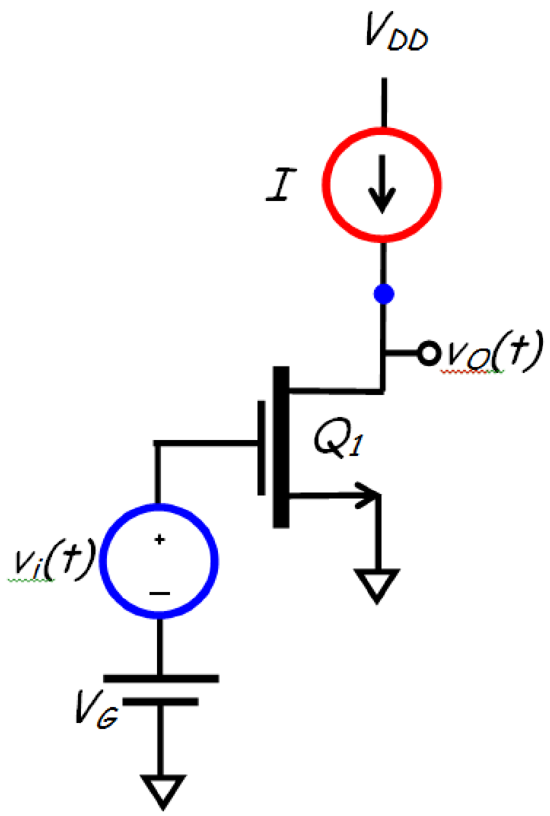
Lecture – 7 **Date: 27.08.2015**

- Common Source Amplifier with Constant Current Source, Triode Load, Source Degenerated Resistor
- Examples

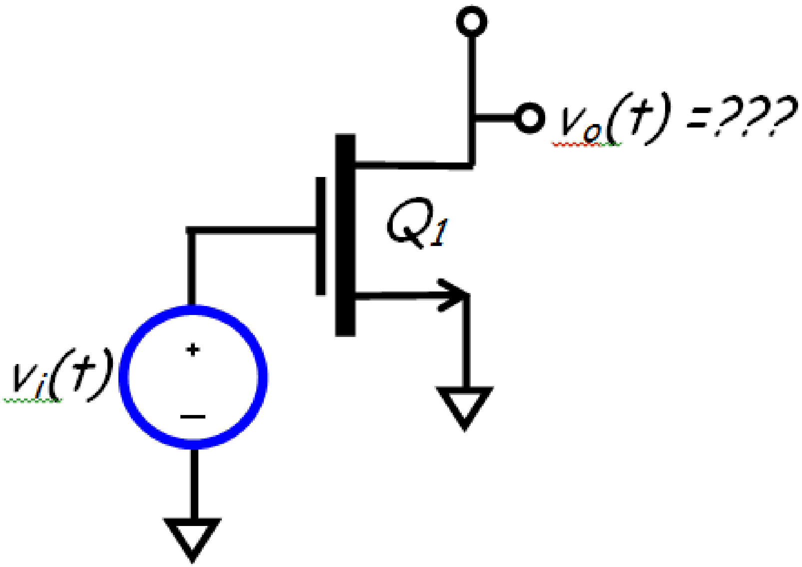
CS Amplifier with Constant Current Source



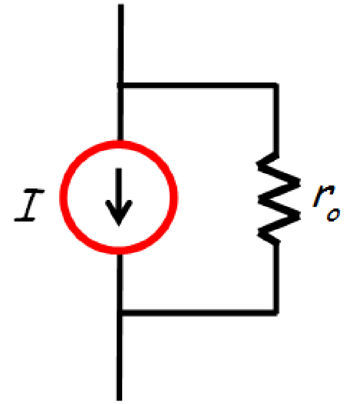
- Now consider this NMOS amplifier using a **current source**.
  - Note **no** resistors or capacitors are present!
  - This is a **common source** amplifier.
  - I_D stability **is not a problem!**

CS Amplifier with Constant Current Source (contd.)

Q: I don't understand! Wouldn't the small-signal circuit be:



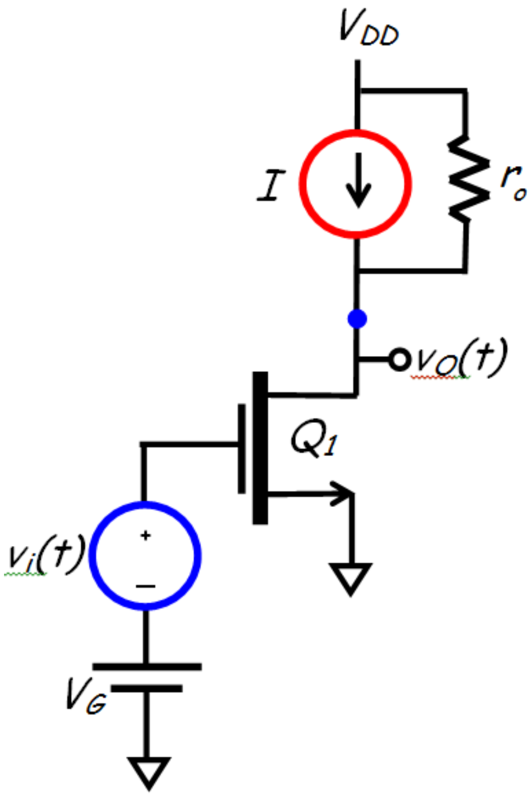
A: Remember, every **real** current source (as with every voltage source) has a **source resistance** $\boldsymbol{r_o}$. A more **accurate** current source model is therefore:



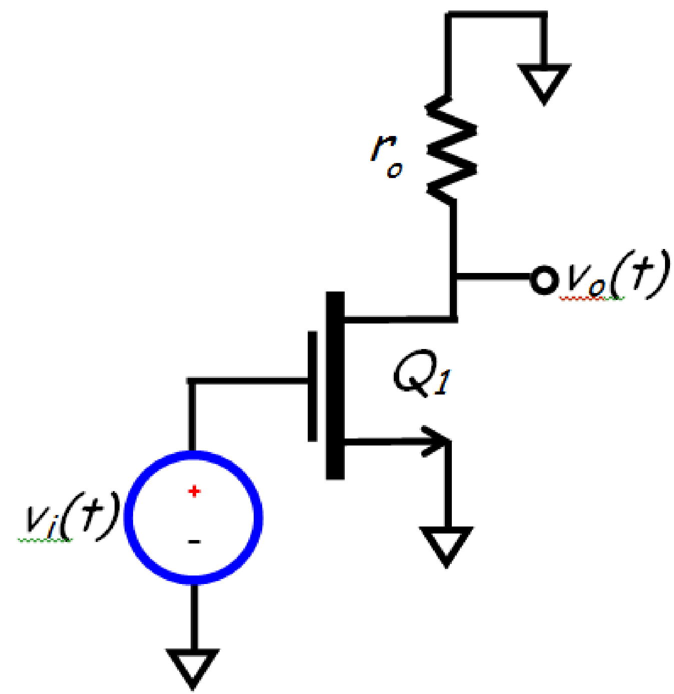
Ideally, $r_o = \infty$. However, for good current sources, this output resistance is large (e.g., $r_o = 100\ k\Omega$). Thus, we mostly **ignore** this value (i.e., approximate it as $r_o = \infty$), but there are some circuits where this resistance makes quite a **difference**. → **This** is one of those circuits!

CS Amplifier with Constant Current Source (contd.)

- Therefore, a more **accurate** amplifier circuit schematic is:

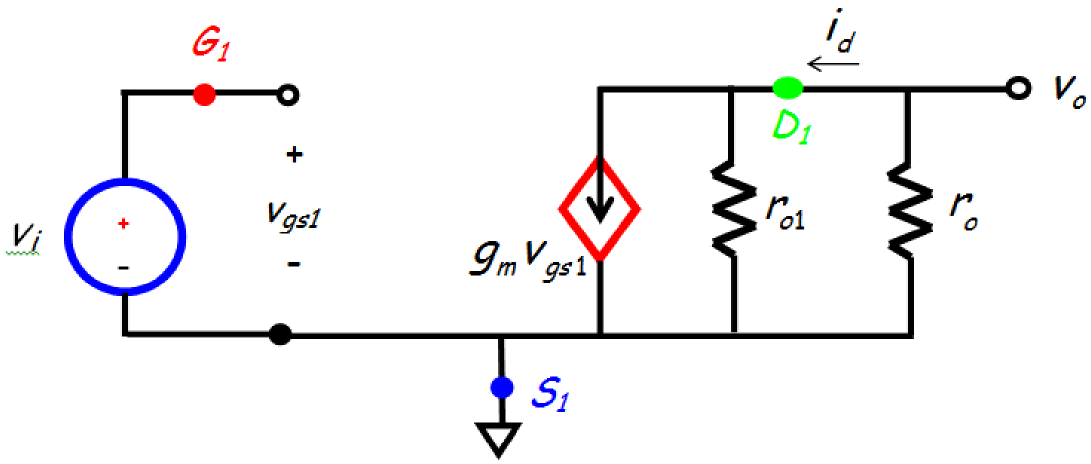


- And so the **small-signal circuit** becomes the familiar:



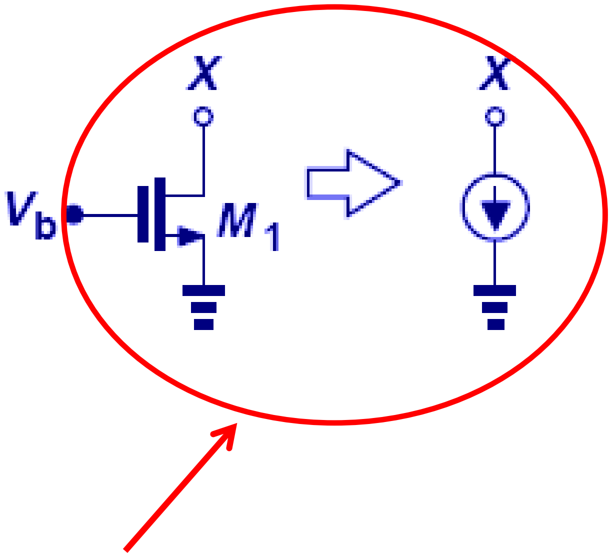
CS Amplifier with Constant Current Source (contd.)

- Therefore, the small signal model is:

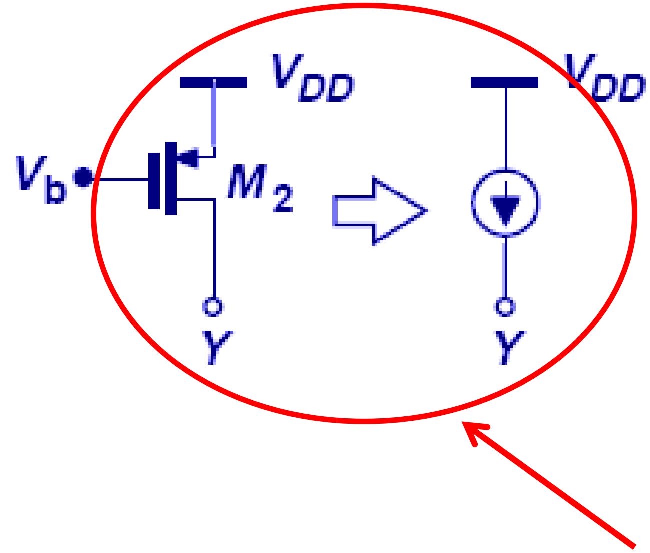


Now go ahead and do the analysis

Constant Current Source



NFET ideal current source

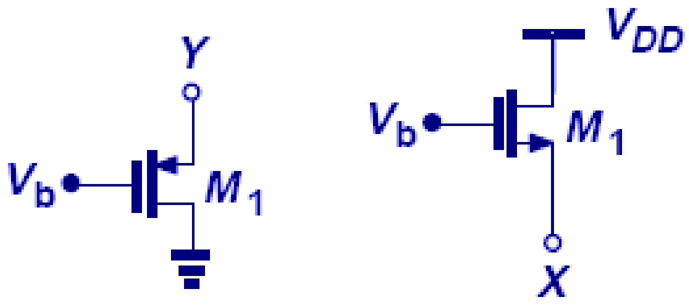


PFET ideal current source

- As long as a MOS transistor is in saturation region and $\lambda=0$, the current is independent of the drain voltage and it behaves as an ideal current source seen from the drain terminal.

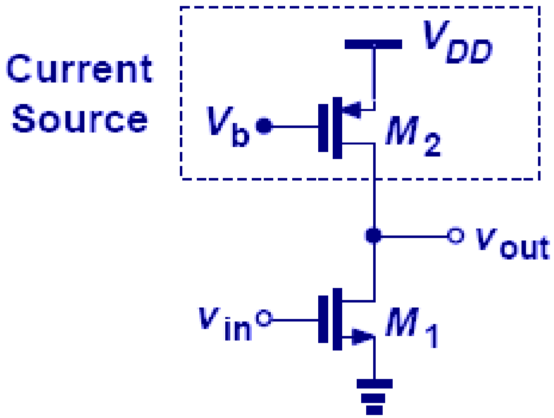
Constant Current Source (contd.)

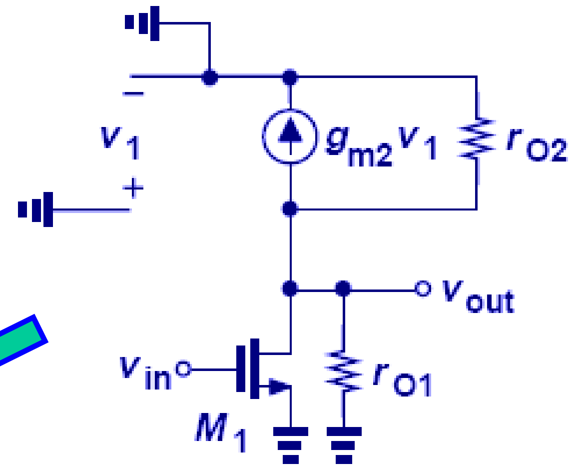
Example of poor current source

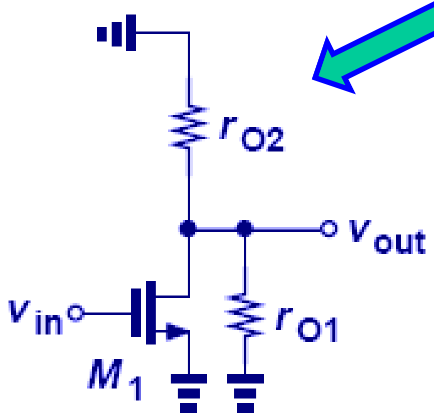


- Since the variation of the source voltage directly affects the current of a MOS transistor, it does not operate as a good current source if seen from the source terminal

CS Amplifier with Constant Current Source (contd.)







- The dc voltage V_{GS2} is constant and therefore v_1 =0 → **leads to $g_{m2}v_1$ =0**

CS Amplifier with Constant Current Source (contd.)

$$A_v = -g_{m1}(r_{o1} \| r_{o2})$$

- Both the load and the device operates in saturation
- The gain is loosely dependent on $|V_{DS}|$ of M_2 → as it regulates the r_{o2}
- The voltage $|V_{DS2,min}| = |V_{GS2} - V_{T2}|$ can be reduced → by increasing $(W/L)_2$ → increases V_{D1} → in essence the output voltage swing
- r_{o2} can be increased → by reducing the channel length modulation effect → through increasing the length and width of M_2 → while keeping $|V_{GS2} - V_{T2}|$ constant → However, this also brings large capacitance at the output of M_2.
- At a given drain current, W has to increase with the increasing L (r_o α L/I_D) for obtaining higher gain
- If length of M_1 is increased by a factor → then the width has to be increased proportionally → for a given I_{D1}, $V_{GS1}–V_{T1}$ is directly proportional to $(W/L)_1$ → if W_1 is not scaled properly then it will reduce $V_{GS1}–V_{T1}$ → will effectively lead to reduced voltage swing

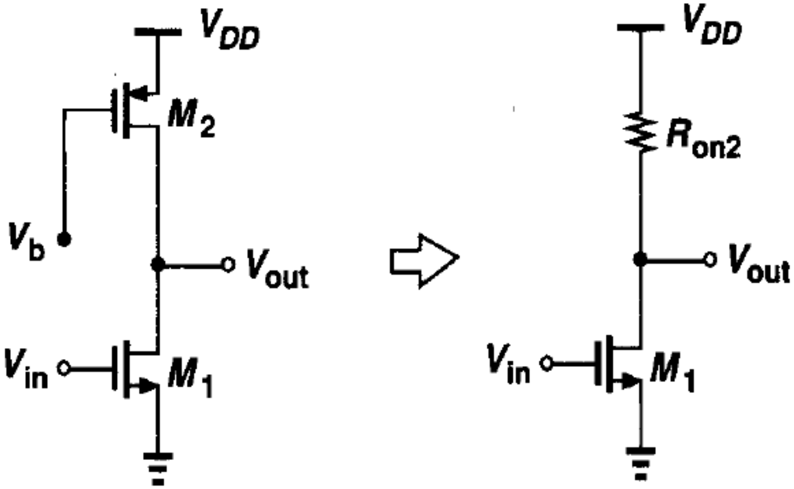
CS Amplifier with Constant Current-Source Load (contd.)

- Furthermore, just scaling of L_1 leads to reduced g_{m1} → in essence possibility of reduced gain
- However,

$$g_{m1}r_{o1} = \sqrt{2\left(\frac{W}{L}\right)_1 \mu_n C_{ox} I_D}\,\frac{1}{\lambda I_D}$$

- The gain will increase with increasing L_1 considering that λ depends more strongly on L than g_m does
- for M_2, increase in L_2 while keeping W_2 constant → increases r_{o2} → increases gain of the CS amplifier → but decreases $|V_{DS2}|$ → reduces the output voltage swing

CS Amplifier with Triode Load

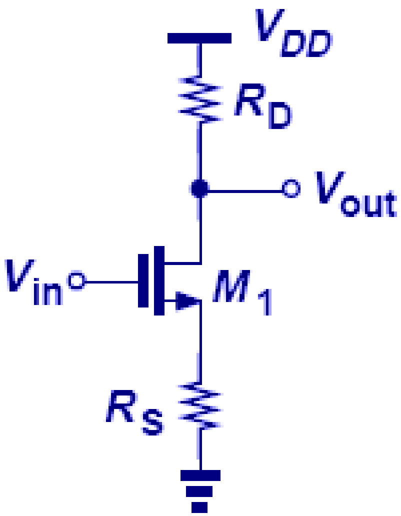


$$R_{on2} = \frac{1}{\mu_p C_{ox}(W/L)_2(V_{DD} - V_b - |V_{TP}|)}$$

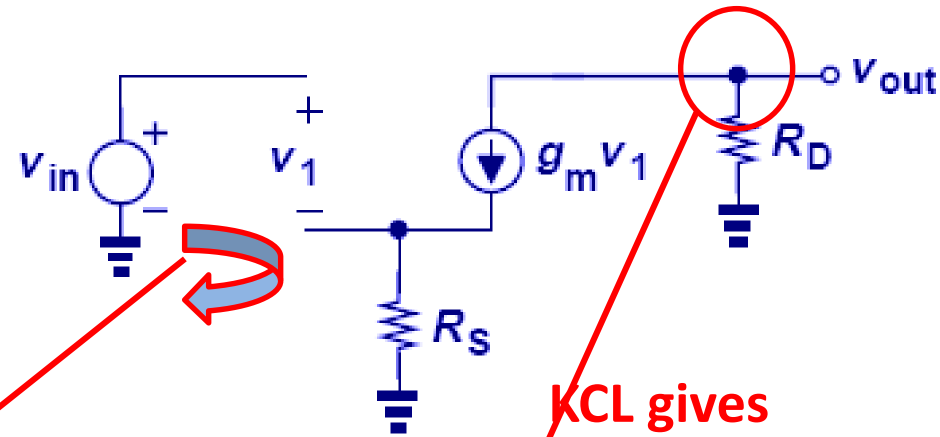
$$A_v = -g_{m1}R_{on2} \qquad A_v = -g_{m1}(r_{o1} \| R_{on2})$$

- The main limitation of this technique is the dependence of gain on the process parameters → because R_{on} is dependent on these parameters
- Process parameters are temperature dependent → makes gain dependent on temperature
- Triode loads consume less voltage headroom as compared to diode-connected load → Here, $V_{out,max}=V_{DD}$

CS Amplifier with Source Degeneration



small signal model



KVL gives

KCL gives

$$v_{in} = v_1 + g_m v_1 R_S$$

$$g_m v_1 = -\frac{v_{out}}{R_D} \quad \Rightarrow v_1 = -\frac{v_{out}}{g_m R_D}$$

$$\therefore v_{in} = -\frac{v_{out}}{g_m R_D}\left(1 + g_m R_S\right)$$

Circuit Design Research Lab

CS Amplifier with Source Degeneration (contd.)

- **Therefore the voltage gain:** $A_v = \frac{v_{out}}{v_{in}} = -\frac{g_m R_D}{(1 + g_m R_S)}$
- **The input resistance:** $R_{in} = \infty$
- **The output resistance:** $R_{out} = R_D$
- **For large R_S:** $A_v = -\frac{R_D}{R_S}$ ← **Linear**

Valid as long as M_1 is in saturation

$V_{DD} - V_{in} + V_T > I_D R_D$ ← $V_{DD} - I_D R_D > V_{in} - V_T$

- **A_v drops when:** $V_{DD} - V_{in} + V_T < I_D R_D$ ← **M_1 goes in triode**

Even with all the supposed benefits of this configuration, the major drawback is the reduced small-signal gain

CS Amplifier with Source Degeneration (contd.)

$$A_v = \frac{v_{out}}{v_{in}} = -\frac{g_m}{(1+g_m R_S)} R_D$$

G_m — **Equivalent Circuit Transconductance**

$$G_m = \frac{g_m}{1+g_m R_S} = \frac{1}{(1/g_m)+R_S}$$

For large V_{in} (while M_1 still in saturation) → g_m is high → G_m approaches $1/R_S$

$$\Rightarrow A_v = -\frac{R_D}{R_S}$$

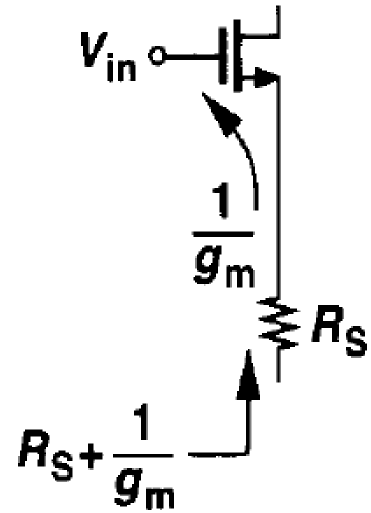
Linear

Reduced Gain

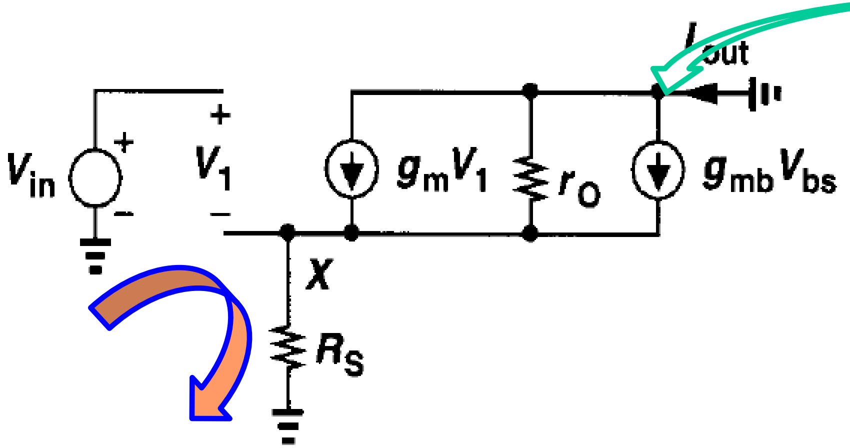
CS Amplifier with Source Degeneration (contd.)

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

Ratio of impedances in the drain and source path



With channel length modulation and body effect



KCL at output:

$$I_{out} = g_m V_1 - g_{mb} V_x - \frac{I_{out} R_S}{r_o}$$

$$\Rightarrow I_{out} = g_m (V_{in} - I_{out} R_S) + g_{mb}(-I_{out} R_S) - \frac{I_{out} R_S}{r_o}$$

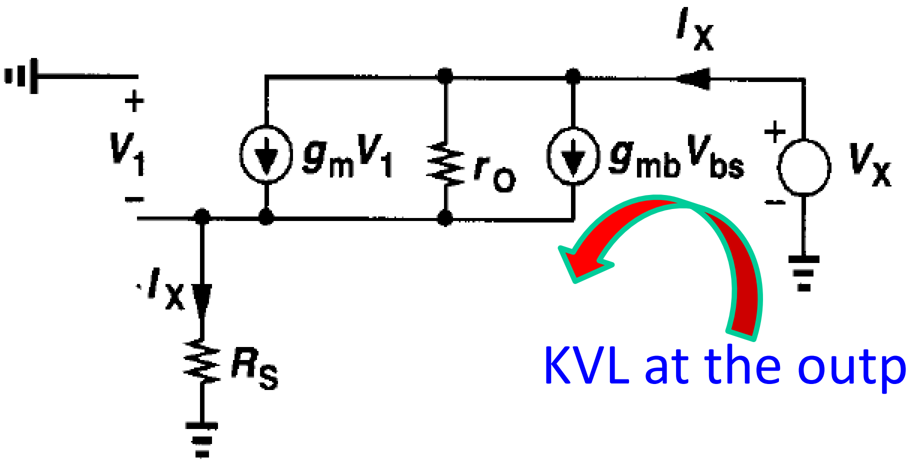
KVL at input:

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

$$\therefore G_m = \frac{I_{out}}{V_{in}} = \frac{g_m r_o}{R_S + [1+(g_m+g_{mb})R_S] r_o}$$

CS Amplifier with Source Degeneration (contd.)

Output Resistance



Current through R_S is I_X

$$\Rightarrow V_1 = -I_X R_S$$

Current through r_o is:

$$\Rightarrow I_{r_o} = I_X - (g_m + g_{mb})V_1$$

KVL at the output: $V_X = r_o\left[I_X + (g_m + g_{mb})R_S I_X\right] + I_X R_S$

$$\Rightarrow R_{out} = \frac{V_X}{I_X} = r_o\left[1 + (g_m + g_{mb})R_S\right] + R_S \;\; = \left[1 + (g_m + g_{mb})r_o\right]R_S + r_o$$

Usually, $(g_m + g_{mb})r_o >> 1$ $\quad \therefore R_{out} \approx (g_m + g_{mb})r_o R_S + r_o$

$$\Rightarrow R_{out} \approx \left[1 + (g_m + g_{mb})R_S\right]r_o$$

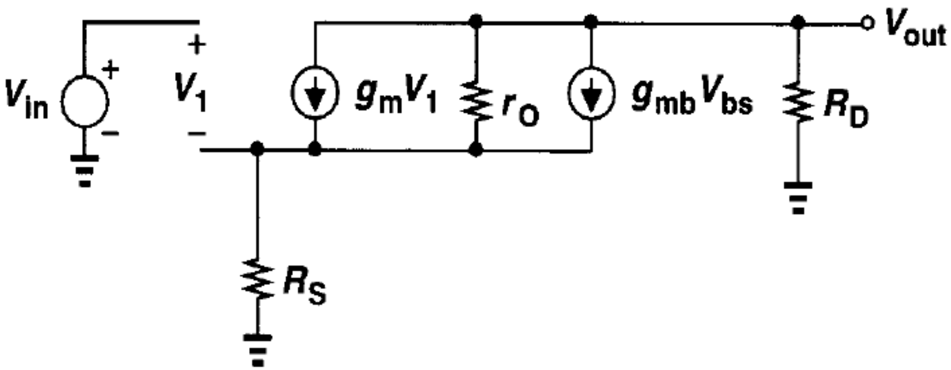
Output impedance has increased by this factor

Definitely a good prospect for applications requiring higher output impedance

Yes! It comes with a price → reduced gain

CS Amplifier with Source Degeneration (contd.)

Small-signal gain



$$A_v = -\frac{V_{out}}{V_{in}}$$

$$= -\frac{g_m r_o R_D}{R_D + R_S + [1 + (g_m + g_{mb}) R_S] r_o}$$

R_{out}

$$A_v = -\frac{g_m r_o R_D}{R_D + R_S + [1 + (g_m + g_{mb}) R_S] r_o} \cdot \frac{R_S + [1 + (g_m + g_{mb}) R_S] r_o}{R_S + [1 + (g_m + g_{mb}) R_S] r_o}$$

For Simplification

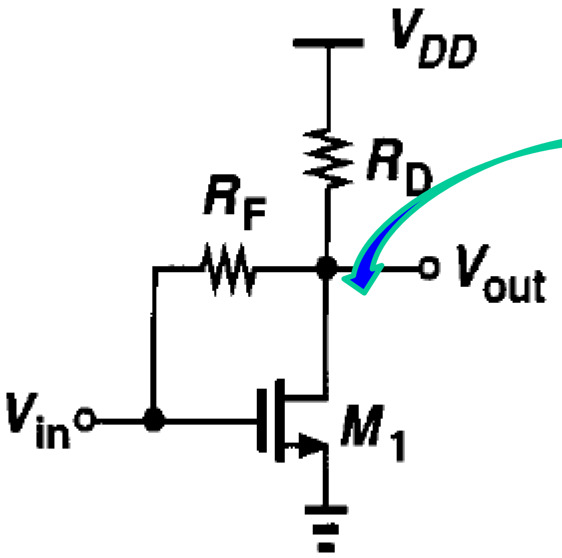
$$A_v = -\frac{g_m r_o}{R_S + [1 + (g_m + g_{mb}) R_S] r_o} \cdot \frac{\left[R_S + [1 + (g_m + g_{mb}) R_S] r_o\right] R_D}{R_D + R_S + [1 + (g_m + g_{mb}) R_S] r_o}$$

G_m

$R_D || R_{out}$

Example – 1

- Assuming M_1 in saturation, calculate the small signal voltage gain of the following:



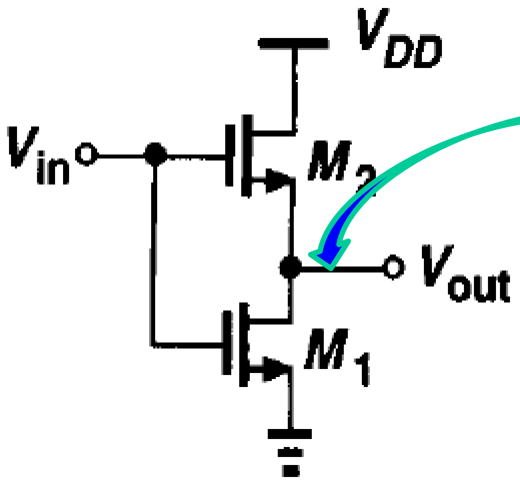
KCL at the output node:

$$\frac{v_{out}-v_{in}}{R_F}+g_{m1}v_{in}+\frac{v_{out}}{r_{o1}}+\frac{v_{out}}{R_D}=0$$

$$A_v=\frac{v_{out}}{v_{in}}=-\frac{g_{m1}-\frac{1}{R_F}}{\frac{1}{R_F}+\frac{1}{r_{o1}}+\frac{1}{R_D}}$$

Example – 2

- Assuming both M_1 and M_2 in saturation, calculate the small signal voltage gain of the following:



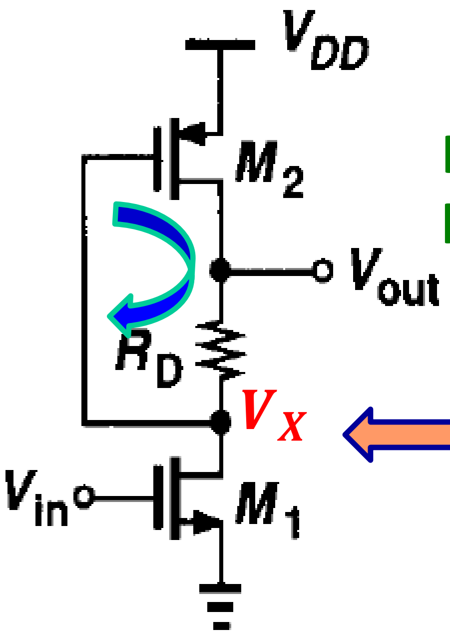
KCL at the output node:

$$g_{m2}(v_{in} - v_{out}) + \left(\frac{-v_{out}}{r_{o2}}\right) = g_{m1}v_{in} + \frac{v_{out}}{r_{o1}}$$

$$A_v = \frac{v_{out}}{v_{in}} = -\frac{g_{m1} - g_{m2}}{g_{m2} + \dfrac{1}{r_{o2}} + \dfrac{1}{r_{o1}}}$$

Example – 3

- Assuming both M_1 and M_2 in saturation, calculate the small signal voltage gain of the following:



KVL in the mesh created by M_2:

$$\left(g_{m1}v_{in} + \frac{v_x}{r_{o1}}\right)R_D + v_x = v_{out}$$

KCL at this node:

$$-\left(g_{m2}v_x + \frac{v_{out}}{r_{o2}}\right) = g_{m1}v_{in} + \frac{v_x}{r_{o1}}$$

$$v_x\left(-g_{m2} - \frac{1}{r_{o1}}\right) = g_{m1}v_{in} + \frac{v_{out}}{r_{o2}}$$

$$\therefore v_x = -\frac{g_{m1}v_{in} + \frac{v_{out}}{r_{o2}}}{g_{m2} + \frac{1}{r_{o1}}}$$

Example – 3 (contd.)

$$\left(g_{m1}v_{in}+\frac{v_x}{r_{o1}}\right)R_D+v_x=v_{out} \Rightarrow g_{m1}R_Dv_{in}+\left(1+\frac{R_D}{r_{o1}}\right)v_x=v_{out}$$

- Simplification of the expressions gives:

$$g_{m1}R_Dv_{in}-\frac{\left(1+\frac{R_D}{r_{o1}}\right)\left(g_{m1}v_{in}+\frac{v_{out}}{r_{o2}}\right)}{g_{m2}+\frac{1}{r_{o1}}}=v_{out}$$

$$A_v=\frac{v_{out}}{v_{in}}=\frac{g_{m1}\left(g_{m2}R_D-1\right)}{g_{m2}+\frac{1}{r_{o1}}+\frac{1}{r_{o2}}\left(1+\frac{R_D}{r_{o1}}\right)}$$