ECE137A, Notes Set 11:
MOS Multi-stage example

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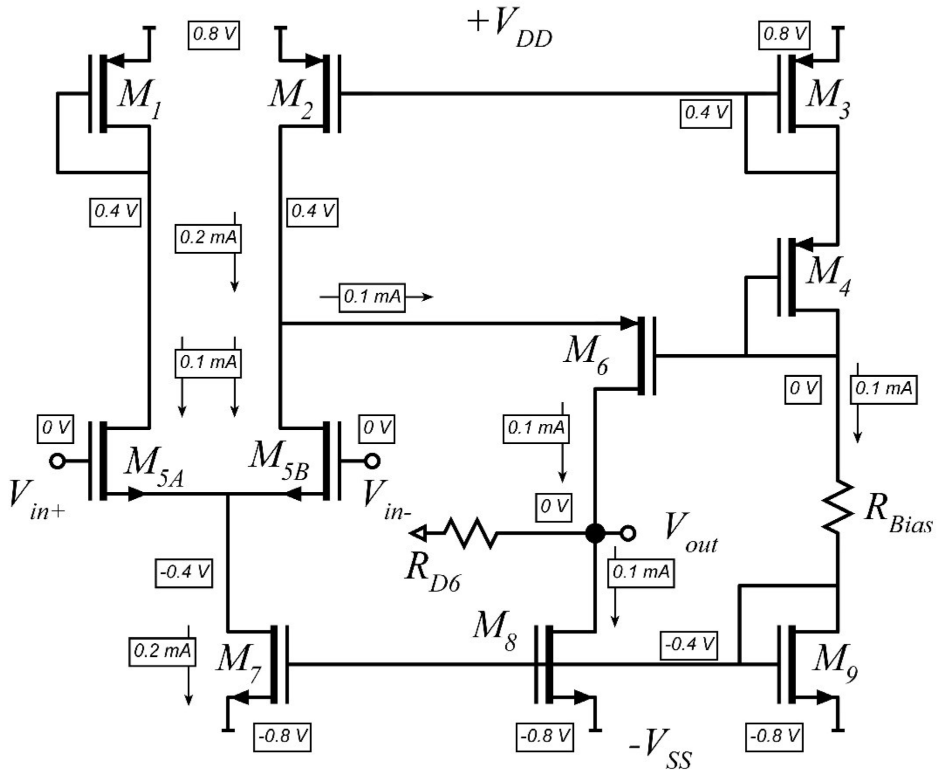
Multistage CMOS example

Differential pair with single-ended folded cascode.



FETs:

$$K_\mu = 10\text{mA/V}^2 (W_g / 1\mu\text{m})$$

$$K_v = 2\text{mA/V} (W_g / 1\mu\text{m})$$

$$\Delta V = 0.1\text{V}$$

$$V_{th} = \pm 0.3\text{V}$$

$$1/\lambda = 4\text{V}$$

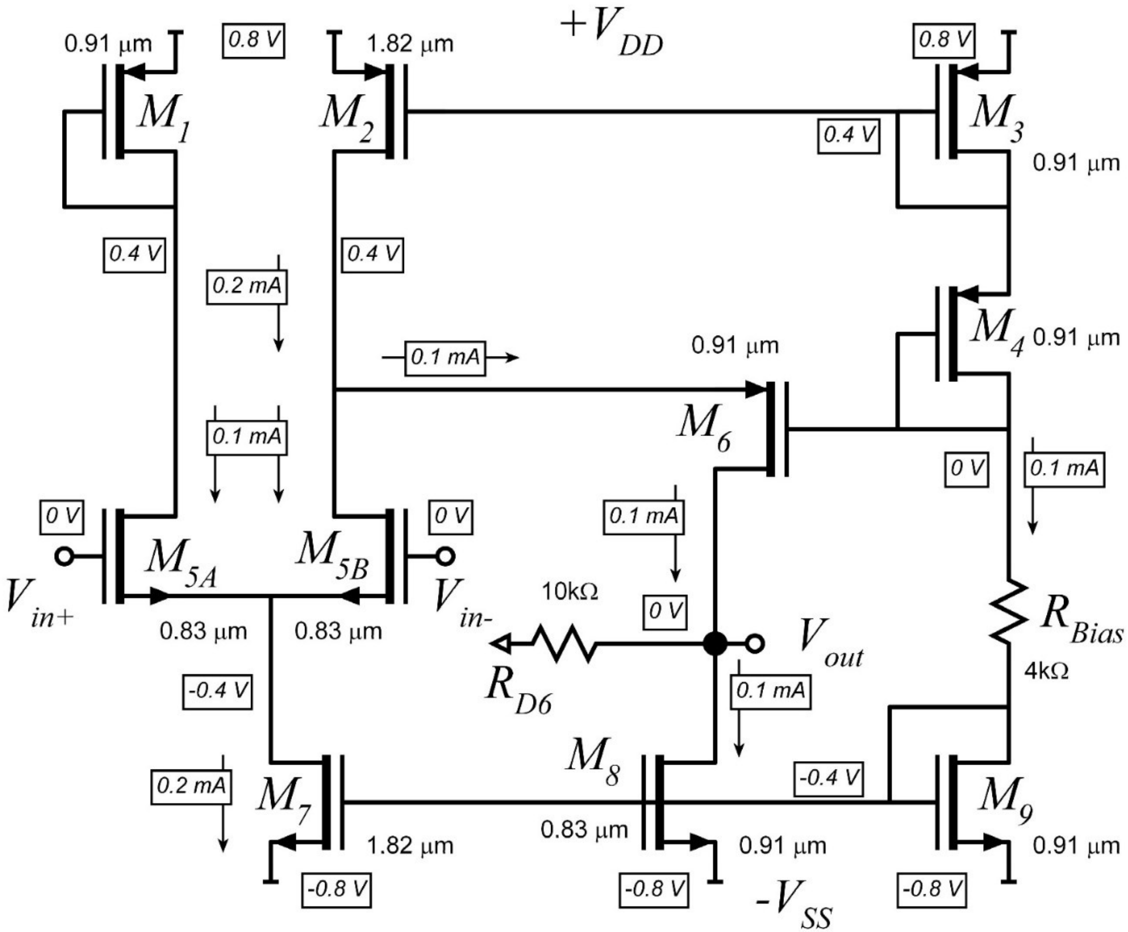
DC bias: V_{gs}=0.4V for all FETs $\rightarrow$ boundary of velocity- and mobility-limited regions.

All FETs except M5A, M5B, M8: $|V_{DS}|$=0.4V.

M5A, M5B, M8: $|V_{DS}|$=0.8V.

M1 forces an equal V_{DS} for M5A, M5B

DC bias analysis



FET widths are calculated from

$$I_D = K_\mu (V_{gs} - V_{th})^2 (1 + \lambda V_{DS})$$

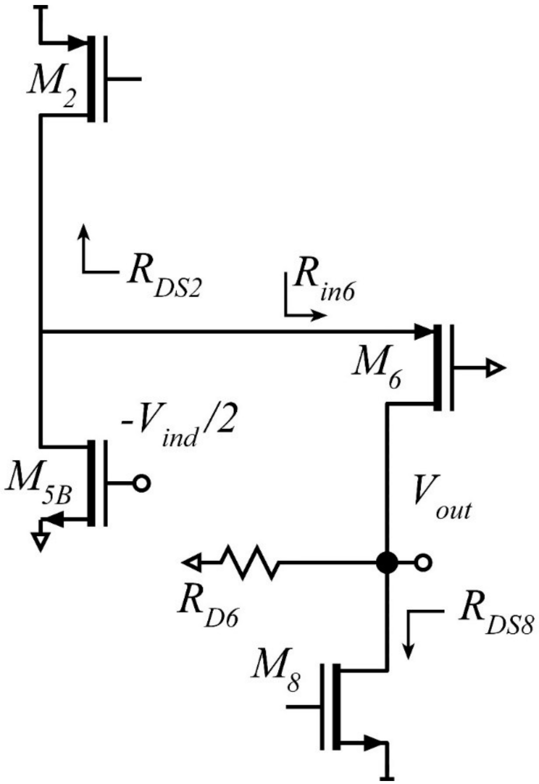
where $K_\mu = 10\text{mA/V}^2 (W_g / 1\mu\text{m})$

FET small-signal parameters from $g_m|_{mobility} = 2I_D / (V_{gs} - V_{th})$, $R_{DS} = 1/\lambda I_D$

M5A,B: $g_m = 2\text{mS}$, $R_{DS} = 40\text{k}\Omega$. M2: $R_{DS} = 20\text{k}\Omega$

M6 : $g_m = 2\text{mS}$, $R_{DS} = 40\text{k}\Omega$. M8: $R_{DS} = 40\text{k}\Omega$

Small signal analysis



$M6$: Common-gate

$$R_{Leq6} = R_{D6} \,\|\, R_{DS8} = 10\text{k}\Omega \| 40\text{k}\Omega = 8\text{k}\Omega$$

$$R_{in6} = (1/g_{m6})(1 + R_{Leq6}/R_{DS6})$$
$$= 500\Omega \cdot (1 + 8\text{k}\Omega / 40\text{k}\Omega) = 600\Omega$$

$$A_{v6} = R_{Leq6}/R_{in6} = 8\text{k}\Omega / 600\Omega = 13.333$$

$M5B$: Common-source

$$R_{Leq5B} = R_{in6} \,\|\, R_{DS2} \,\|\, R_{DS5B} = 600\Omega \,\|\, 20\text{k}\Omega \,\|\, 40\text{k}\Omega = 574\Omega$$

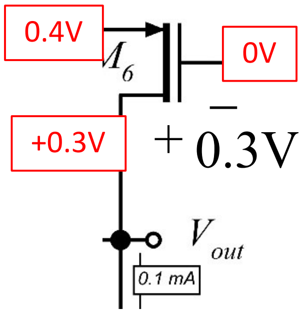
$$A_{v5B} = -g_{m5B} R_{Leq5B} = 2\text{mS} \cdot 574\Omega = -1.15$$

$$V_{out}/V_d = -A_{v6} A_{v5B}/2 = 15.333/2 = 7.6666$$

Alternatively, tracking currents:

$$A_{v6}A_{v5B} = -g_{m5B}\left(\frac{R_{DS2} \,\|\, R_{DS5B}}{R_{DS2} \,\|\, R_{DS5B} + R_{in6}}\right) R_{Leq6} = -2\text{mS} \cdot \left(\frac{13.33\text{k}\Omega}{13.33\text{k}\Omega + 600\Omega}\right) 8\text{k}\Omega$$
$$= -2\text{mS} \cdot (0.957)\, 8\text{k}\Omega = -15.333$$

Maximum signal swings



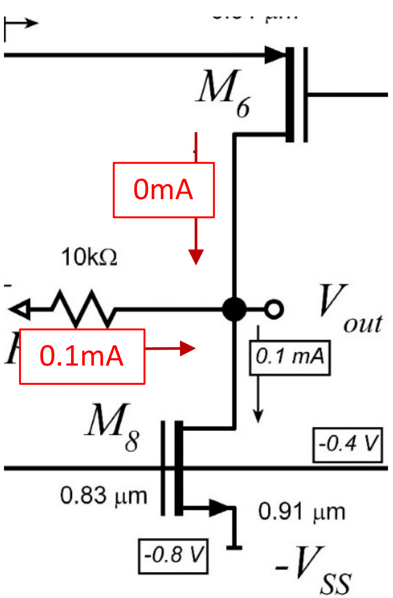
Knee voltage of M6:

Transistor is biased at $V_G = 0.4\text{V}$ and $V_S = 0.0\text{V}$

Knee (saturation): when $V_{DG} = V_{th} = 0.3\text{V}.$

Voltages as indicated on drawing

Output can swing to +0.3V.



M6 cutoff:

We can decrease I_{D6} from $100\mu\text{A}$ to $0\mu\text{A}$.

$R_{Leq6} = 10\text{k}\Omega \| R_{DS8} = 8\text{k}\Omega$

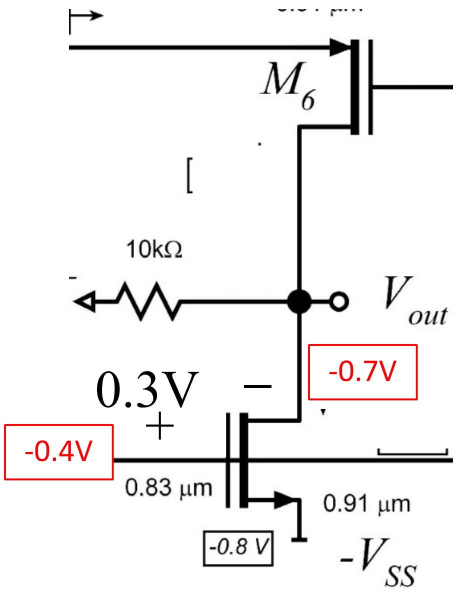
$\Delta V_{out} = -\,100\mu\text{A} \cdot 8\text{k}\Omega = -0.8\text{V}.$

Output can swing to -0.8V.

note: R_{DS8} accounts for the variation of I_{D8} with V_{out};

as V_{out} goes negative, I_{D8} decreases due to $(1+\lambda V_{DS})$.

Maximum signal swings



Knee voltage of M8:

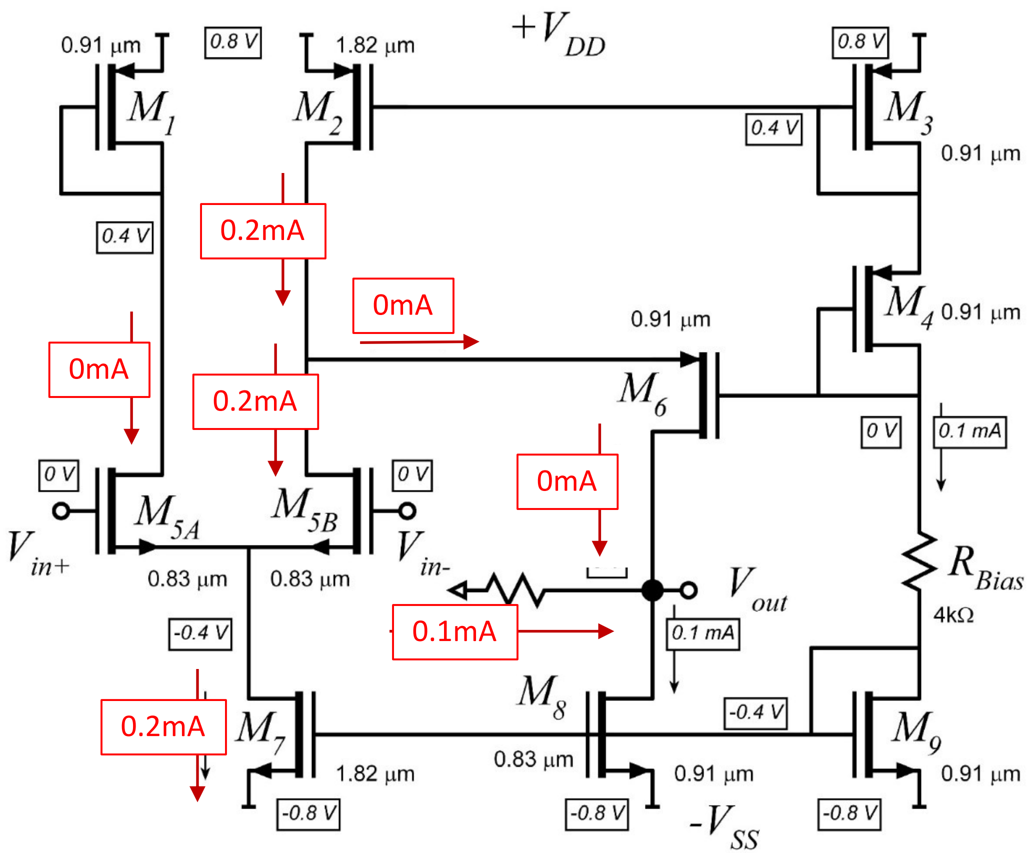
Transistor is biased at $V_G = -0.4\text{V}$ and $V_S = -0.8\text{V}$

Knee (saturation): when $V_{DG} = -V_{th} = -0.3\text{V}$.

Voltages as indicated on drawing

Output can swing to -0.7V.

Maximum signal swings: M5A cutoff



Can be calculated approximately by tracking the currents as shown to the right.

$\Delta V_{out} = -0.1\text{mA} \cdot 10\text{k}\Omega = -1\text{V}$?

We are ignoring the effect of $R_{DS8}, R_{DS6}, R_{DS2}, R_{DS5B}$

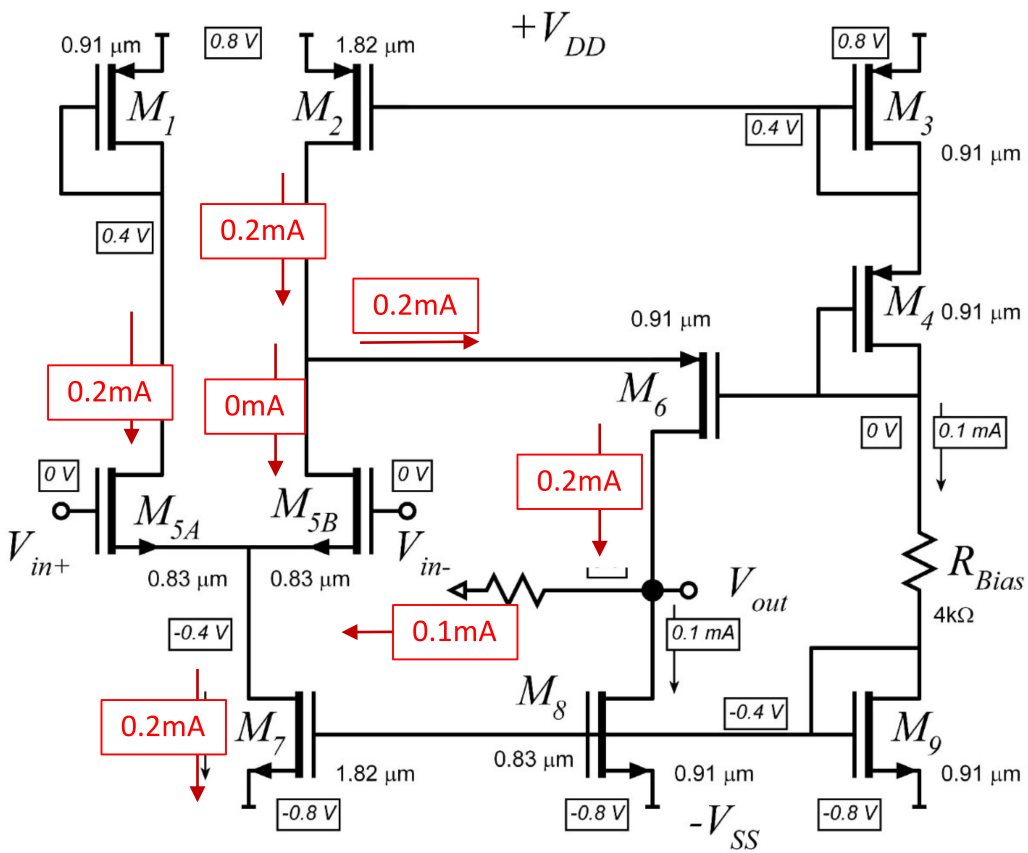
More carefully:

$$\Delta I_{D5A} = 100\mu\text{A to } 0\mu\text{A} = -100\mu\text{A} \rightarrow \Delta I_{D5B} = +100\mu\text{A}$$

$$\Delta I_{D6} = -\Delta I_{D5A}\left(\frac{R_{DS2} \,||\, R_{DS5B}}{R_{DS2} \,||\, R_{DS5B} + R_{in6}}\right) = -100\mu\text{A} \cdot (0.957) = 95.7\mu\text{A}$$

$\Delta V_{out} = -\Delta I_{D6} R_{Leq6} = -96\mu\text{A} \cdot 8\text{k}\Omega = -0.768\text{V}$. V_{out} can swing to -0.77V.

Maximum signal swings: M5B cutoff



Can be calculated approximately by tracking the currents as shown to the right.

$\Delta V_{out} = 0.1\text{mA} \cdot 10\text{k}\Omega = +1\text{V}\,?$

We are ignoring the effect of $R_{DS8}, R_{DS6}, R_{DS2}, R_{DS5B}$

More carefully:

$$\Delta I_{D5B} = -100\mu\text{A}$$

$$\Delta I_{D6} = -\Delta I_{D5A}\left(\frac{R_{DS2} \parallel R_{DS5B}}{R_{DS2} \parallel R_{DS5B} + R_{in6}}\right) = +100\mu\text{A} \cdot (0.957) = 95.7\mu\text{A}$$

$$\Delta V_{out} = \Delta I_{D6} R_{Leq6} = 96\mu\text{A} \cdot 8\text{k}\Omega = 0.768\text{V}.\ \text{Output can swing to } 0.77\text{V}.$$