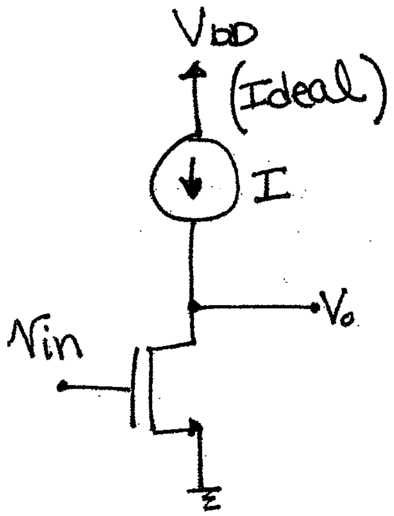
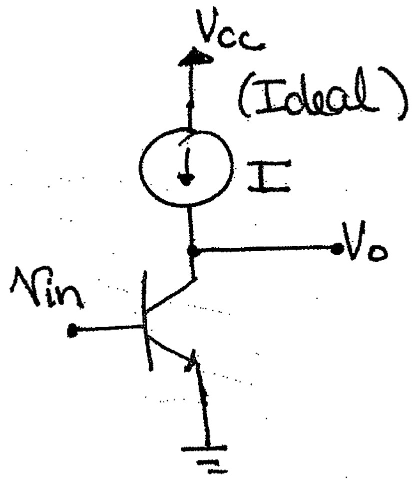
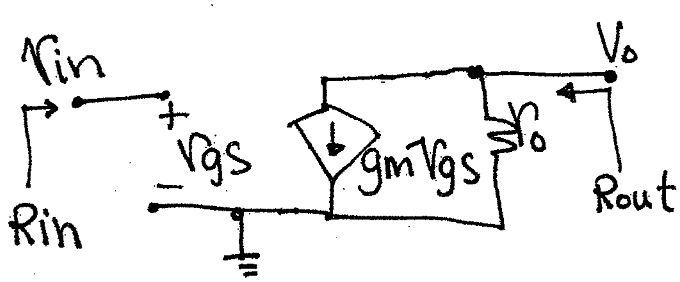
CS/CE Amplifiers





Ideal current source is open:

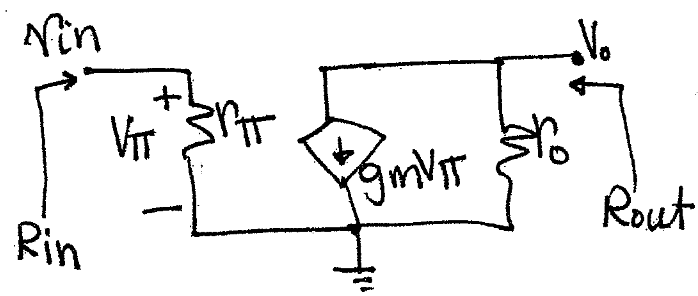


$R_{in} = \infty$

$R_{out} = r_o = \frac{V_A}{I_D}$

$\frac{v_o}{v_{in}} = A_{vo} = -g_m r_o$ ($g_m = \frac{2I_D}{V_{OV}}$)

$A_{vo} = -\frac{2V_A}{V_{OV}}$



$R_{in} = r_\pi$

$R_{out} = r_o = \frac{V_A}{I_C}$

$\frac{v_o}{v_{in}} = A_{vo} = -g_m r_o$ ($g_m = \frac{I_C}{V_T}$)

$A_{vo} = -\frac{V_A}{V_T}$

· Definition:

"intrinsic gain", $A_o = g_m r_o$

Example: $I = 100\mu A$ (for both)

$(\mu_n C_{ox}) = 267 \mu A/V^2$

$\left(\frac{W}{L}\right) = \left(\frac{4um}{.4um}\right)$

$V_A = V_A' \cdot L = 10 \frac{V}{um} \cdot 0.4 um$

$\beta = 100$

$V_A = 10V$

MOSFET:

$100\mu = I_D = \frac{1}{2}(267\mu) \cdot \left(\frac{4}{.4}\right)(V_{ov})^2$

$\therefore V_{ov} = 0.27 V$

$g_m = \frac{2 I_D}{V_{ov}} = \frac{2(100\mu)}{0.27} = 0.74m$

$R_{in} = \underline{\underline{\infty}}$

$R_{out} = r_o = \frac{V_A' \cdot L}{I_D} = \frac{10 \times 0.4}{100\mu} = \underline{\underline{40 K\Omega}}$

$A_o = g_m r_o = 0.74m \times 40K = \underline{\underline{29.6 V/V}}$

BJT:

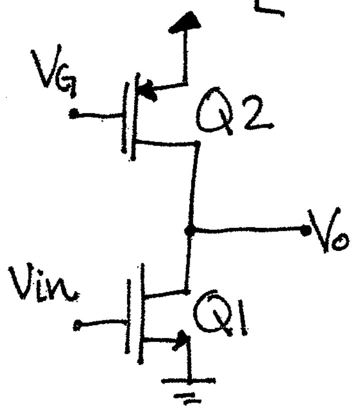
$g_m = \frac{I_c}{V_T} = \frac{100\mu}{25m} = 4m A/V$

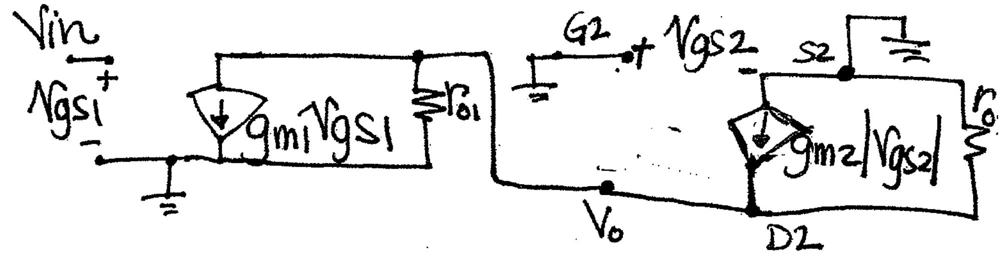
$R_{in} = r_\pi = \frac{\beta}{g_m} = \frac{100}{4m} = \underline{\underline{25K\Omega}}$

$r_o = \frac{V_A}{I_c} = \frac{10}{100\mu} = \underline{\underline{100K\Omega}} = R_{out}$

$A_o = 4m(100K) = \underline{\underline{400 V/V}}$

[Not ideal current source]:





$$V_{gs1} = V_{in}$$

Node-Voltage:

$$+g_{m1}V_{gs1} + \frac{+V_o}{r_{o1}} - g_{m2}|V_{gs2}| + \frac{V_o}{r_{o2}} = 0$$

$$V_{gs2} = 0$$

$$V_o = \frac{-g_{m1}V_{gs1}}{\frac{1}{r_{o1}} + \frac{1}{r_{o2}}} = -g_{m1}V_{gs1}(r_{o1} \| r_{o2})$$

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

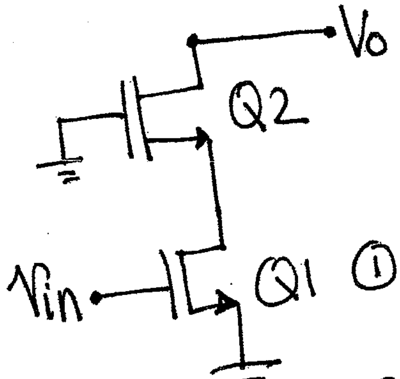
Cascode Amplifier

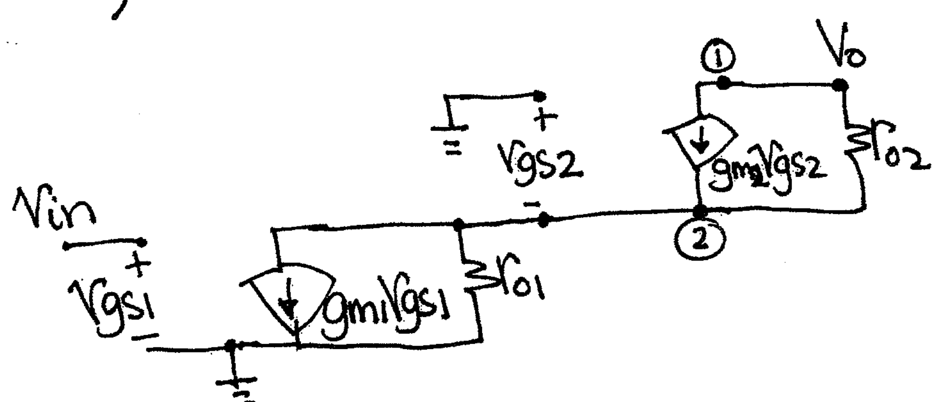
- current buffer: unity current, ↑ R_{out}
- voltage buffer: unity voltage, ↓ R_{out}
- Cascoding:

$$V_o = -g_m V_{in}(r_{o1} \| r_{o2})$$

method: connect CG (or CB) at output of CS (or CE)

mos cascode:





① $+g_{m2}V_{gs2} + \frac{(V_o-(-V_{gs2}))}{r_{o2}} = 0$

② $+g_{m1}V_{gs1} + \frac{-V_{gs2}}{r_{o1}} - g_{m2}V_{gs2} + \frac{(-V_{gs2}-V_o)}{r_{o2}} = 0$

From ①: $V_{gs2}\left(g_{m2} + \frac{1}{r_{o2}}\right) = -\frac{V_o}{r_{o2}}$

$$V_{gs2} = -\frac{V_o}{r_{o2}}\left[\frac{1}{\frac{r_{o2}g_{m2}+1}{r_{o2}}}\right] = \frac{-V_o}{r_{o2}\cdot g_{m2}+1}$$

plug into ②

$$g_{m1}(v_{in}) = V_{gs2}\left[\frac{1}{r_{o1}} + g_{m2} + \frac{1}{r_{o2}}\right] + \frac{V_o}{r_{o2}}$$

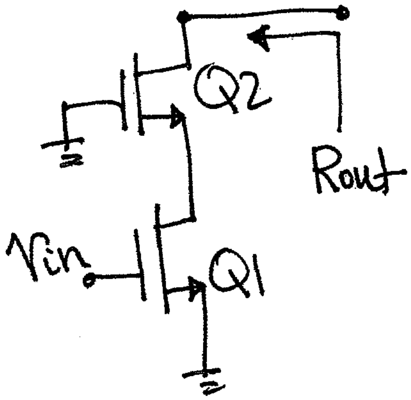
$$g_{m1}(v_{in}) = \frac{-V_o}{(1+g_{m2}r_{o2})}\left[\frac{r_{o2} + g_{m2}r_{o1}r_{o2} + r_{o1}}{r_{o1}r_{o2}}\right] + \frac{V_o(1+g_{m2}r_{o2})r_{o1}}{(1+g_{m2}r_{o2})r_{o1}r_{o2}}$$

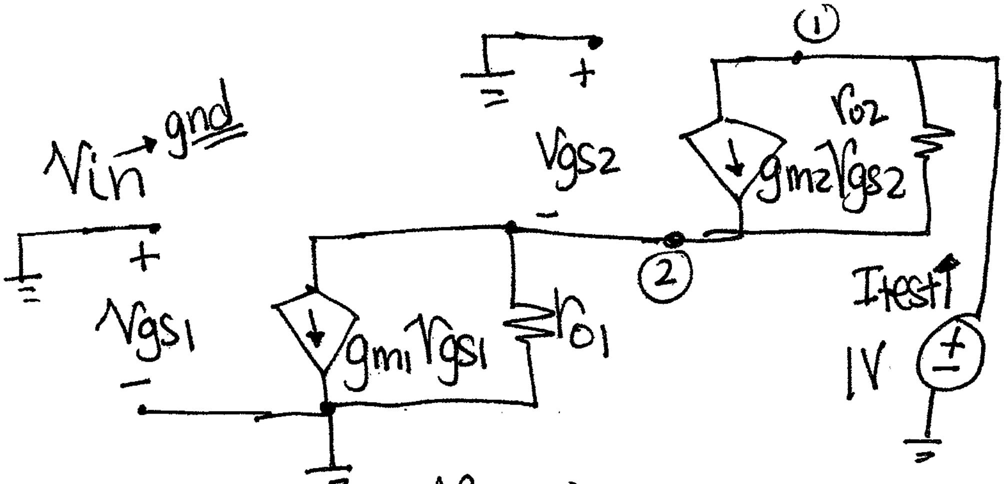
$$\left[\frac{-r_{o2} - g_{m2}r_{o1}r_{o2} - r_{o1} + r_{o1} + g_{m2}r_{o1}r_{o2}}{(1+g_{m2}r_{o2})r_{o1}r_{o2}}\right]V_o = g_{m1}(v_{in})$$

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

$$\frac{V_o}{v_{in}} = \frac{-g_{m1}(1+g_{m2}r_{o2})r_{o1}\cancel{r_{o2}}}{\cancel{r_{o2}}} = -g_{m1}r_{o1}(1+g_{m2}r_{o2})$$

Output R





$V_{gs1} = 0$

① $+g_{m2}V_{gs2} + \frac{(1+V_{gs2})}{r_{o2}} = I_{test}$

② $+\frac{-V_{gs2}}{r_{o1}} - g_{m2}V_{gs2} + \frac{(-V_{gs2}-1)}{r_{o2}} = 0$

$$V_{gs2}\left[\frac{1}{r_{o1}} + g_{m2} + \frac{1}{r_{o2}}\right] = \frac{-1}{r_{o2}}$$

$$V_{gs2}\left[\frac{r_{o2}+g_{m2}r_{o1}r_{o2}+r_{o1}}{r_{o1}r_{o2}}\right] = \frac{-1}{r_{o2}} \Rightarrow V_{gs2} = \frac{-r_{o1}}{r_{o1}+r_{o2}+g_{m2}r_{o1}r_{o2}}$$

plug back into ①

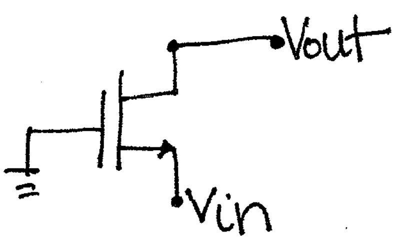
$$I_{test} = V_{gs2}\left(g_{m2}+\frac{1}{r_{o2}}\right) + \frac{1}{r_{o2}}$$

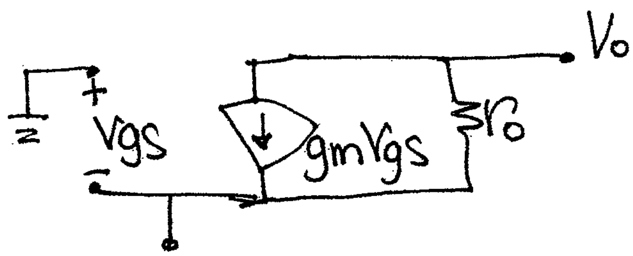
$$I_{test} = \frac{-r_{o1}[g_{m2}r_{o2}+1]}{r_{o2}(r_{o1}+r_{o2}+g_{m2}r_{o1}r_{o2})} + \frac{(r_{o1}+r_{o2}+g_{m2}r_{o1}r_{o2})}{r_{o2}(r_{o1}+r_{o2}+g_{m2}r_{o1}r_{o2})}$$

$$I_{test} = \frac{\cancel{r_{o2}}}{\cancel{r_{o2}}\left(r_{o1} + r_{o2} + g_{m2} r_{o1} r_{o2}\right)}$$

$$R_{out} = R_{th} = \frac{1}{I_{test}} = r_{o1} + r_{o2} + g_{m2} r_{o1} r_{o2}$$

CG:





$$V_{in} = -V_{gs}$$

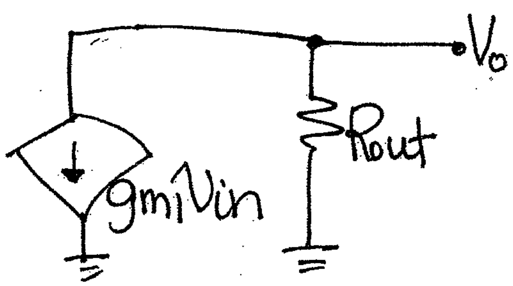
$$V_o = -g_m V_{gs} r_o = +g_m V_{in} r_o$$

($g_m r_o$ ← Intrinsic gain)

$\therefore$

$$R_{out} \approx (g_{m2} r_{o2}) \cdot r_{o1}$$

$$A_v \cong -g_{m1} r_{o1} (g_{m2} r_{o2})$$



voltage gain can be easily found as

$$A_v = \frac{v_o}{v_i} = -g_{m1}[R_{on} \| R_{op}]$$

Thus,

$$A_v = -g_{m1}\{[(g_{m2}r_{o2})r_{o1}] \| [(g_{m3}r_{o3})r_{o4}]\} \quad (7.29)$$

For the case in which all transistors are identical,

$$A_v = -\frac{1}{2}(g_m r_o)^2 = -\frac{1}{2}A_0^2 \quad (7.30)$$

By comparison to the gain expression in Eq. (7.18′), we see that using the cascode configuration for both the amplifying transistor and the current-source load transistor results in an increase in the magnitude of gain by a factor equal to A_0.

Example 7.4

It is required to design the cascode current-source of Fig. 7.10 to provide a current of 100 μA and an output resistance of 500 kΩ. Assume the availability of a 0.18-μm CMOS technology for which $V_{DD} = 1.8$ V, $V_{tp} = -0.5$ V, $\mu_p C_{ox} = 90$ μA/V² and $V'_A = -5$ V/μm. Use $|V_{OV}| = 0.3$ V and determine L and W/L for each transistor, and the values of the bias voltages V_{G3} and V_{G4}.

Solution

The output resistance R_o is given by

$$R_o = (g_{m3}r_{o3})r_{o4}$$

Assuming Q_3 and Q_4 are identical,

$$R_o = (g_m r_o)r_o$$
$$= \frac{|V_A|}{|V_{OV}|/2} \times \frac{|V_A|}{I_D}$$

Using $|V_{OV}| = 0.3$ V, we write

$$500\ \text{k}\Omega = \frac{|V_A|}{0.15} \times \frac{|V_A|}{0.1\ \text{mA}}$$

Thus we require

$$|V_A| = 2.74\ \text{V}$$

Now, since $|V_A| = |V'_A| L$ we need to use a channel length of

$$L = \frac{2.74}{5} = 0.55\ \mu\text{m}$$

which is about three times the minimum channel length. With $|V_t| = 0.5$ V and $|V_{OV}| = 0.3$ V,

$$V_{SG4} = 0.5 + 0.3 = 0.8\ \text{V}$$

and thus,

$$V_{G4} = 1.8 - 0.8 = 1.0 \text{ V}$$

To allow for the largest possible signal swing at the output terminal, we shall use the minimum required voltage across Q_4, namely, $|V_{OV}|$ or 0.3 V. Thus,

$$V_{D4} = 1.8 - 0.3 = 1.5 \text{ V}$$

Since the two transistors are identical and are carrying equal currents,

$$V_{SG3} = V_{SG4} = 0.8 \text{ V}$$

Thus,

$$V_{G3} = 1.5 - 0.8 = +0.7 \text{ V}$$

We note that the maximum voltage allowed at the output terminal of the current source will be constrained by the need to allow a minimum voltage of $|V_{OV}|$ across Q_3; thus,

$$v_{D3\text{max}} = 1.5 - 0.3 = +1.2 \text{ V}$$

To determine the required W/L ratios of Q_3 and Q_4, we use

$$I_D = \frac{1}{2}(\mu_p C_{ox})\left(\frac{W}{L}\right)|V_{OV}|^2\left(1 + \frac{V_{SD}}{|V_A|}\right)$$

$$100 = \frac{1}{2} \times 90 \times \left(\frac{W}{L}\right) \times 0.3^2\left(1 + \frac{0.3}{2.74}\right)$$

which yields

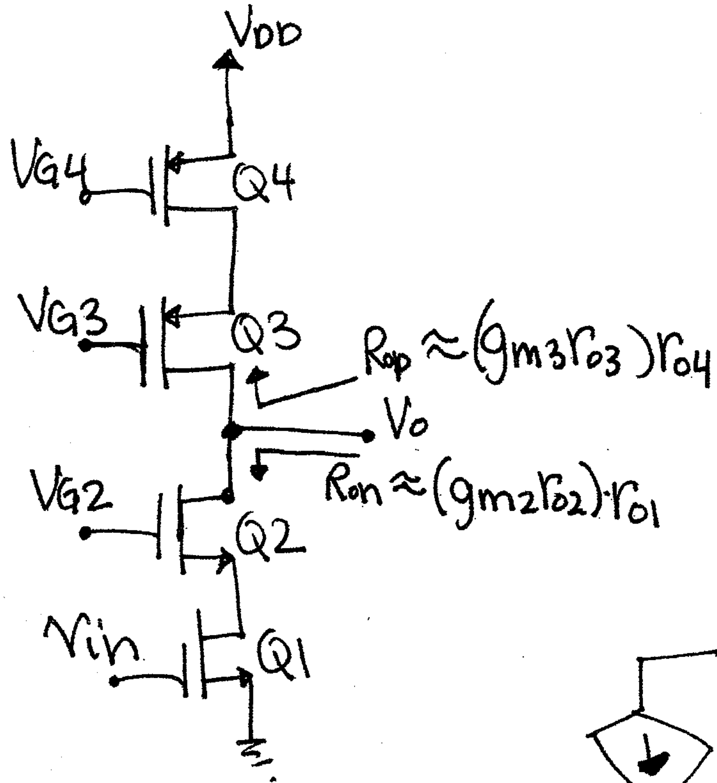
$$\frac{W}{L} = 22.3$$

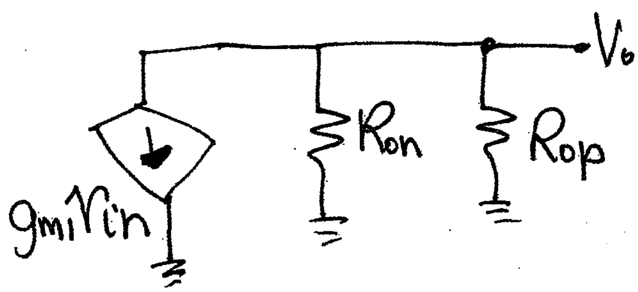
EXERCISES

D7.4 If in Example 7.4, L of each of Q_3 and Q_4 is halved while W/L is changed to allow I_D and V_{OV} to remain unchanged, find the new values of R_o and W/L. [*Hint*: In computing the required (W/L), note that $|V_A|$ has changed.]
Ans. 125 kΩ; 20.3

7.5 Consider the cascode amplifier of Fig. 7.11 with the dc component at the input, $V_I = 0.7$ V, $V_{G2} = 1.0$ V, $V_{G3} = 0.8$ V, $V_{G4} = 1.1$ V, and $V_{DD} = 1.8$ V. If all devices are matched (i.e., if $k_{n1} = k_{n2} = k_{p3} = k_{p4}$), and have equal $|V_t|$ of 0.5 V, what is the overdrive voltage at which the four transistors are operating? What is the allowable voltage range at the output?
Ans. 0.2 V; 0.5 V to 1.3 V

7.6 The cascode amplifier in Fig. 7.11 is operated at a current of 0.2 mA with all devices operating at $|V_{OV}| = 0.2$ V. All devices have $|V_A| = 2$ V. Find g_{m1}, the output resistance of the amplifier, R_{on}, and the output resistance of the current source, R_{op}. Also find the overall output resistance and the voltage gain realized.
Ans. 2 mA/V; 200 kΩ, 200 kΩ; 100 kΩ; −200 V/V





$$\therefore \; A_v = -g_{m1}(R_{on} \| R_{op})$$

Example:

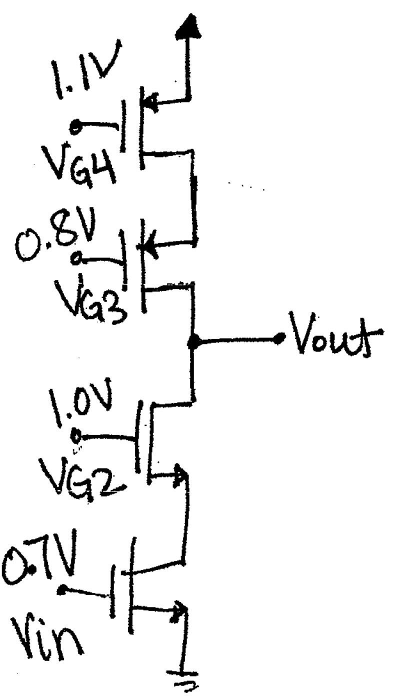
$V_{G2} = 1V$, $V_{G3} = 0.8V$, $V_{G4} = 1.1V$, $V_{DD} = 1.8V$

all devices have equal values $r_{o1} = r_{o2} = r_{o3} = r_{o4}$

$|V_t| = 0.5V$ $g_{m1} = g_{m2} = g_{m3} = g_{m4}$

overdrive voltage? ($V_{in} = 0.7V$)

Allowable voltage range at output?



current = 0.2mA

$|V_{ov}| = 0.2V$ for all

$|V_A| = 2V$

Find g_{m1}, R_{out}, A_V

$$g_{m1} = \frac{2I_D}{V_{ov}} = \frac{2(0.2m)}{0.2} = 2mA/V$$

$$r_o = \frac{|V_A|}{I_D} = \frac{2}{.2m} = 10K\Omega$$

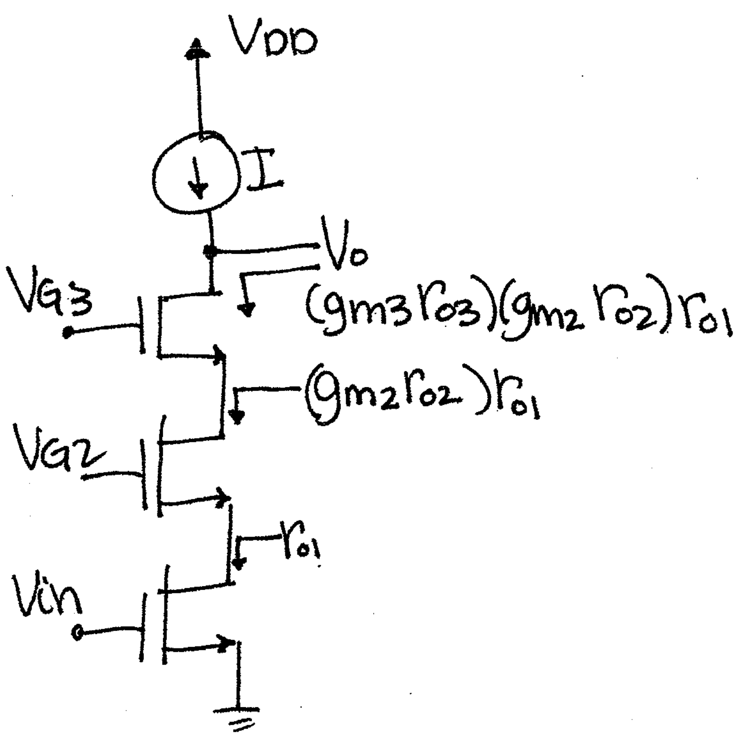
$$R_{on} = (g_{m2}r_{o2})r_{o1} = 2m(10K)^2 = 200K\Omega$$

$$R_{op} = (g_{m3}r_{o3})r_{o4} = 200K$$

$$R_{out} = R_{on} \| R_{op}$$

$$A_v = -g_{m1}(R_{on}\|R_{op}) = -2m(200k\|200k) = -200V$$

Double Cascoding



Folded Cascode