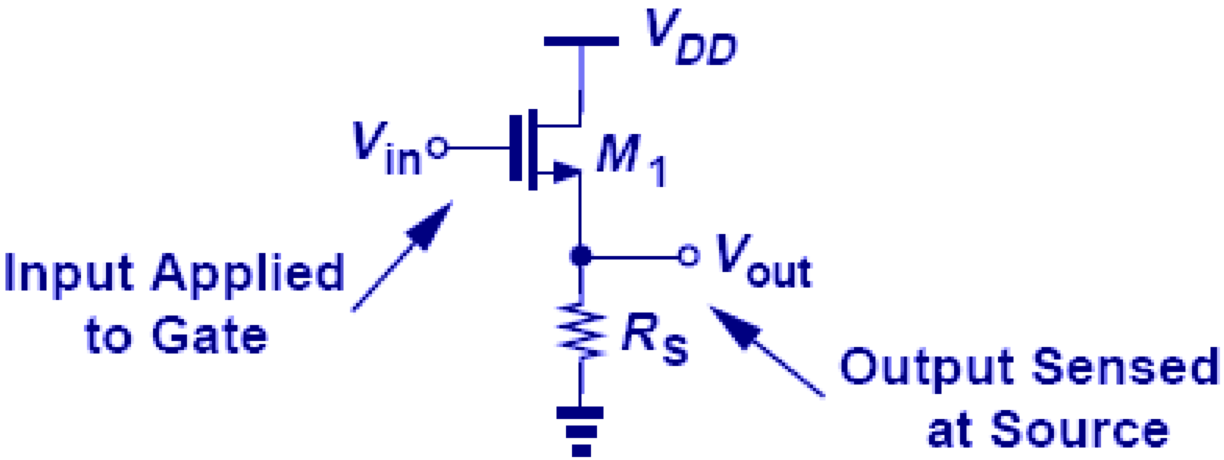
Lecture – 8

Date: 31.08.2015

- Common Drain Amplifier
- Common Gate Amplifier
- Examples

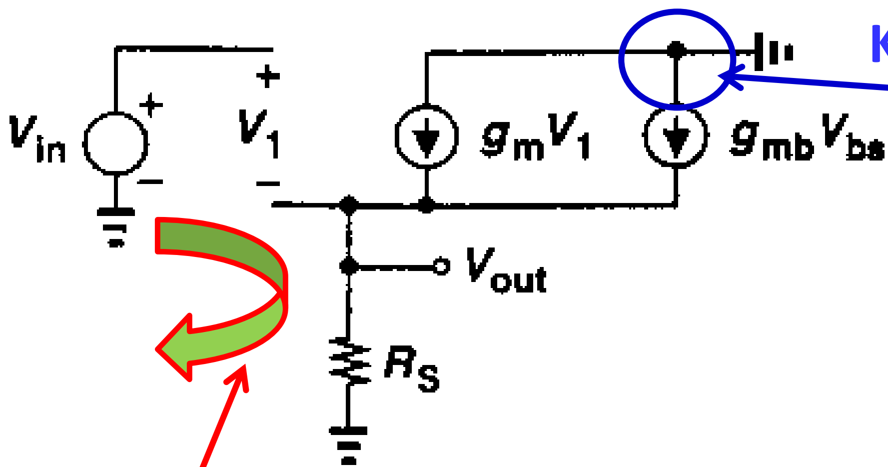
CD Amplifier (Source Follower)



- It senses the input at the gate and produces the output at the source
- CS-stage identifies that for achieving high voltage gain, the load impedance must be large → if CS-stage is to be succeeded by a low impedance circuitry → a buffer is needed as a low impedance can't be driven by a CS-stage amplifier → CD-stage works as a buffer

CD Amplifier (Source Follower) – contd.

Let us look at the small-signal voltage gain of CD-stage:



KCL at drain

$$g_m V_1 + g_{mb} V_{bs} = \frac{V_{out}}{R_S}$$

$$V_{bs} = -V_{out}$$

KVL at input

$$V_{in} - V_1 = V_{out}$$

- **Simplification gives:**

$$A_v = \frac{V_{out}}{V_{in}} = \frac{g_m R_S}{[1 + (g_m + g_{mb}) R_S]}$$

Non-inverting action

Can you derive A_v without explicitly using the small signal model ?

CD Amplifier (Source Follower) – contd.

$$A_v = \frac{V_{out}}{V_{in}} = \frac{g_m R_S}{\left[1 + (g_m + g_{mb}) R_S\right]}$$

Observations

- For $V_{in} = V_T$, the transconductance $g_m = 0$ and therefore $A_v = 0$
- V_{in} increases → I_D increases → leads to increase in g_m → A_v increases and approaches:

$$A_v = \frac{g_m}{g_m + g_{mb}} = \frac{1}{1+\eta}$$

η decreases with increase in V_{out} → leads to increase in A_v → η is typically 0.2 and therefore $A_v < 1$

Even for $R_S = \infty$, the small signal voltage gain $A_v < 1$

CD Amplifier (Source Follower) – contd.

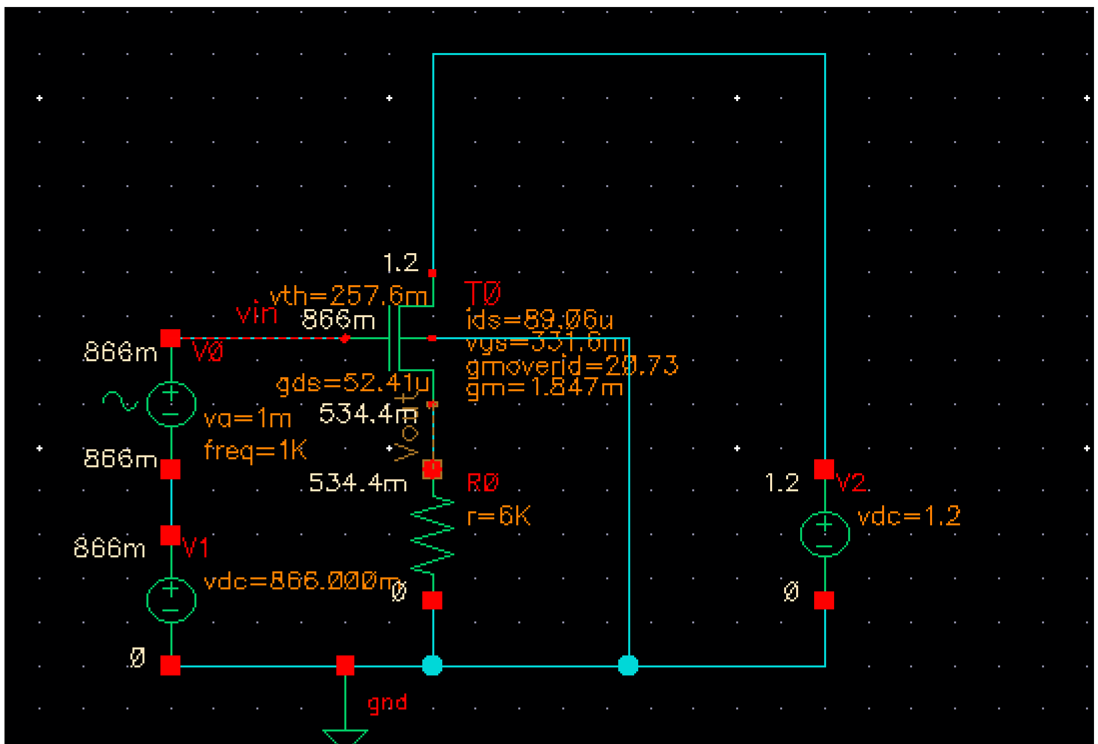
Example:

g_m=2 mS

g_{mb}=0.328 mS

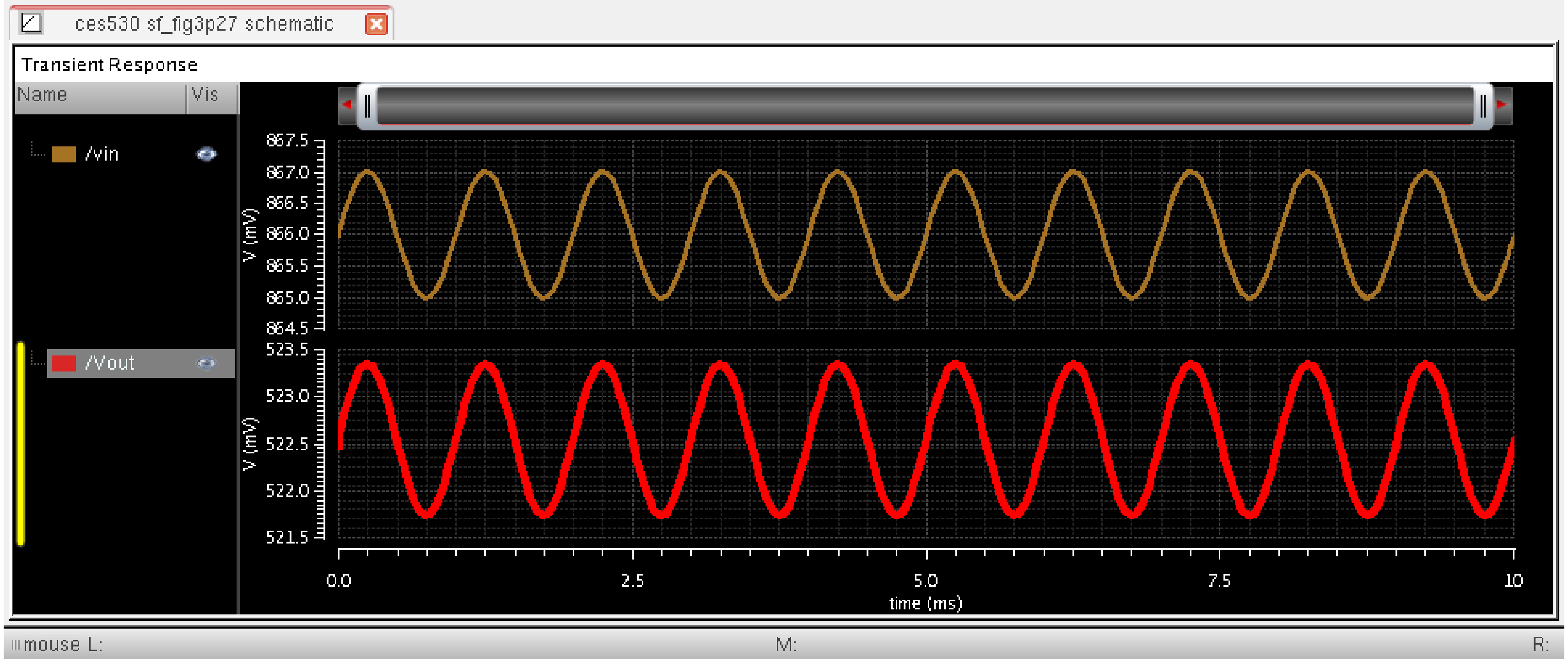
R_S=6 kΩ

Calculated A_v= 0.801



CD Amplifier (Source Follower) – contd.

Example (contd.):



$V_{in,\ pp}$=2 mV

$V_{out,\ pp}$=1.596 mV

Simulated: $A_v = 0.798$

CD Amplifier (Source Follower) – contd.

$A_v < 1$ ← Definitely not an amplifier

- In the best case scenario when R_S is extremely high and body effect is ignored then:

$A_v = 1$ ← Usefulness as buffer

- How can you ignore body effect?

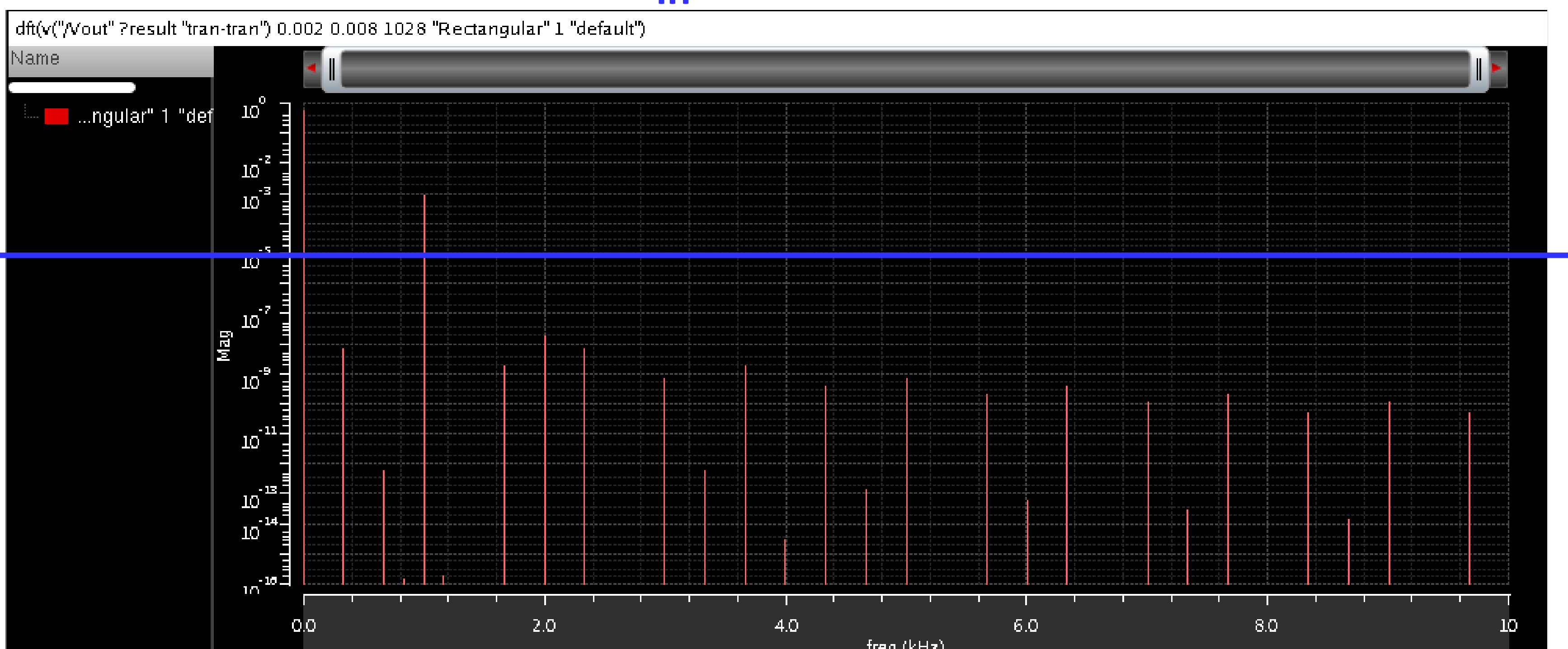
Definitely not for NMOS

By employing a PMOS and with appropriate biasing

CD Amplifier (Source Follower) – contd.

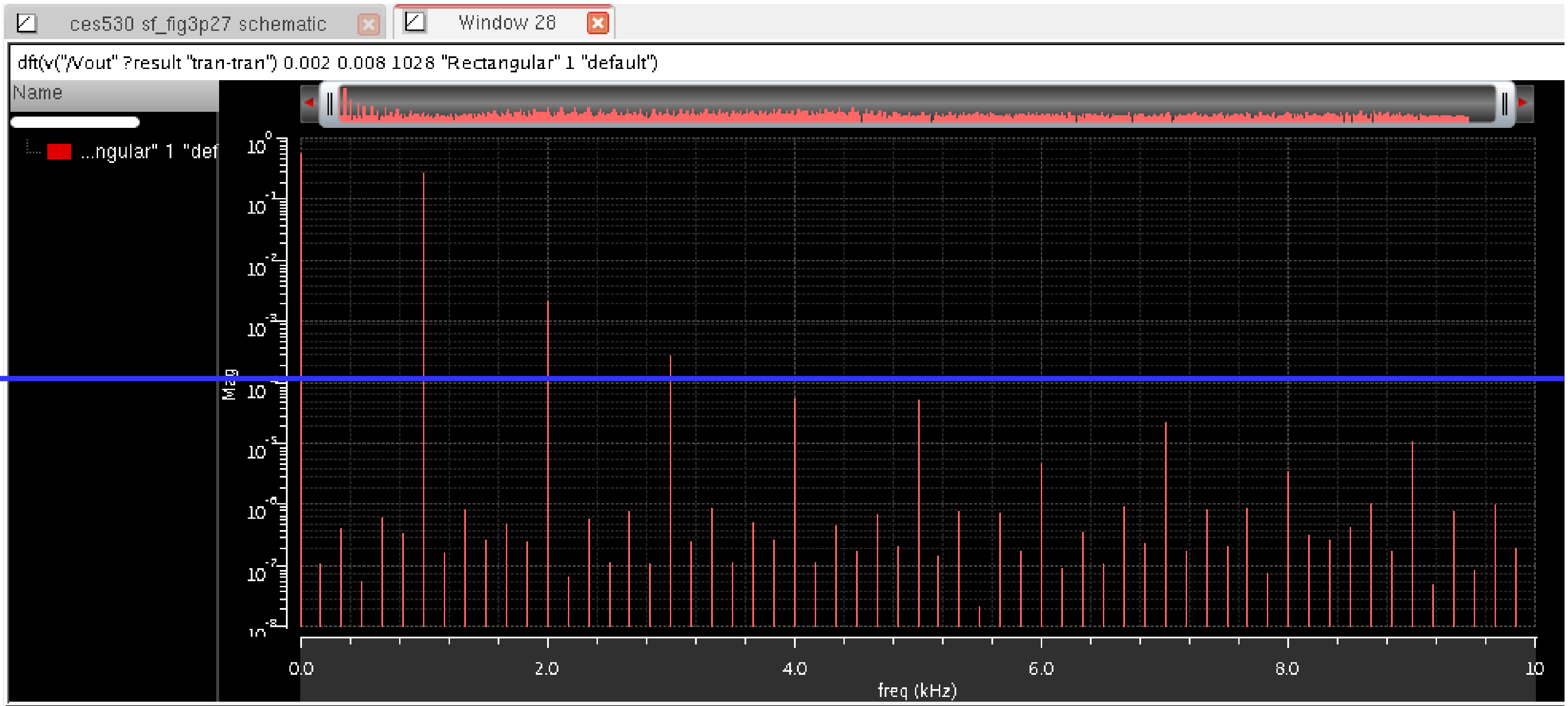
- Furthermore, the strong dependence of A_v on the input voltage makes it a nonlinear configuration → Its due to strong dependence of I_D and therefore g_m on the input voltage V_{in}

V_{in} = 1mV



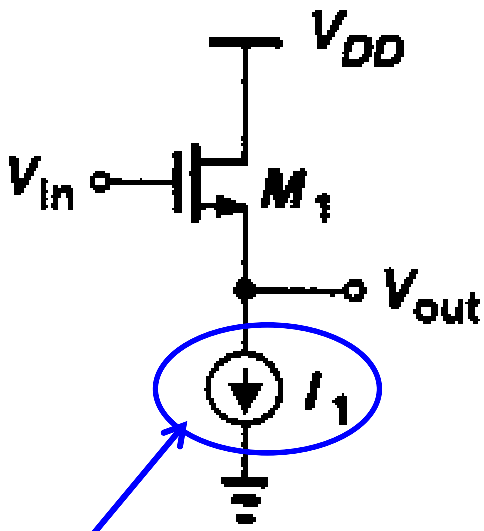
CD Amplifier (Source Follower) – contd.

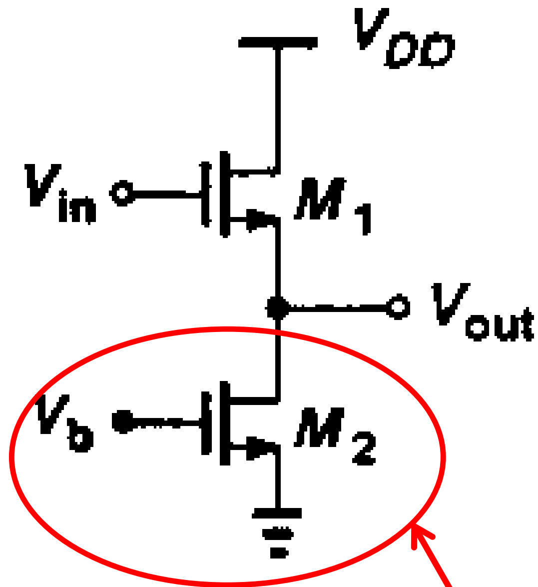
V_{in} = 330mV



CD Amplifier (Source Follower) – contd.

- To mitigate this dependence → resistor R_S is replaced by a current source → the current source is realized using an NMOS operating in saturation mode





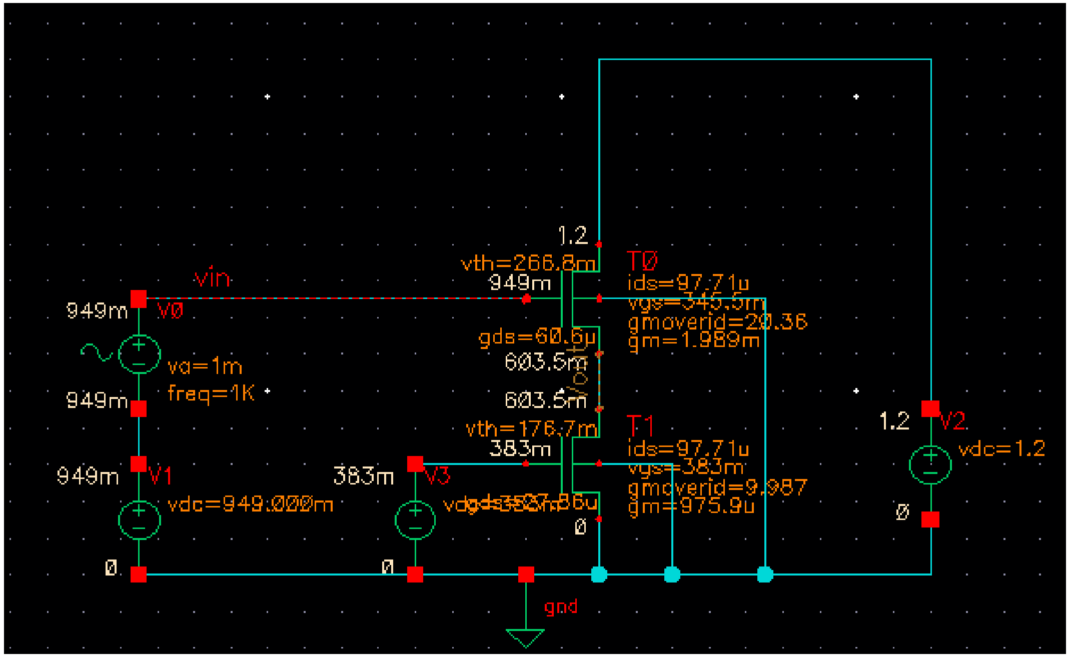
$$A_v = \frac{\frac{1}{g_{mb}} \parallel r_{01} \parallel r_{02}}{\frac{1}{g_{mb}} \parallel r_{01} \parallel r_{02} + \frac{1}{g_m}}$$

Current source providing high R_S

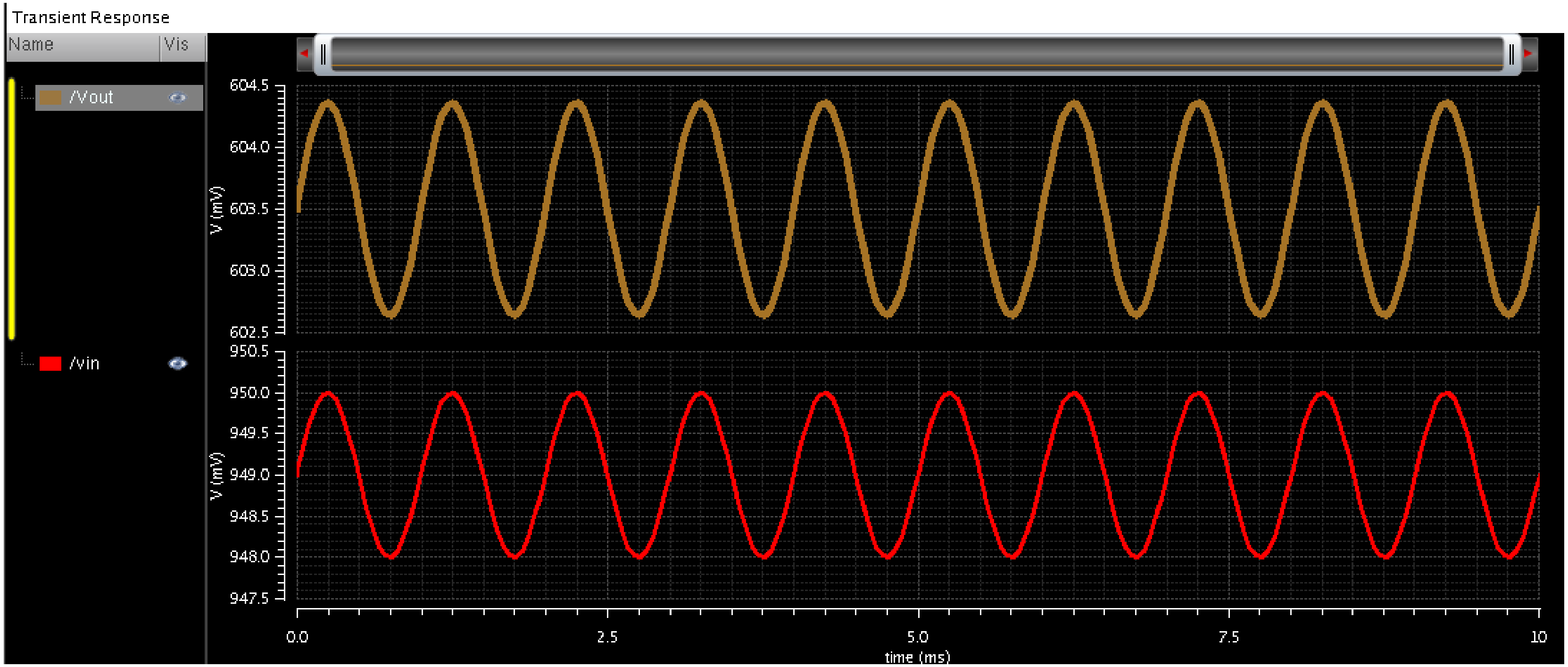
NMOS Operating in Saturation

CD Amplifier (Source Follower) – contd.

- Let us get back to that example



CD Amplifier (Source Follower) – contd.

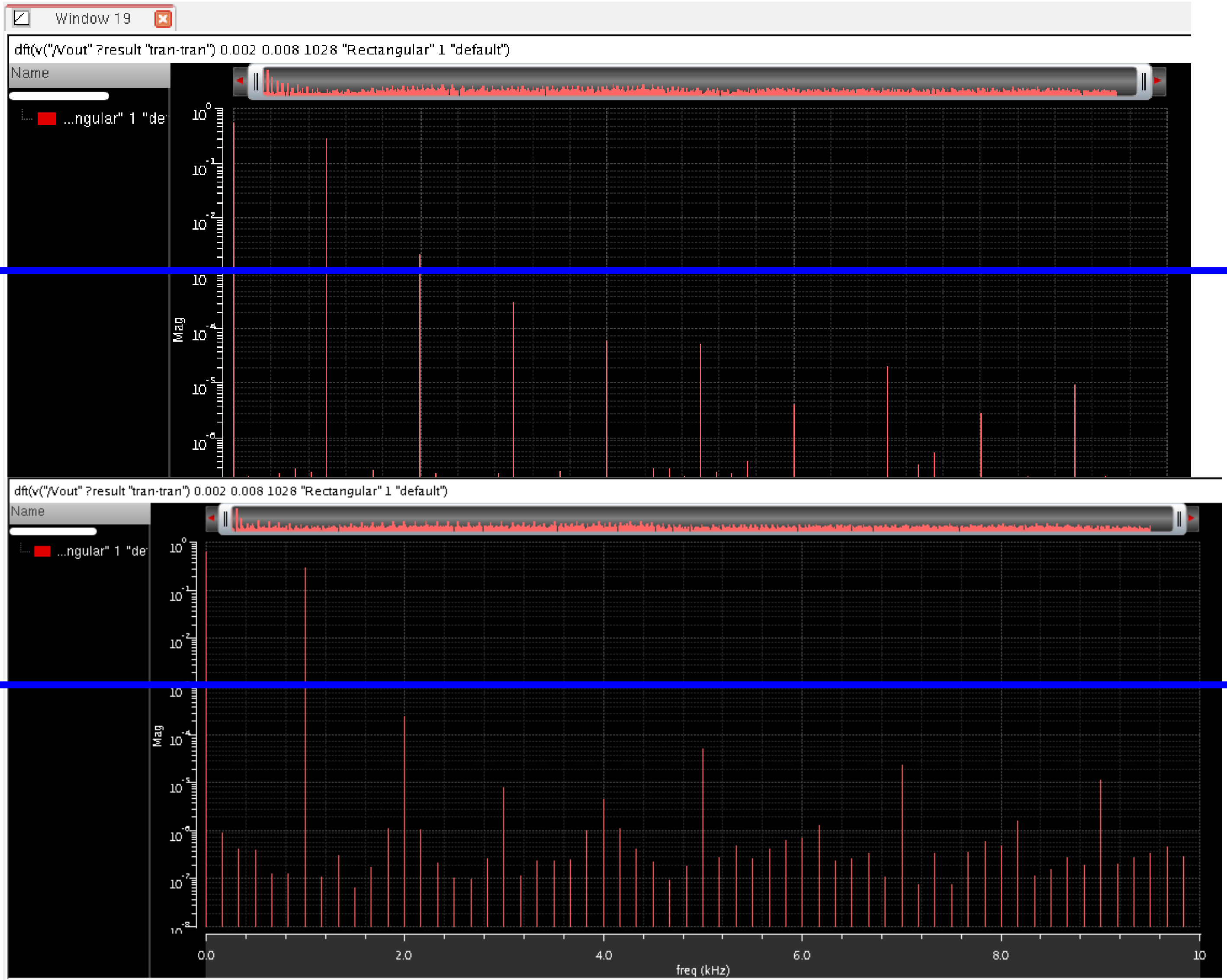


$V_{in,\,pp}$=2 mV **$V_{out,\,pp}$=1.705 mV**

Simulated: $A_v = 0.8525$

CD Amplifier (Source Follower) – contd.

V_{in} = 330mV

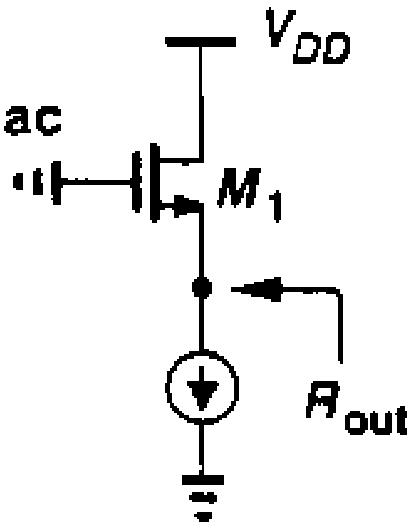


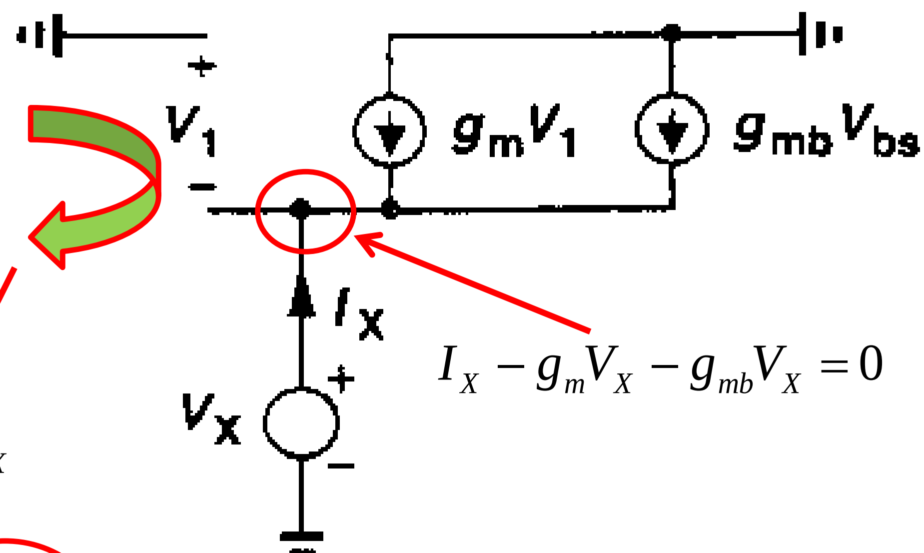
R_S= 6kΩ

R_S=CS

CD Amplifier (Source Follower) – contd.

- Let us look into the small-signal output resistance:





$$V_1 = -V_X$$

$$I_X - g_m V_X - g_{mb} V_X = 0$$

$$R_{out} = \frac{1}{g_m + g_{mb}}$$

Body effect reduces the output impedance

- If channel length modulation is taken into account then:

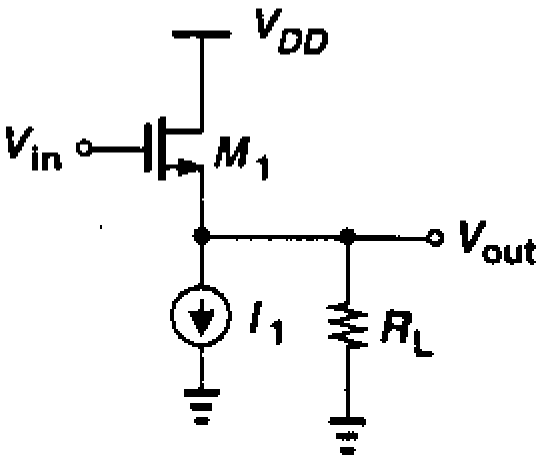
$$\therefore R_{out} = \frac{1}{g_m + g_{mb}} \,||\, r_o$$

Further Reduction in output impedance

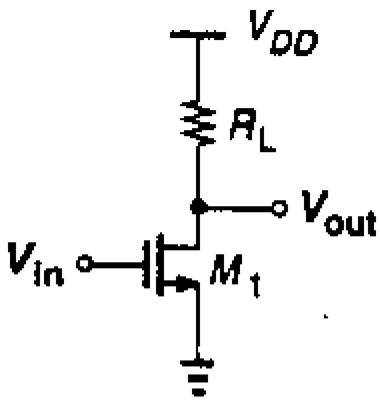
CD Amplifier (Source Follower) – contd.

- High input impedance and low output impedance with near unity gain enables CD stage to work as buffer (not always!) → useful for CS stage specially when the load impedance is raised very high to enhance the gain
- Reduced output voltage swing when used as buffer for a CS stage
- CD topology is nonlinear → due to body effect and channel length modulation → also the gain is dependent on g_m
- CD topology generates substantial noise → hence not suitable for low noise applications (beyond this course!!)

Comparison of CD and CS Stages



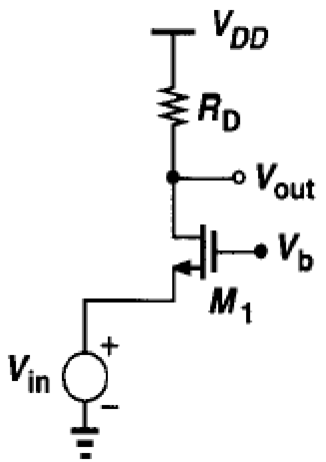
$$A_v|_{CD} \approx \frac{R_L}{R_L + \frac{1}{g_{m1}}}$$

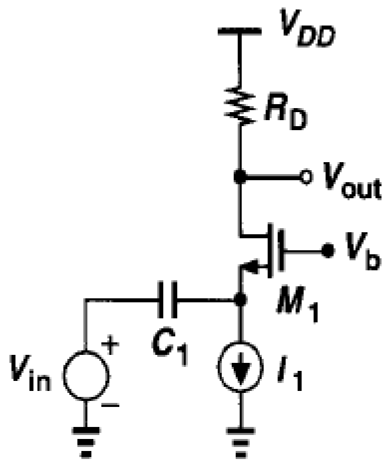


$$A_v|_{CS} \approx -g_{m1}R_L$$

- **CD is non-inverting whereas CS is inverting**
- **CS provides higher gain**
- **For example, if $1/g_{m1} = R_L$ then the gain provided by the CS stage equals 1 whereas the output of CD stage is 0.5 of the input**

Common Gate (CG) Amplifier





- CG Amplifier- Input is applied at the Source and the output is sensed at the Drain. The Gate terminal is used for establishing appropriate bias conditions for the transistor.
- Its characteristic can be studies through large-signal behavior as well.
- For large V_{in} i.e. for $V_{in} > V_b - V_T$: M_1 is off and therefore: $V_{out} = V_{DD}$
- For lower V_{in}: $I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_b - V_{in} - V_T)^2$

Common Gate (CG) Amplifier (contd.)

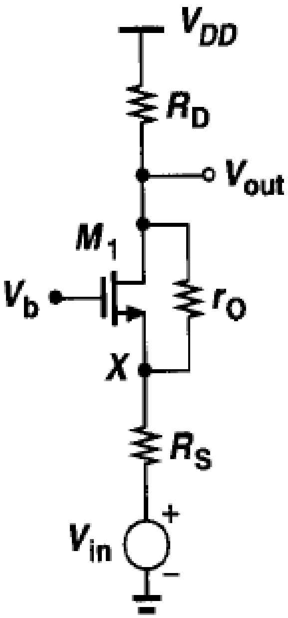
- For saturated M_1: $V_{out} = V_{DD} - I_D R_D = V_{DD} - \left(\frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_b - V_{in} - V_T)^2 \right) R_D$
- Then small signal gain is: $\frac{\partial V_{out}}{\partial V_{in}} = -\left(\mu_n C_{ox} \frac{W}{L} (V_b - V_{in} - V_T) \left(-1 - \frac{\partial V_T}{\partial V_{in}} \right) \right) R_D$
- Since, $\partial V_T / \partial V_{in} = \partial V_T / \partial V_{SB} = \eta$: $\frac{\partial V_{out}}{\partial V_{in}} = \mu_n C_{ox} \frac{W}{L} (V_b - V_{in} - V_T)(1 + \eta) R_D$

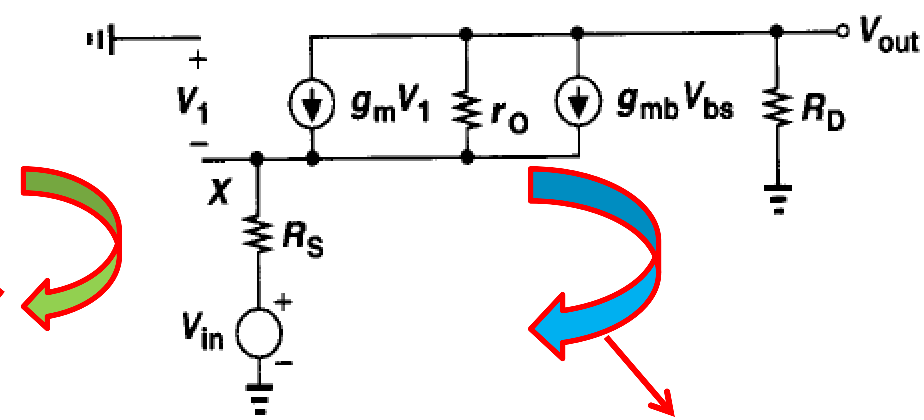
$$A_v = g_m (1 + \eta) R_D$$

Non-inverting Amplifier

Higher as compared to CS gain

Common Gate (CG) Amplifier (contd.)





KVL in loop-1:

$$V_1 - \frac{V_{out}}{R_D} R_S + V_{in} = 0$$

KVL in loop-2:

$$V_{out} = r_o \left(\frac{-V_{out}}{R_D} - g_m V_1 - g_{mb} V_1 \right) - \frac{V_{out}}{R_D} R_S + V_{in}$$

- **Simplification gives:** $$\frac{V_{out}}{V_{in}} = A_v = \frac{(g_m + g_{mb}) r_o + 1}{r_o + (g_m + g_{mb}) r_o R_S + R_S + R_D} R_D$$

CG Amplifier (contd.)

$$\frac{V_{out}}{V_{in}} = A_v = \frac{(g_m + g_{mb})r_o + 1}{r_o + (g_m + g_{mb})r_o R_S + R_S + R_D} R_D$$

Non-inverting with slightly higher value as compared to the CS stage → body effect is useful in this scenario

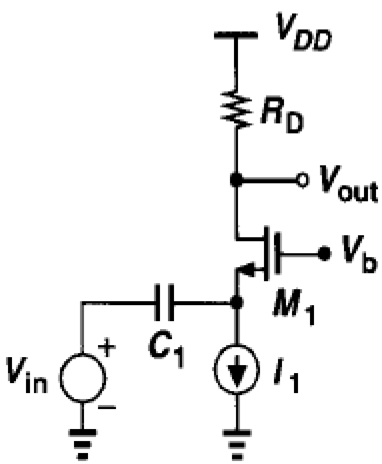
- If the resistor R_D is replaced by a current source then:

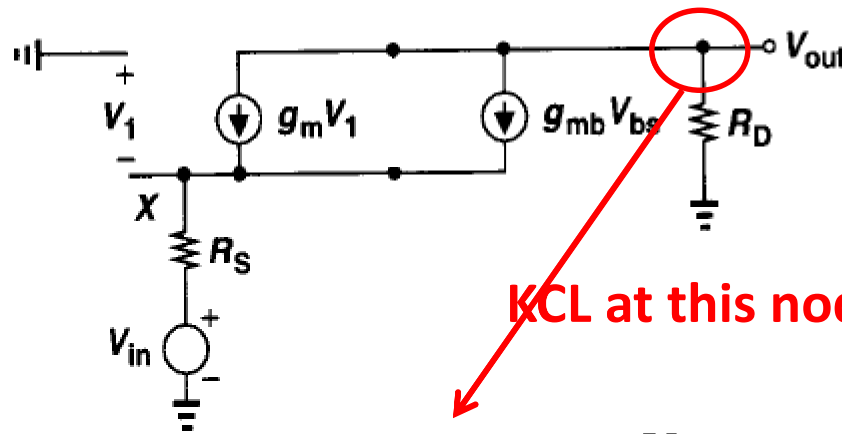
$$\frac{V_{out}}{V_{in}} = A_v = (g_m + g_{mb})r_o + 1$$

$R_D \rightarrow \infty$ for an ideal current source

CG Amplifier (contd.)

- Let us look at small-signal model – without channel length modulation and biased with a constant current source





KVL in loop-1

KCL at this node

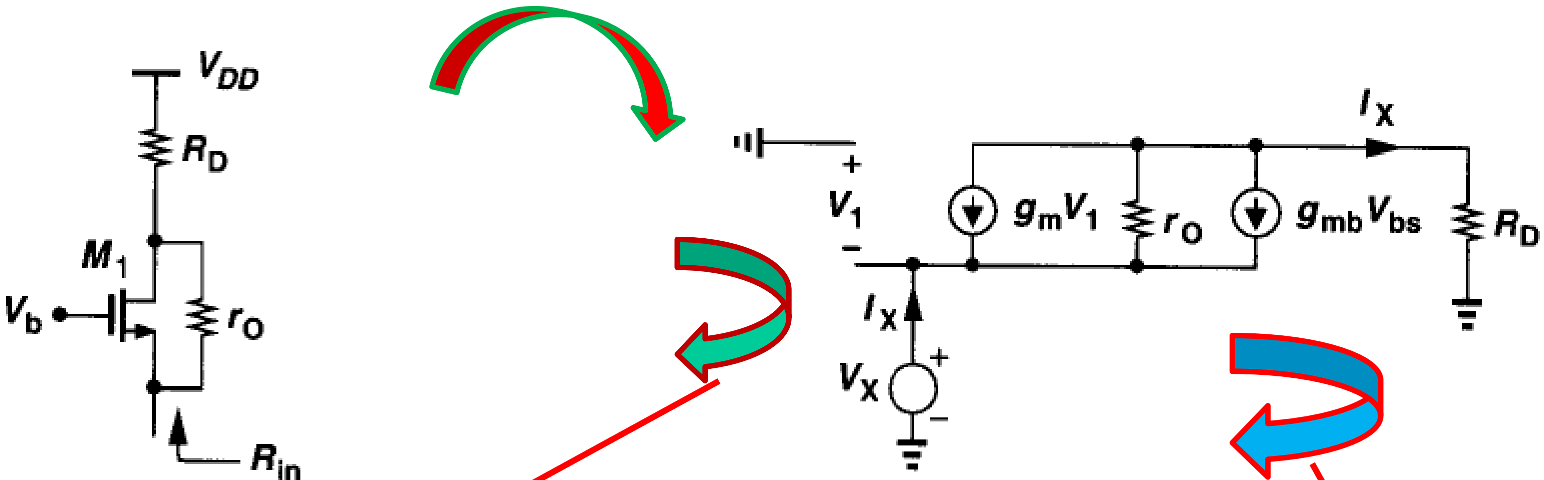
$$v_1 + v_{in} = 0$$

$$(g_m + g_{mb})V_1 + \frac{V_{out}}{R_D} = 0$$

$$\Rightarrow A_v = \frac{V_{out}}{V_{in}} = (g_m + g_{mb})R_D = g_m(1+\eta)R_D$$

CG Amplifier (contd.)

- **Input Impedance**



KVL in loop-1:

KVL in loop-2:

$$V_1 = -V_X$$

$$R_D I_X + r_o\left[I_X - (g_m + g_{mb})V_X\right] = V_X$$

$$R_{in} = \frac{V_X}{I_X} = \frac{R_D + r_o}{1 + (g_m + g_{mb})r_o} \approx \frac{R_D}{(g_m + g_{mb})r_o} + \frac{1}{(g_m + g_{mb})}$$

CG Amplifier (contd.)

$$R_{in} = \frac{V_X}{I_X} = \frac{R_D + r_o}{1 + (g_m + g_{mb}) r_o} \approx \frac{R_D}{(g_m + g_{mb}) r_o} + \frac{1}{(g_m + g_{mb})}$$

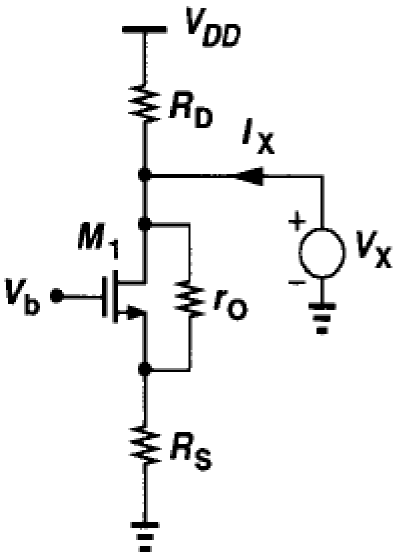
- **Case-I:** $R_D = 0$ ⇒ $R_{in} = \frac{V_X}{I_X} = \frac{r_o}{1 + (g_m + g_{mb}) r_o}$

- **Case-II:** R_D is an ideal current source ie, $R_D \rightarrow \infty$ ⇒ $R_{in} \rightarrow \infty$

It is apparent that the input impedance of common-gate stage is low only if the load impedance connected to the drain is low

CG Amplifier (contd.)

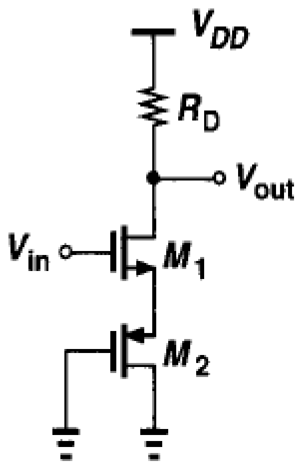
- **Output Impedance**



$$R_{out} = \{[1 + (g_m + g_{mb})r_o]R_S + r_o\} \,||\, R_D$$

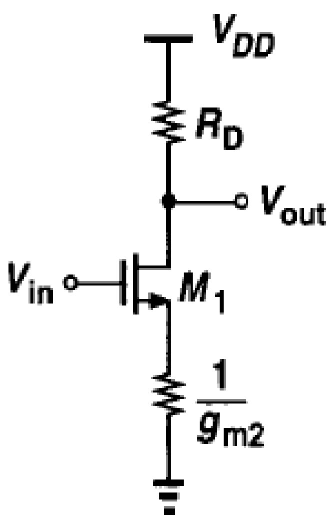
Example – 1

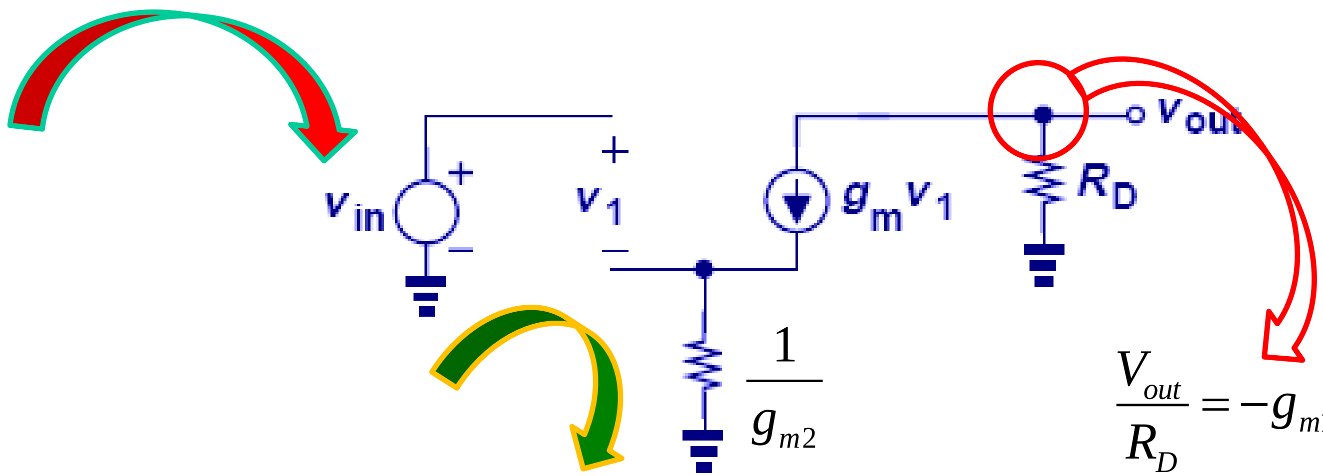
- Derive the small-signal voltage gain expression for the following amplifier. Consider the cases when channel length modulation are absent and present.



Example – 1 (contd.)

- **Case-I:** $\lambda = 0$ both for M_1 and M_2 → In such a case M_2 presents a degenerating impedance of $1/g_{m2}$ to a single stage CS amplifier as shown below.





$$\frac{V_{out}}{R_D} = -g_{m1}V_1$$

$$V_{in} = V_1 + g_{m1}V_1 \cdot \frac{1}{g_{m2}} = V_1\left(1 + \frac{g_{m1}}{g_{m2}}\right)$$

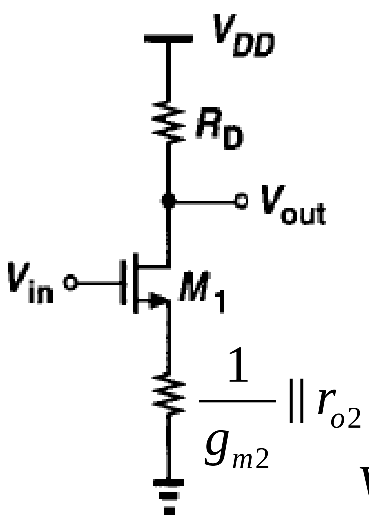
Simplification gives: $V_{out} = -g_{m1}V_1R_D$

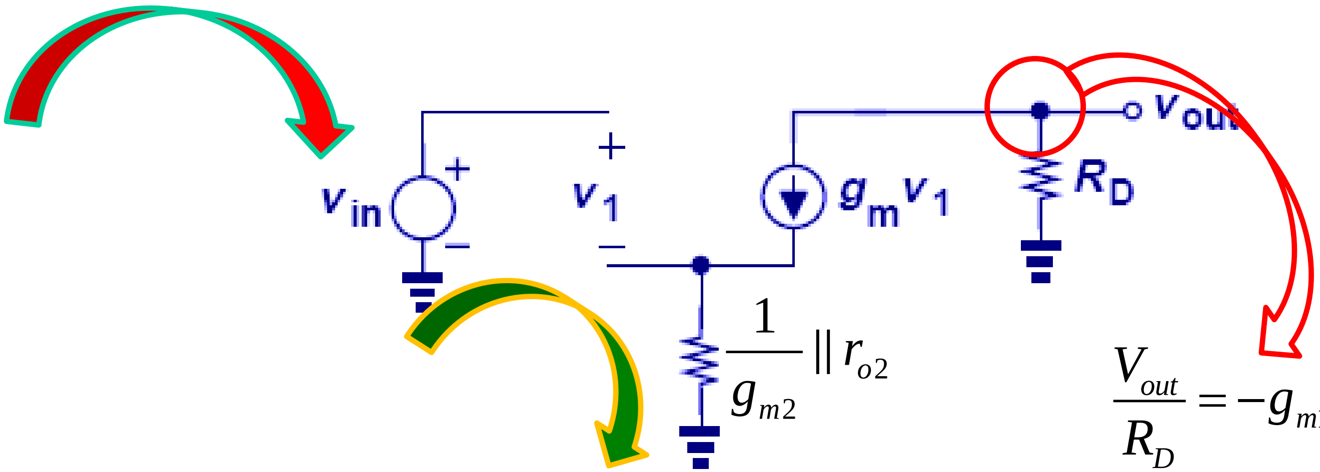
$$\Rightarrow V_{out} = -g_{m1}R_D \cdot \frac{g_{m2} \cdot V_{in}}{g_{m2} + g_{m1}}$$

$$\therefore A_v = -\frac{R_D}{\dfrac{1}{g_{m1}} + \dfrac{1}{g_{m2}}}$$

Example – 1 (contd.)

- **Case-II:** $\lambda = 0$ for M_1 and $\lambda \neq 0$ for M_2 → In such a case M_2 presents a degenerating impedance of $(1/g_{m2} \| r_{o2})$ as shown below.





$$\frac{V_{out}}{R_D} = -g_{m1} V_1$$

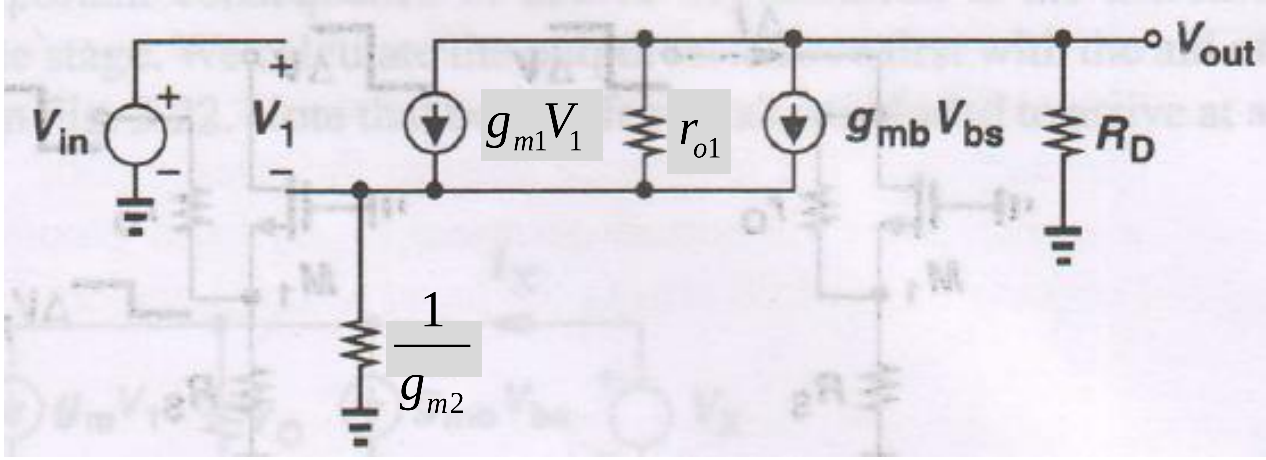
$$V_{in} = V_1 + g_{m1} V_1 \cdot \left(\frac{1}{g_{m2}} \| r_{o2} \right) = V_1 \left(1 + g_{m1} \left(\frac{1}{g_{m2}} \| r_{o2} \right) \right)$$

Simplification gives:

$$\therefore A_v = -\frac{R_D}{\frac{1}{g_{m1}} + \left(\frac{1}{g_{m2}} \| r_{o2} \right)}$$

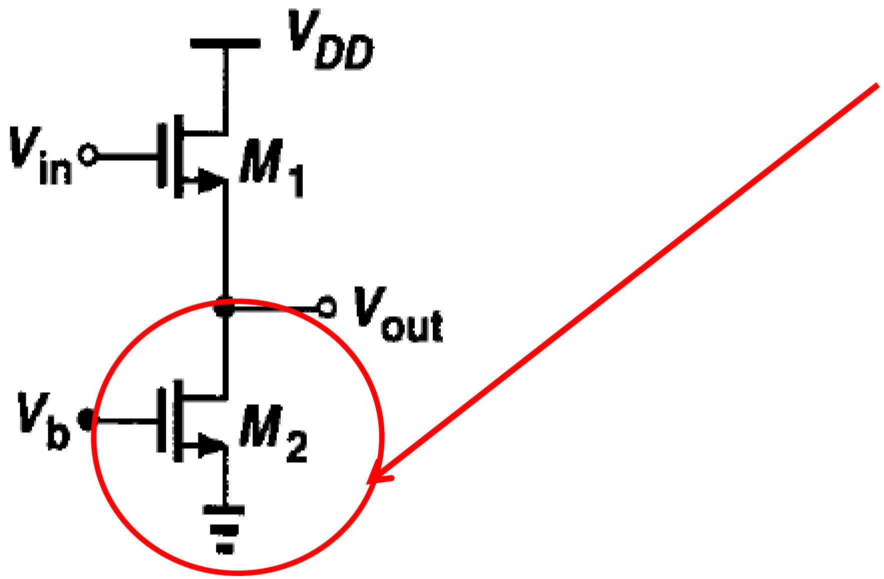
Example – 1 (contd.)

- **Case-III:** $\lambda = 0$ for M_2 and $\lambda \neq 0$ for M_1 → In such a case the small signal model looks like:

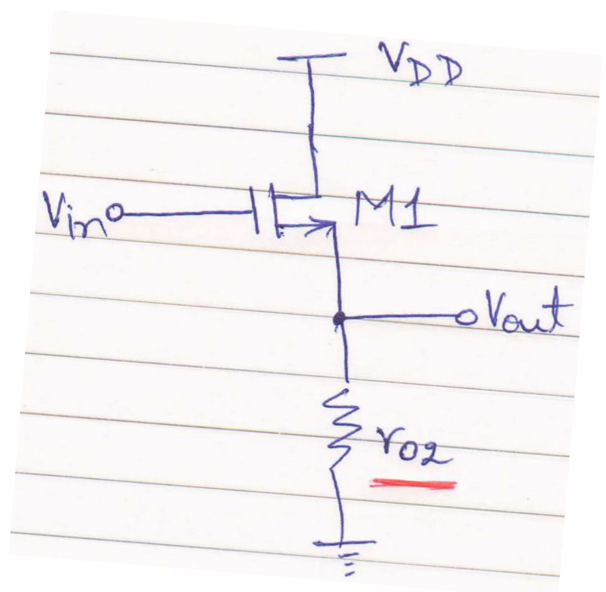


Example – 2

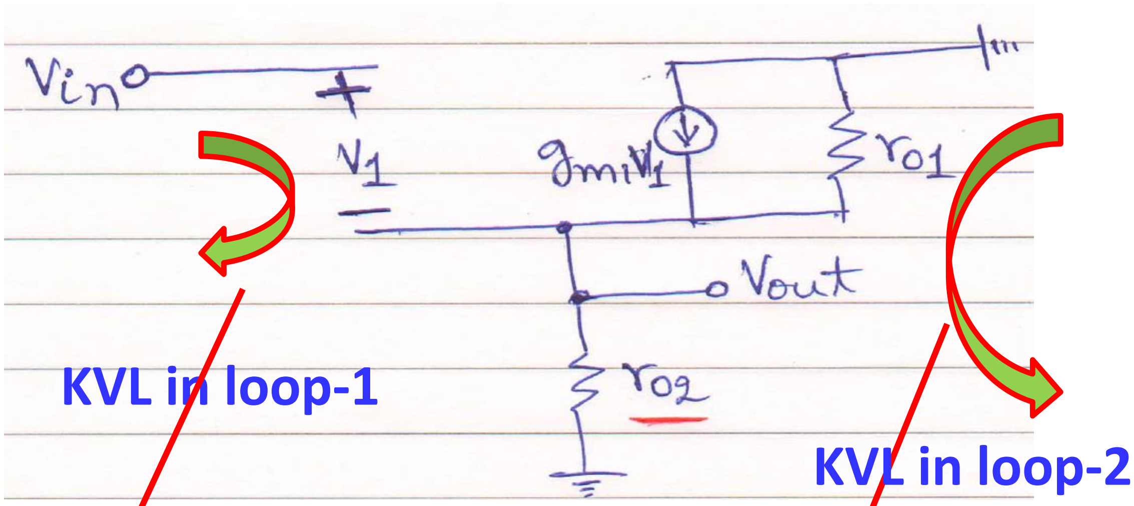
- Derive expression for the small-signal voltage gain of the following circuit. (Assume: $\lambda \neq 0$ for both M_1 and M_2. Neglect body effect)



Gate and Source are fixed. Therefore this NMOS works as a constant current source with an impedance r_{o2} across its drain and source



Example – 2 (contd.)



$$V_{in} = V_1 + V_{out}$$

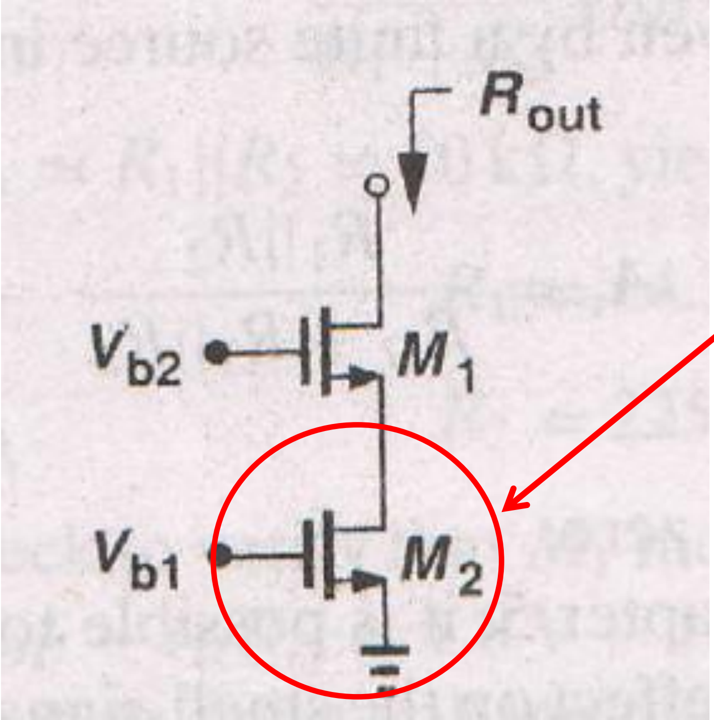
$$g_{m1} V_1 (r_{o1} \| r_{o2}) = V_{out}$$

$$g_{m1}(V_{in} - V_{out})(r_{o1} \| r_{o2}) = V_{out}$$

$$\therefore A_v = \frac{V_{out}}{V_{in}} = \frac{(r_{o1} \| r_{o2})}{\left[\frac{1}{g_{m1}} + (r_{o1} \| r_{o2})\right]}$$

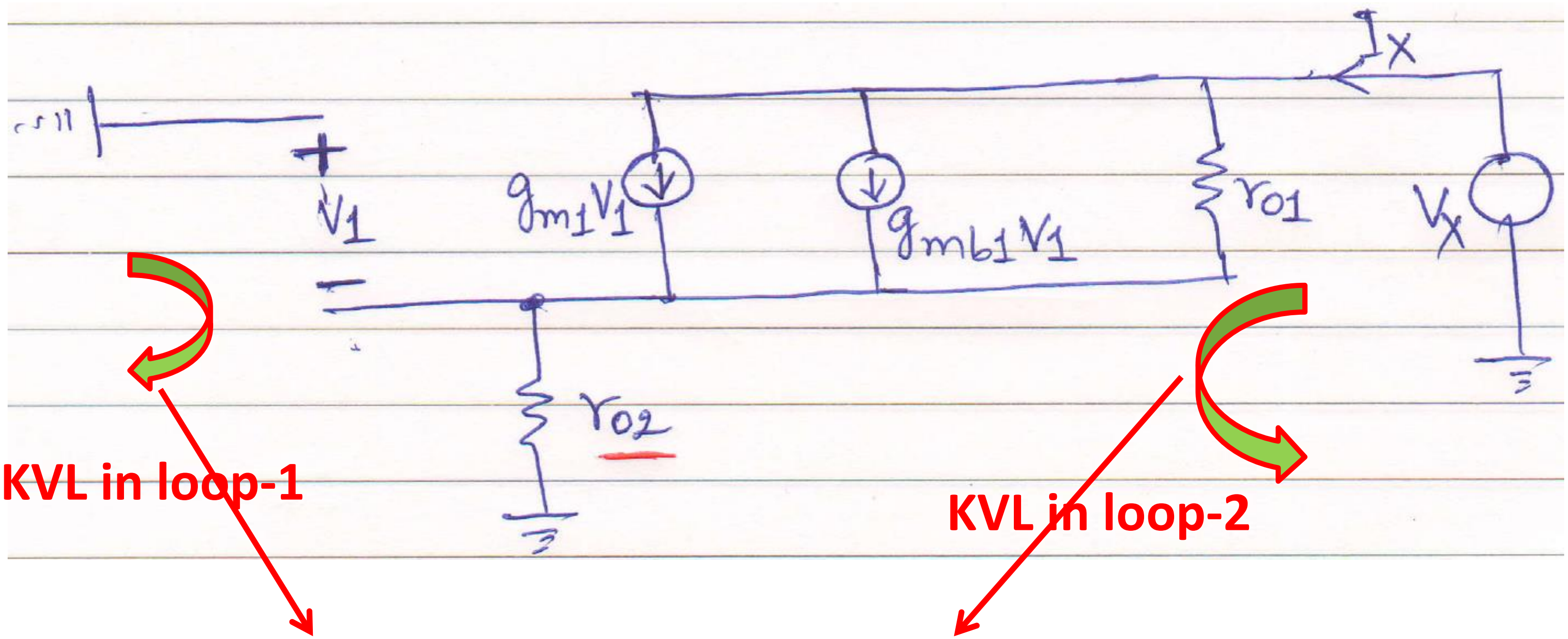
Example – 3

- What is R_{out} in the following circuit. (Assume: $\lambda \neq 0$ for both M_1 and M_2 and both are in saturation.)



Gate and Source are fixed.
Therefore this NFET works as a constant current source with an impedance r_{o2} across its drain and source

Example – 3 (contd.)



$$V_1 = -I_X r_{o2}$$

$$V_X = I_X r_{o2} + (I_X - g_{m1}V_1 - g_{mb1}V_1) r_{o1}$$

$$\Rightarrow \frac{V_X}{I_X} = r_{o2} + r_{o1} + r_{o1}(g_{m1} r_{o2} + g_{mb1} r_{o2}) = R_{out}$$

Example – 3 (contd.)

$$R_{out} = r_{o2} + r_{o1} + r_{o1}(g_{m1}r_{o2} + g_{mb1}r_{o2})$$

$$\Rightarrow R_{out} = r_{o2} + r_{o1}\left[1 + r_{o2}(g_{m1} + g_{mb1})\right]$$

$$\therefore R_{out} = r_{o1} + r_{o2}\left[1 + r_{o1}(g_{m1} + g_{mb1})\right]$$

However: $r_{o1}(g_{m1}r_{o2} + g_{mb1}r_{o2}) \gg r_{o1}$

$$\Rightarrow r_{o1}(g_{m1}r_{o2} + g_{mb1}r_{o2}) \gg r_{o2}$$

$$\therefore R_{out} \approx (g_{m1} + g_{mb1})r_{o1}r_{o2}$$