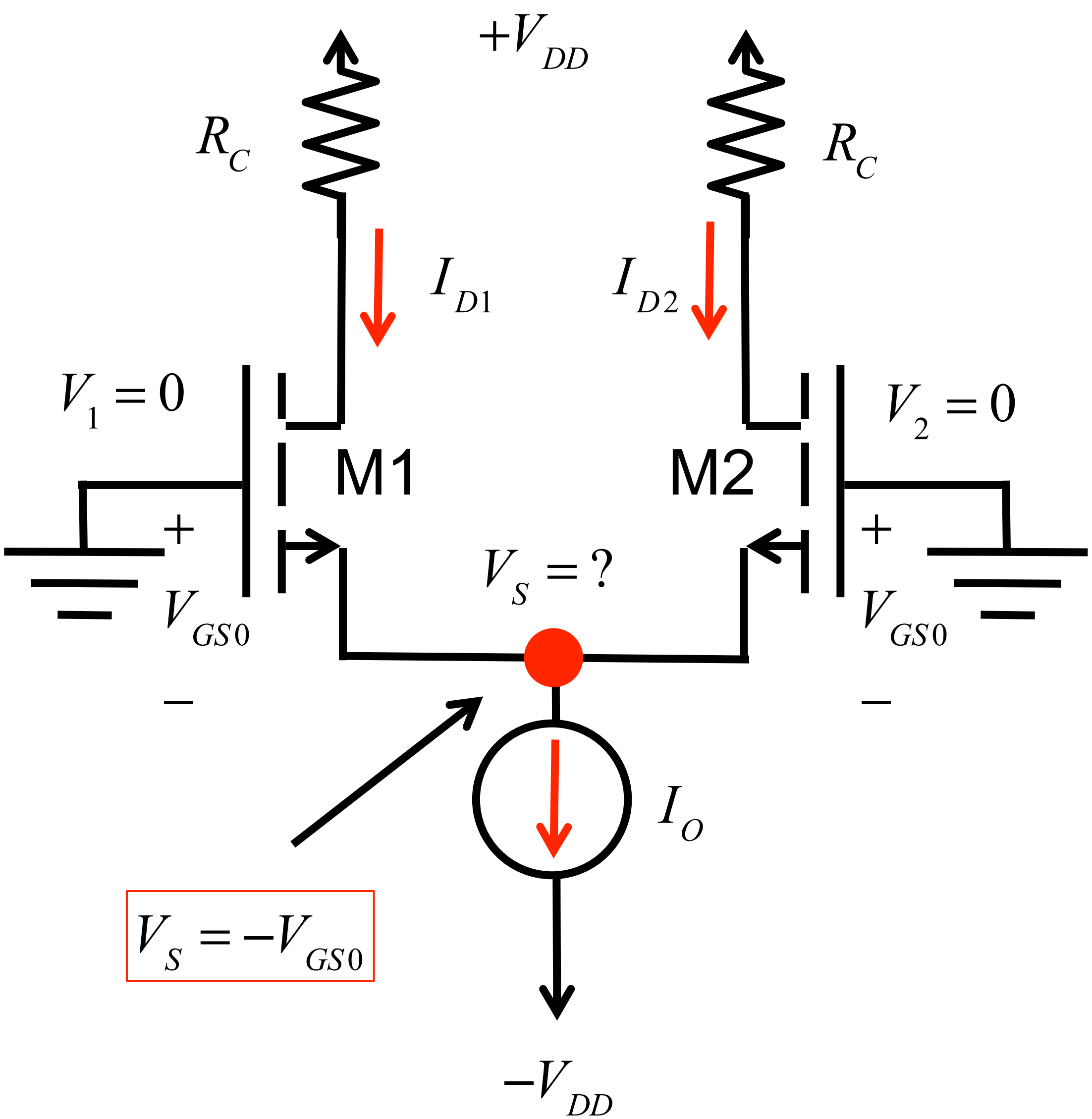
$$I_{D1} = I_{D2} = \frac{I_0}{2}$$

$$V_{D1} = V_{D2} = V_{DD} - \frac{I_0}{2} R_C$$

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

How do we find the source voltage of the source-coupled pair?

Basic circuit: inputs grounded



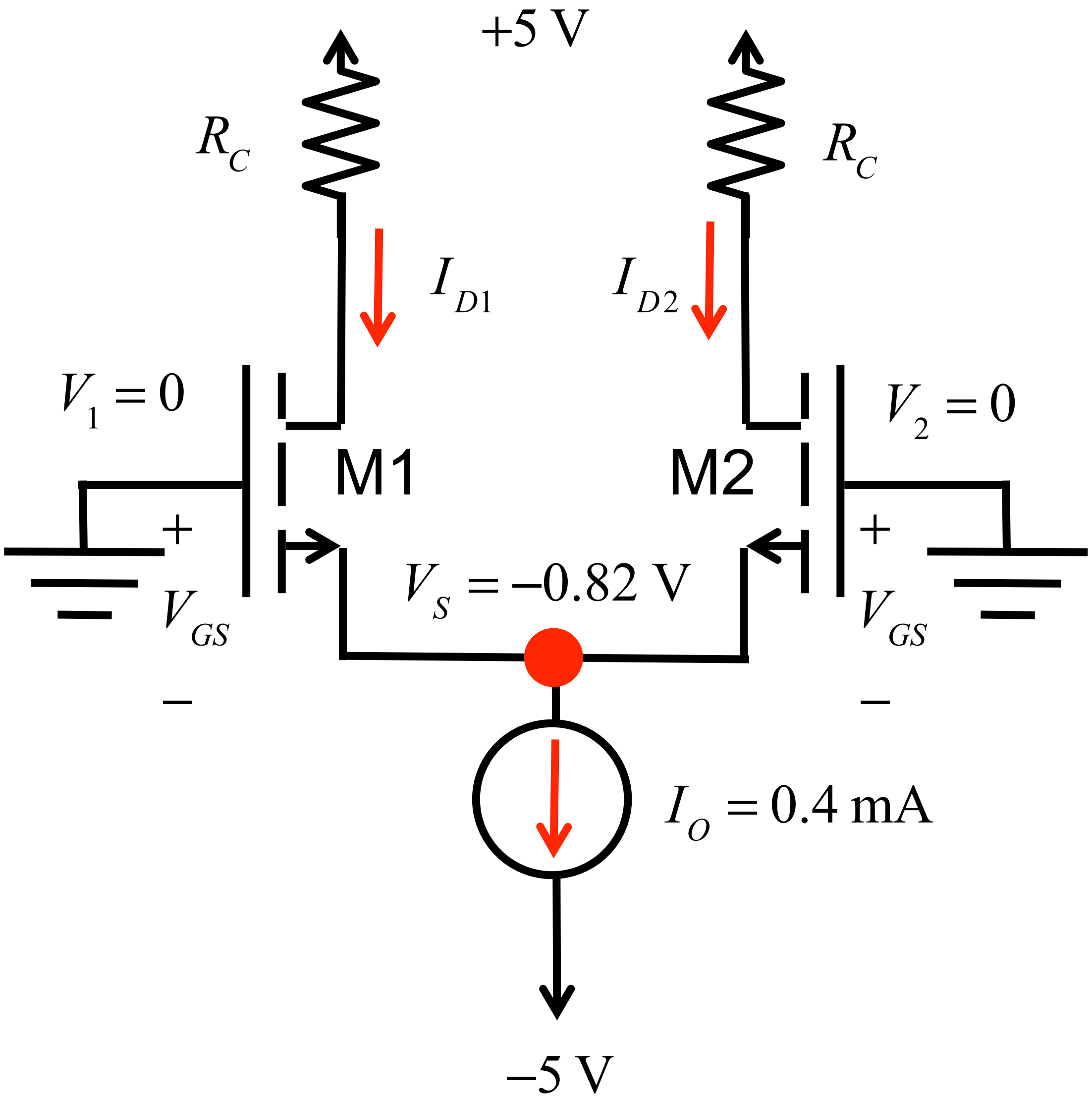
$$I_D = \frac{k_n}{2}\left(V_{GS} - V_{tn}\right)^2$$

$$I_{D1} = I_{D2} = \frac{I_0}{2}$$

$$\frac{I_0}{2} = \frac{k_n}{2}\left(V_{GS0} - V_{tn}\right)^2$$

$$V_{GS0} = \sqrt{I_0/k_n} + V_{tn}$$

Example



$$k_n = 4 \text{ mA/V}^2$$

$$V_{tn} = 0.5 \text{ V}$$

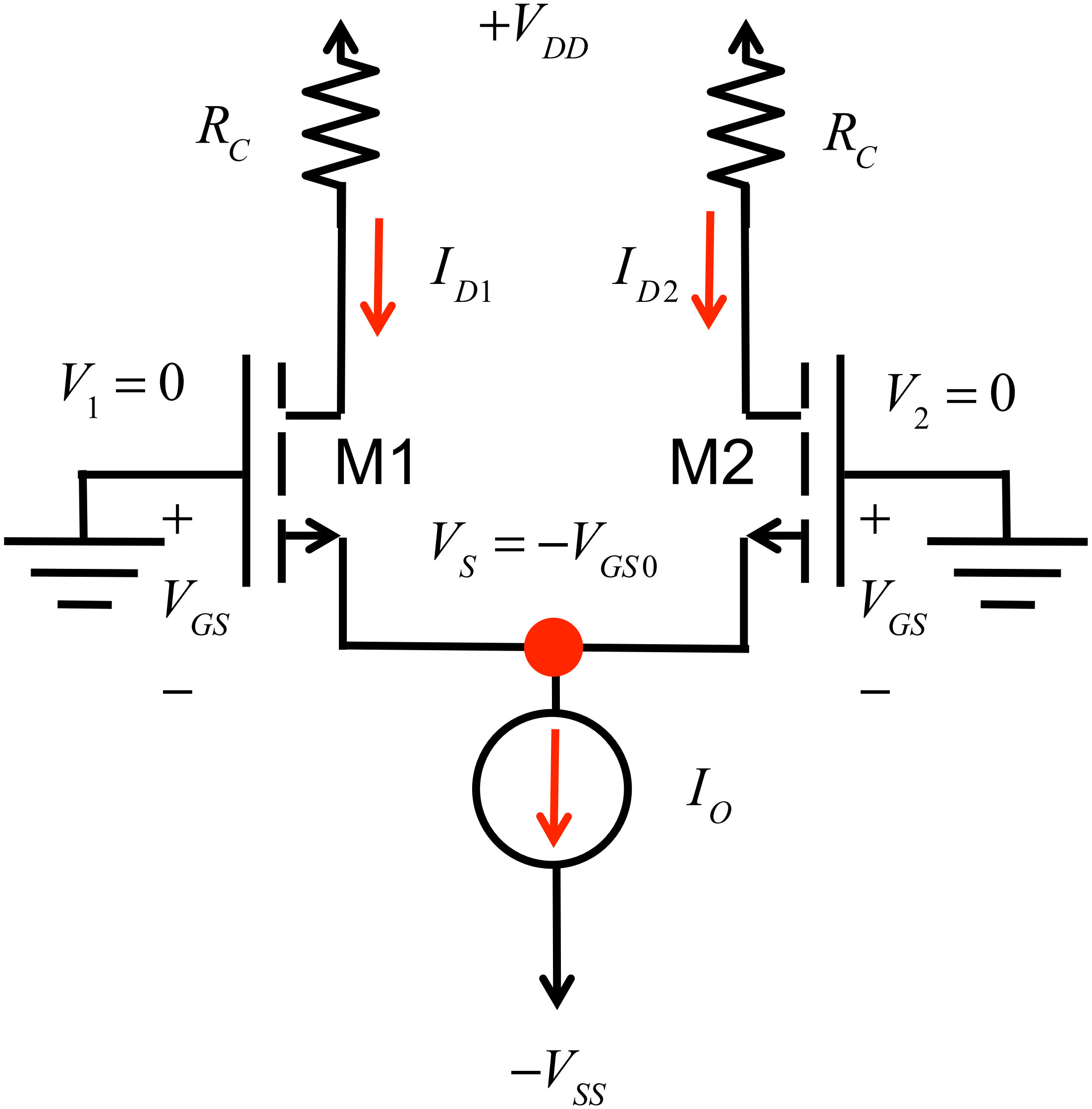
$$I_D = \frac{k_n}{2}\left(V_{GS0} - V_{tn}\right)^2 = 0.2 \text{ mA}$$

$$2\left(V_{GS0} - 0.5\right)^2 = 0.2 \text{ mA}$$

$$\left(V_{GS0} - 0.5\right) = 0.316$$

$$V_{GS0} = 0.816$$

General case



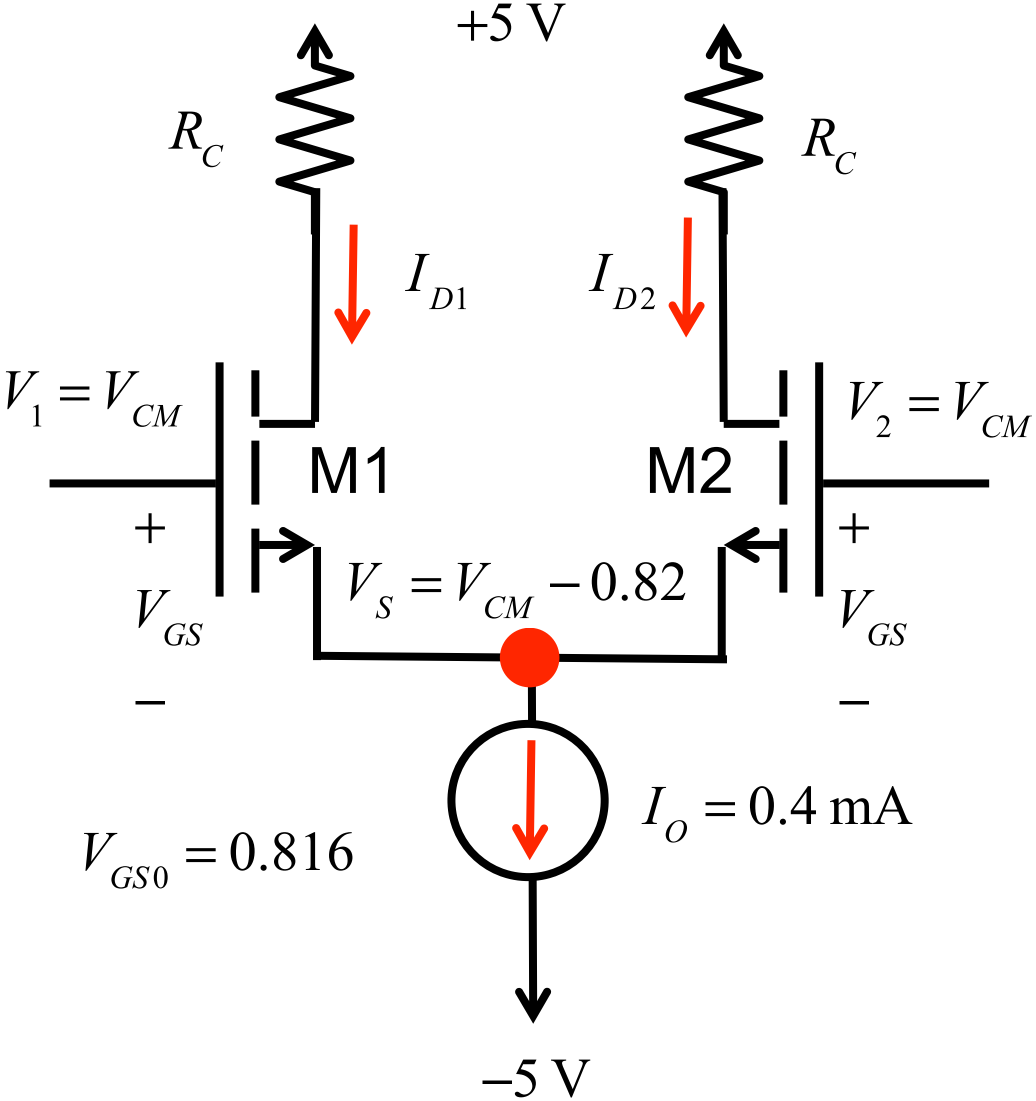
$$I_D = \frac{k_n}{2}\left(V_{GS0} - V_{tn}\right)^2 = \frac{I_0}{2}$$

$$\left(V_{GS0} - V_{tn}\right) = \sqrt{\frac{I_0}{k_n}}$$

$$V_{GS0} = V_{tn} + \sqrt{\frac{I_0}{k_n}}$$

$$V_S = -V_{GS0}$$

2) Common mode voltage non-zero



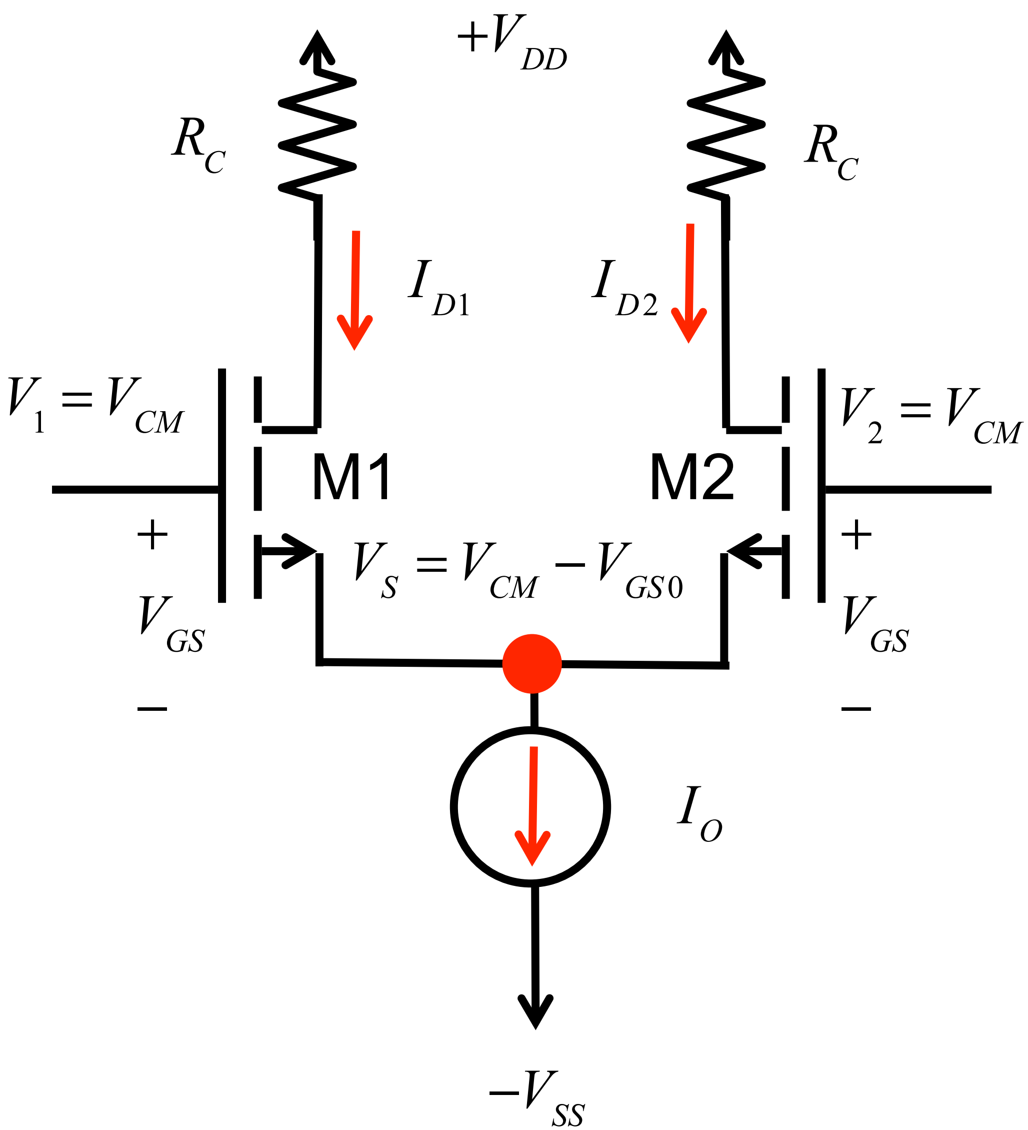
$$I_{D1} = I_{D2} = \frac{I_0}{2}$$

$$V_{GS1} = V_{GS2} = V_{GS0}$$

$$V_S = V_{CM} - V_{GS0}$$

$$V_{GS0} = 0.82$$

2) Common mode voltage non-zero

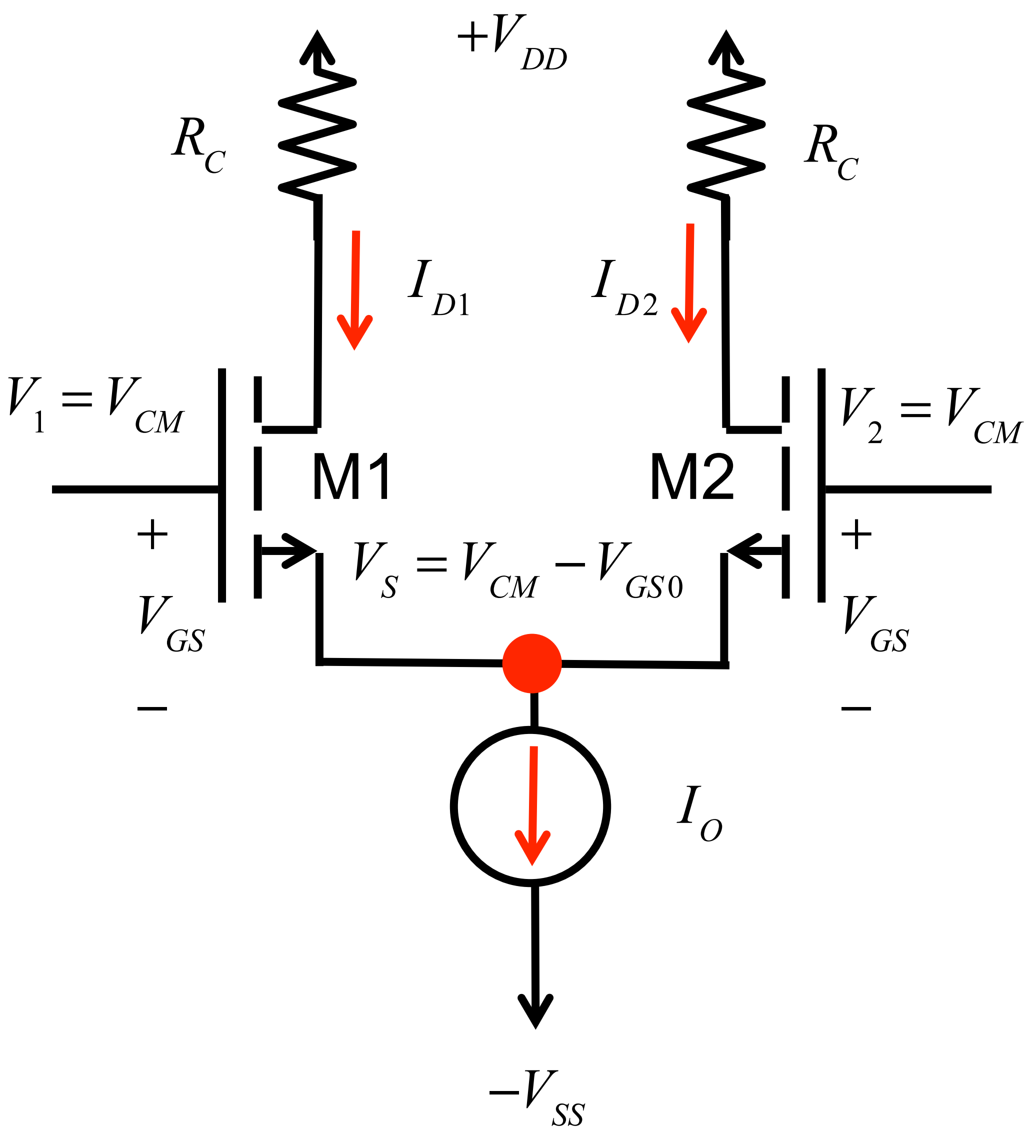


What determines the **maximum** common mode input voltage?

The transistors must stay in the saturation region.

$$V_{DS} \geq V_{GS} - V_{tn}$$

Maximum common mode voltage

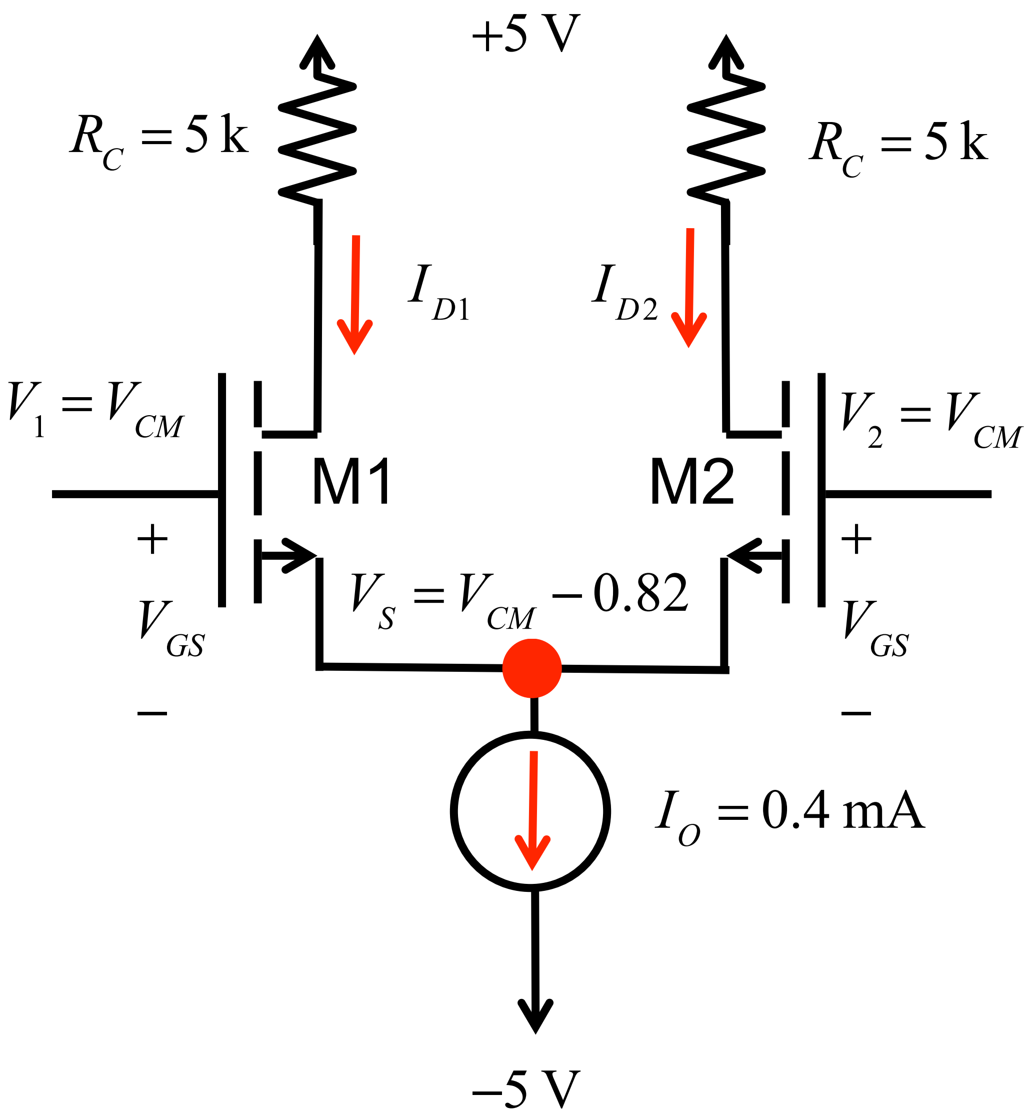


$$V_{DS} \geq V_{GS} - V_{tn}$$

$$\left(V_{DD} - \frac{I_0}{2} R_C \right) - \left(V_{CM} - V_{GS0} \right)$$
$$\geq V_{GS0} - V_{tn}$$

$$\left. V_{CM} \right)_{\max} = V_{tn} + V_{DD} - \frac{I_0 R_D}{2}$$

Example: Maximum common mode voltage



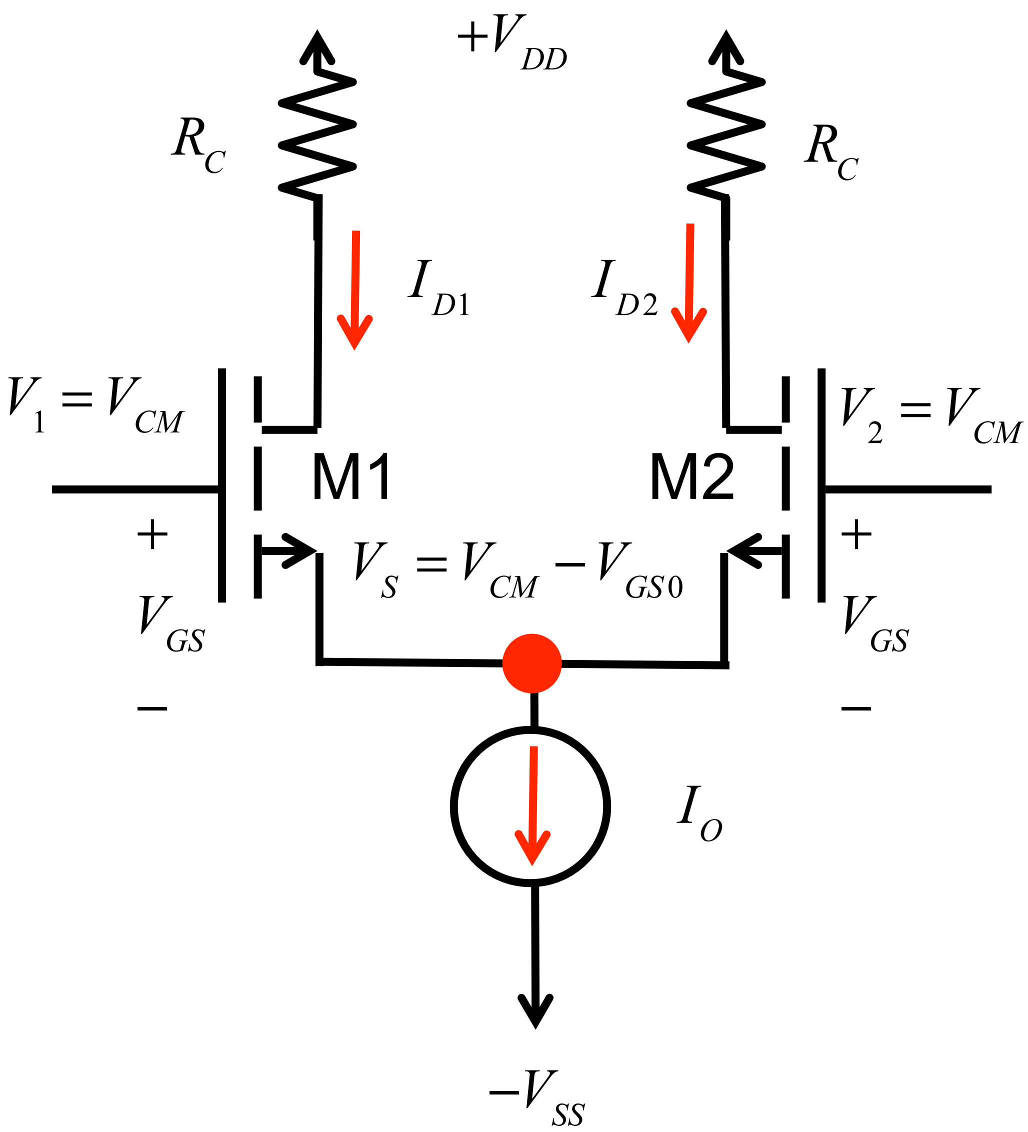
$$\left.V_{CM}\right)_{\max} = V_{tn} + V_{DD} - \frac{I_0 R_D}{2}$$

$$\left.V_{CM}\right)_{\max} = 0.5 + 5 - 1.0 = 4.5\text{ V}$$

$$V_{DS} = 4 - \left(4.5 - 0.82\right) = 0.32$$

$$V_{GS} = V_{GS0} - V_{tn} = 0.32$$

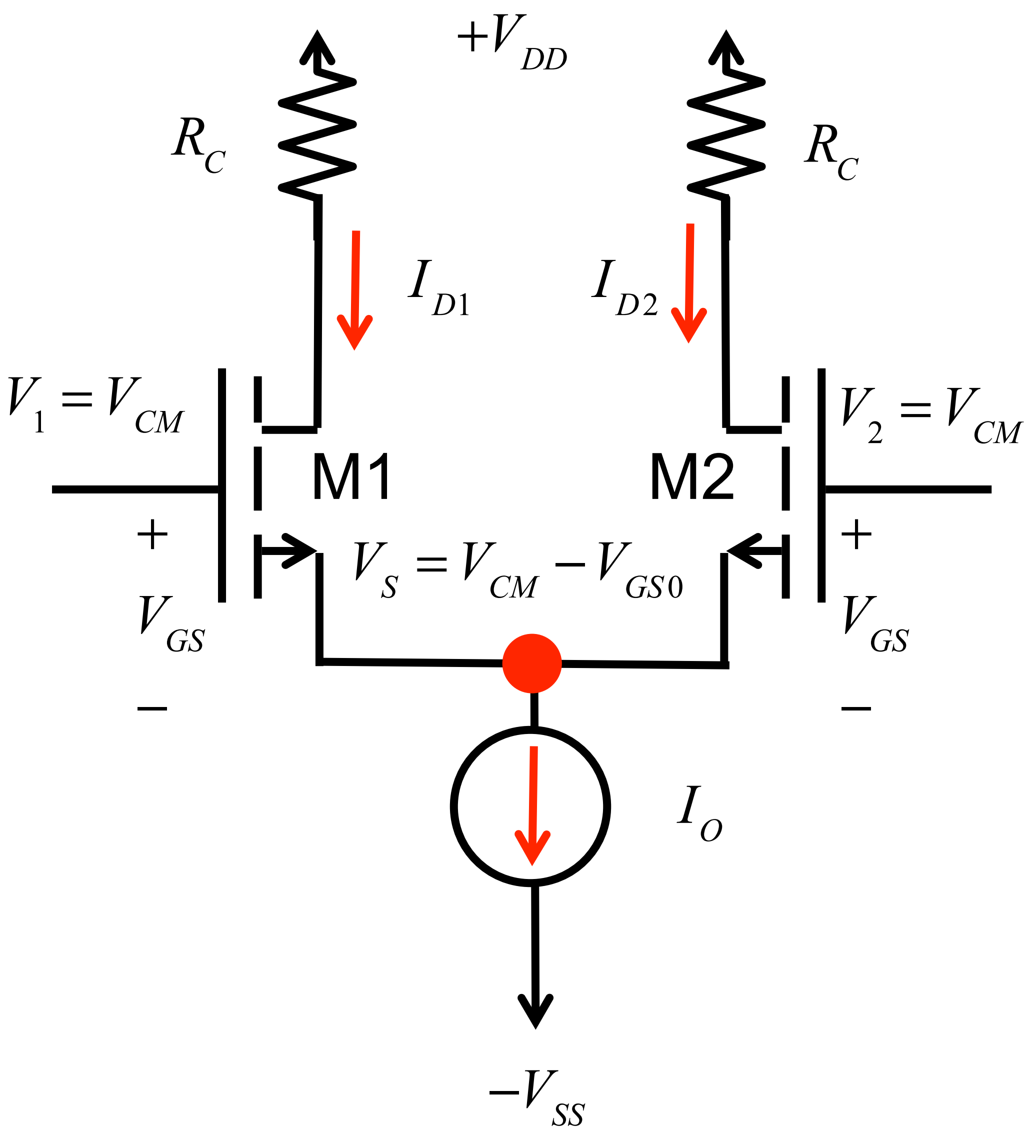
Minimum common mode voltage



What determines the **minimum** common mode input voltage?

The current source requires a minimum voltage across it to function V_{CS}

Minimum common mode voltage



$$V_S + V_{SS} \geq V_{CS}$$

$$\left(V_{CM} - V_{GS0}\right) + V_{SS} \geq V_{CS}$$

$$\left.V_{CM}\right)_{\min} = -V_{SS} + V_{CS} + V_{GS0}$$

Outline

1) Quick Op Amp Review
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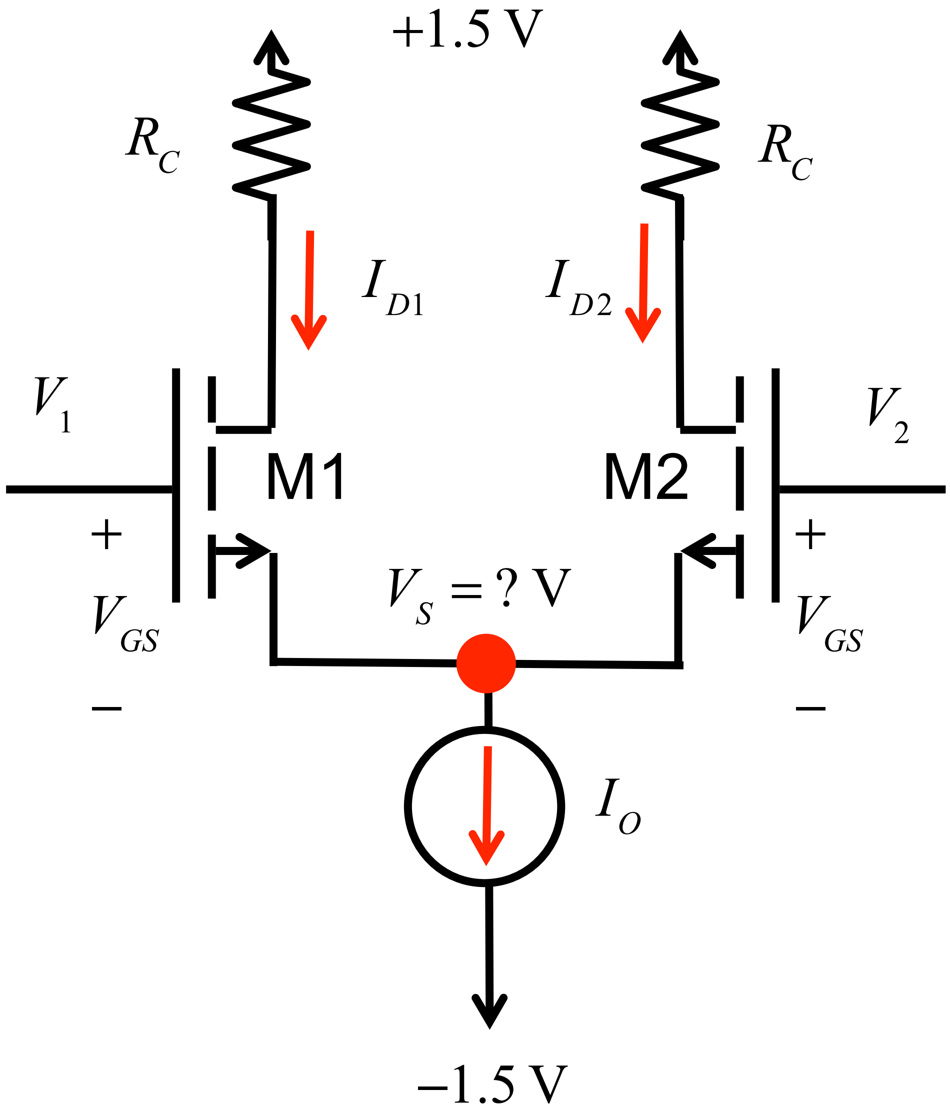
3) Large signal: common mode
4) Large signal: differential mode
5) Small signal

Basic operation



Expect:

1) For $V_1 = V_2 = 0$

$$I_{D1} = I_{D2} = I_0/2$$

2) For $V_1 = V_2 = V_{CM} \neq 0$

$$I_{D1} = I_{D2} = I_0/2$$

3) For $V_1 = -V_2 > 0$

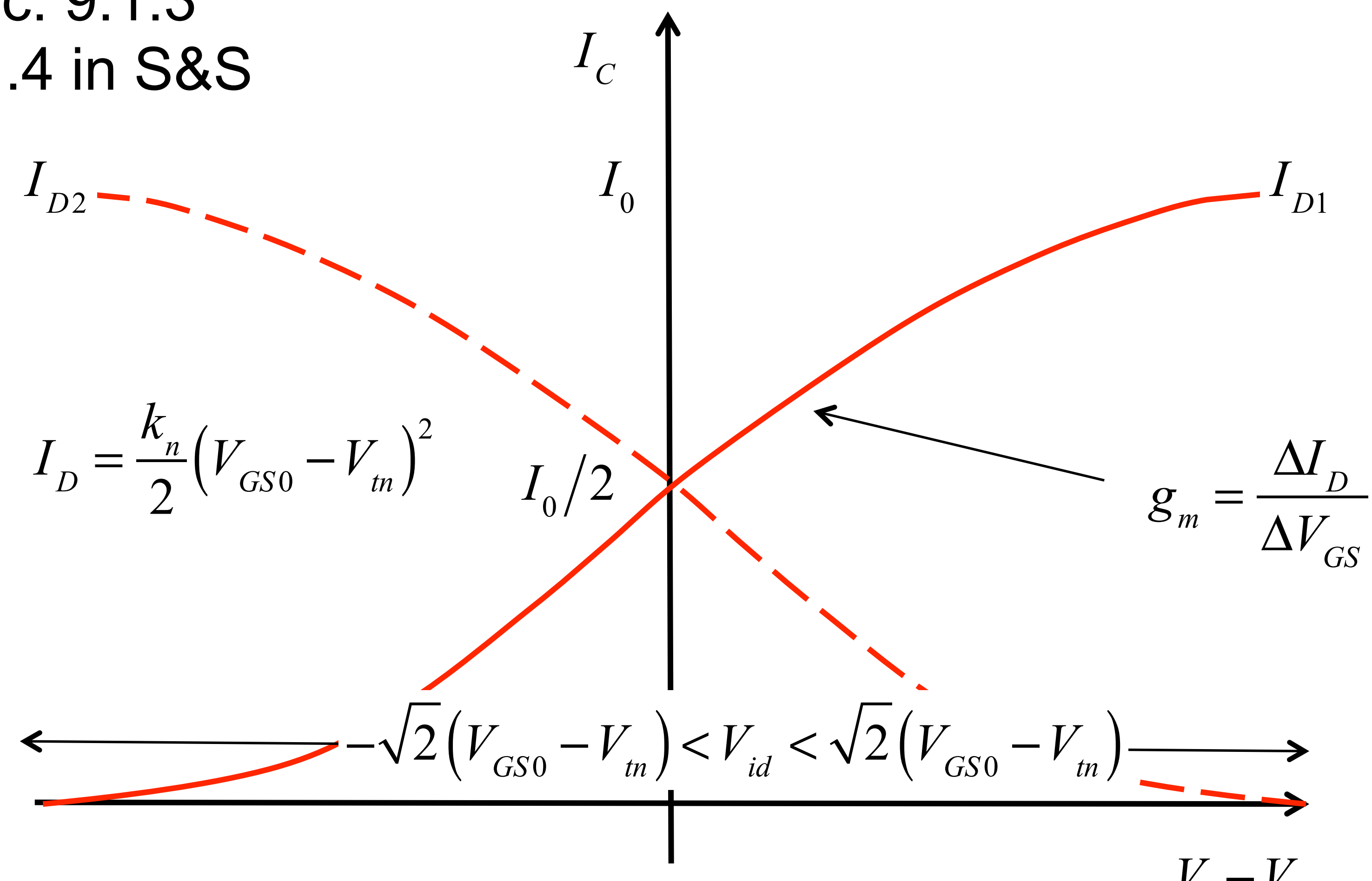
$$I_{D1} > I_0/2 \quad I_{D2} < I_0/2$$

4) For $V_1 = -V_2 >> 0$

$$I_{D1} = I_0 \quad I_{D2} = 0$$

MOS Current steering

See Sec. 9.1.3
and 9.1.4 in S&S



$$-0.45 = \sqrt{2}\left(0.32\right) < V_{id} < \sqrt{2}\left(0.32\right) = 0.45$$

Outline

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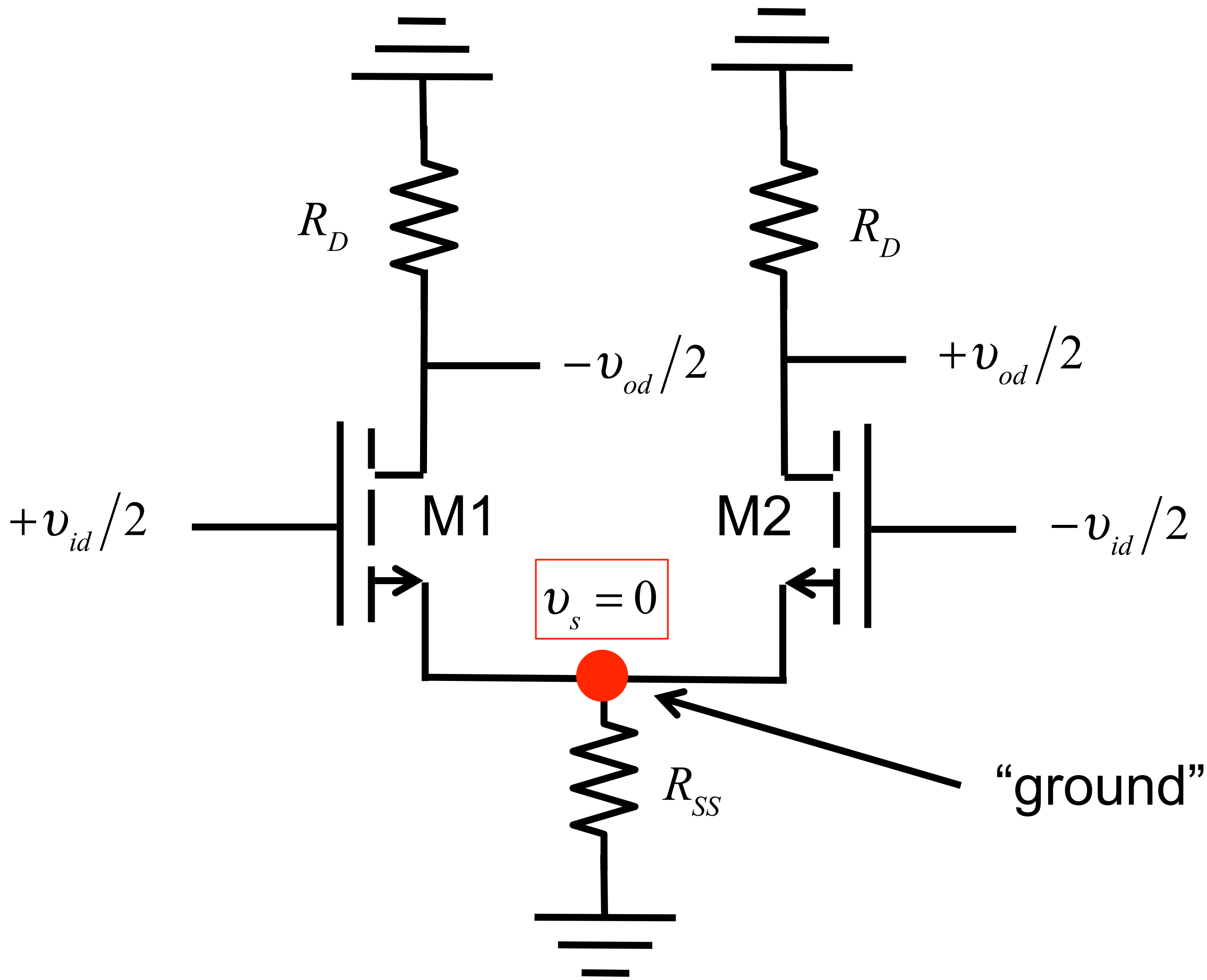
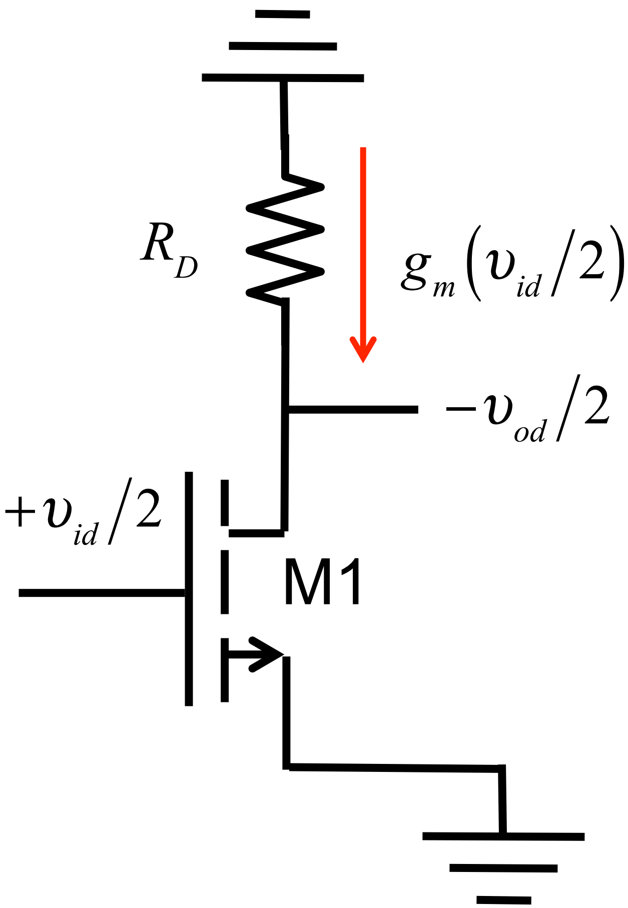
4) Large signal: differential mode
5) **Small signal**

ss differential operation



ss differential half-circuit



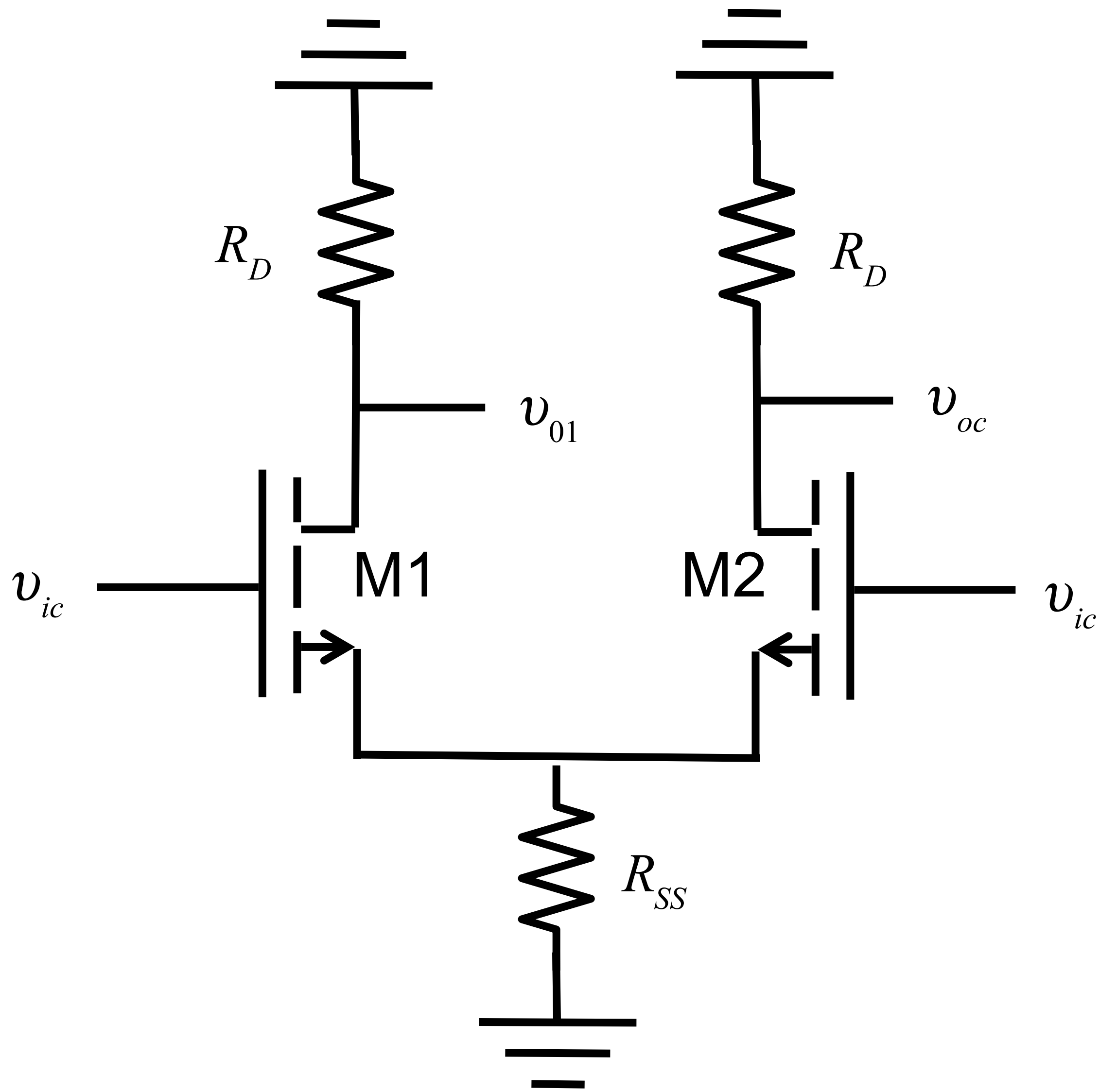
$$A_{dm} = +g_m R_D$$

$$g_m = \frac{I_0/2}{2(V_{GS} - V_{tn})}$$

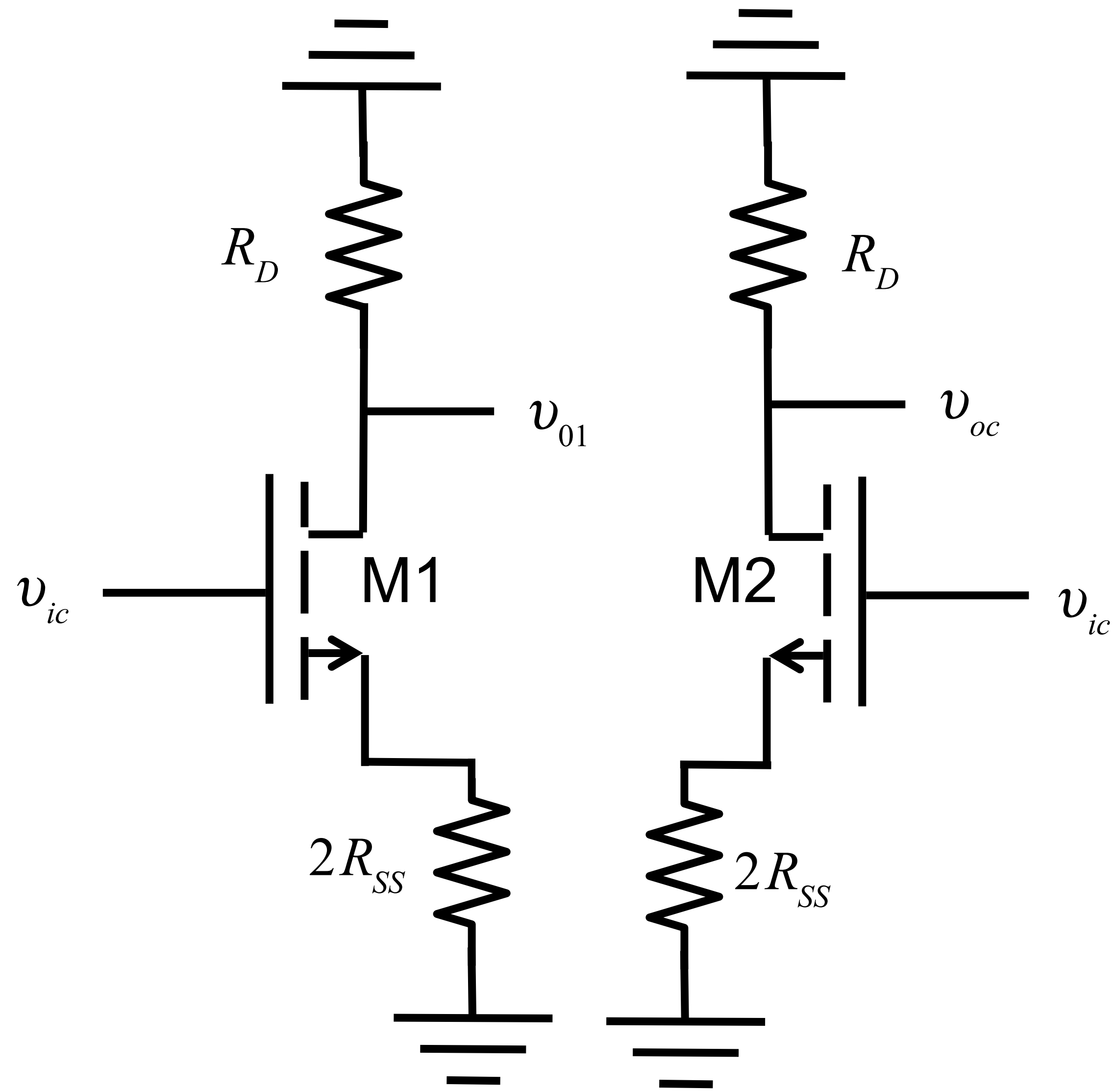
$$R_{in} = \infty$$

$$R_{do} = 2R_D$$

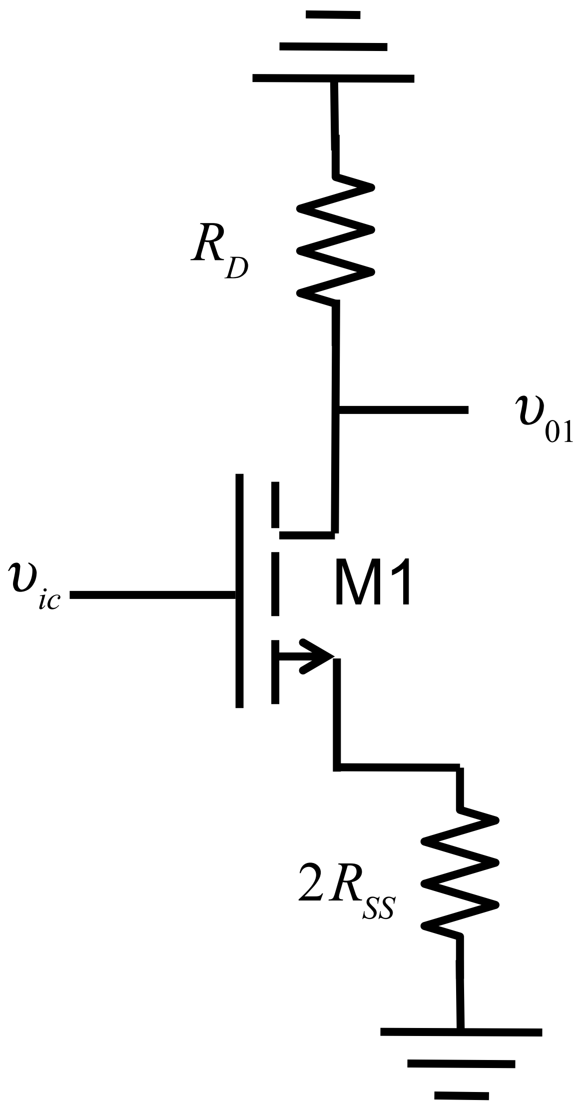
ss common mode operation



ss common mode operation



ss common mode half-circuit



$$\upsilon_{01} = A_\upsilon \upsilon_{ic} = \upsilon_{02}$$

$$A_\upsilon = -\frac{g_m R_D}{1 + g_m 2R_{SS}} \approx -\frac{R_D}{2R_{SS}}$$

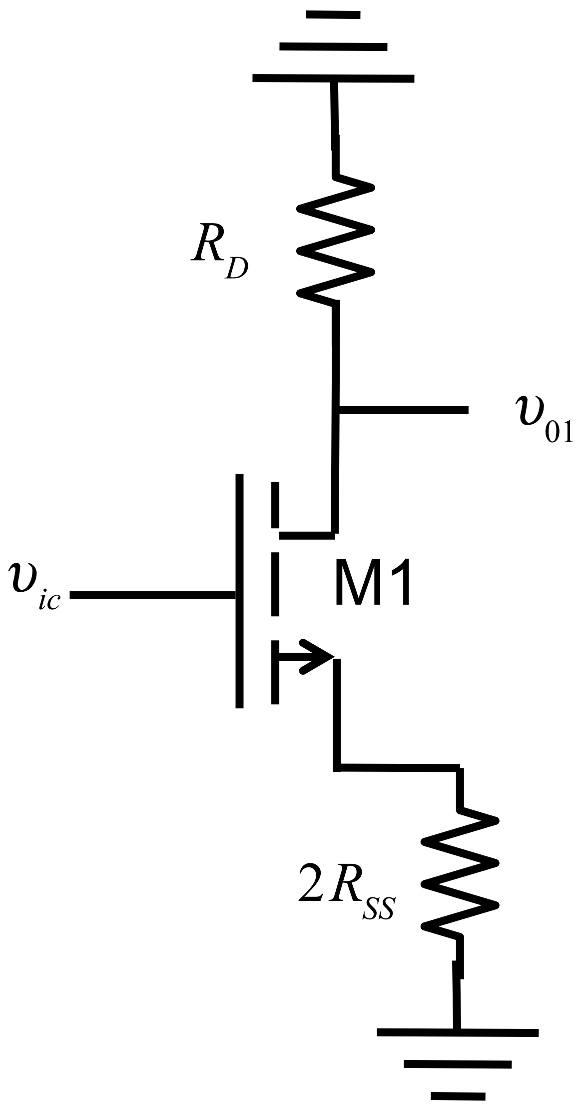
$$\upsilon_{od} = \upsilon_{02} - \upsilon_{01} = 0$$

$$A_{cm} = \frac{\upsilon_{od}}{\upsilon_{ic}} = 0$$

(no mismatch)

$$CMRR = \frac{|A_{dm}|}{|A_{cm}|} = \infty$$

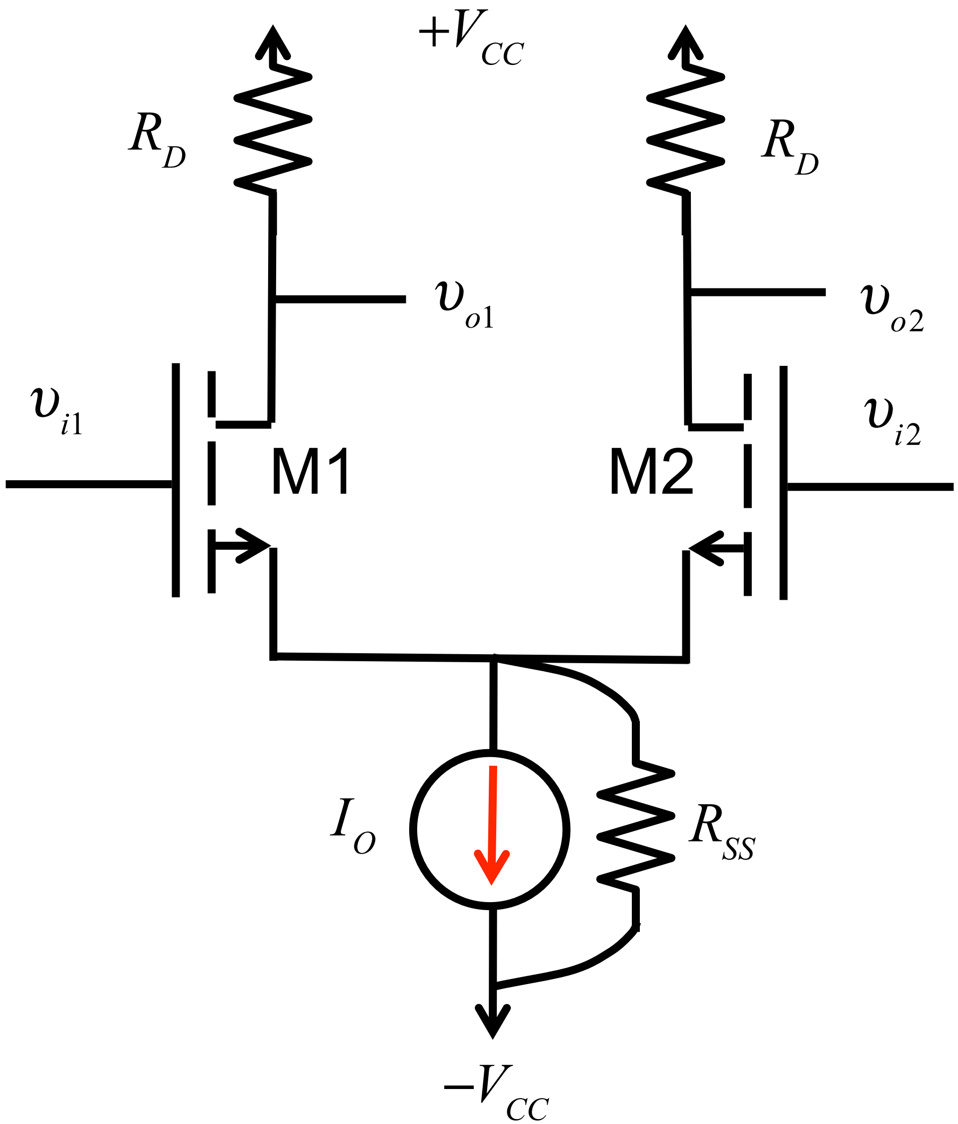
ss common mode half-circuit



$$v_{01} \approx -\frac{R_D}{2R_{SS}} v_{ic} \qquad v_{02} \approx -\frac{R_D + \Delta R_D}{2R_{SS}} v_{ic}$$

$$CMRR = \frac{|A_{dm}|}{|A_{cm}|} = \frac{2g_m R_{SS}}{\Delta R_D / R_D}$$

MOS summary



$$A_{dm} = +g_m R_D$$

$$R_{id} = \infty$$

$$R_{od} = 2R_D$$

$$A_{cm} = -\frac{\Delta R_D}{2R_{SS}}$$

$$CMRR = \frac{2g_m R_{SS}}{\Delta R_D / R_D}$$

$$g_m = \frac{I_0/2}{2(V_{GS} - V_{tn})}$$

Questions

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