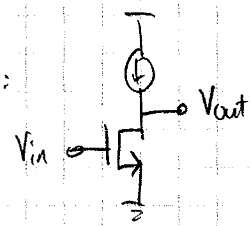
5720/6720 Lecture #9

Feb. 7

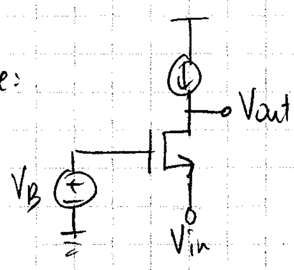
→ We have talked about 2 of the 3 single transistor amplifier configurations:

Common-Source:



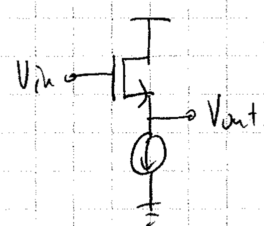
- good for voltage gain (especially with cascode variant)
- high input impedance ($= \frac{1}{j\omega C_{gs}}$) at low freq.

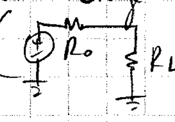
Common-Gate:



- also provides voltage gain (similar to common-source)
- low input impedance ($\approx \frac{1}{g_m}$ if $R_L \ll r_{ds}$), can be useful for matching (eg. to 50Ω)

Common-Drain: (Source-follower)

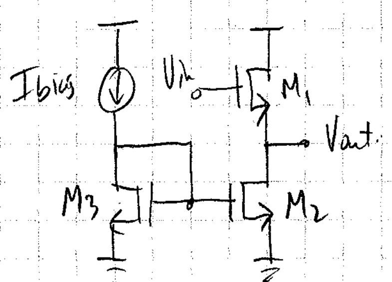


- provides ~unity voltage gain
- commonly used as a buffer stage due to low output impedance ()

- can provide power gain (by increasing current).

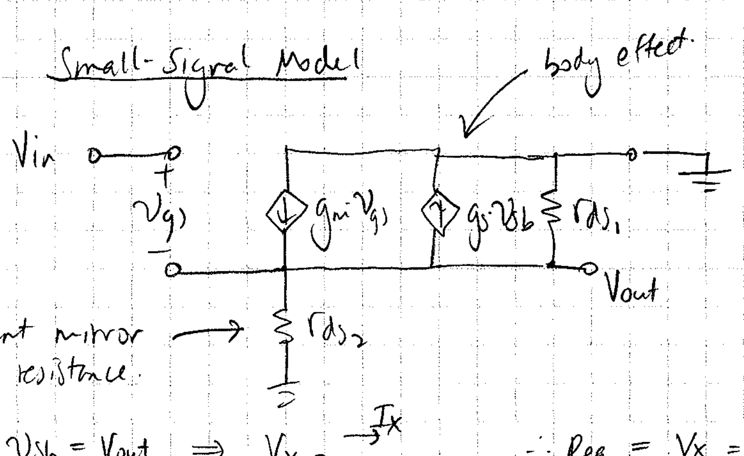
→ Let's complete the analysis of the Source Follower

Source-Follower [3.3]

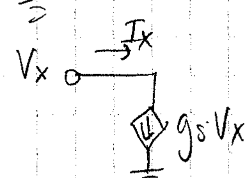


→ Let's find small-signal gain and small signal output impedance.

Small-Signal Model

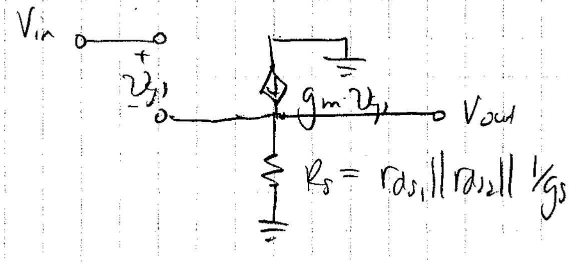


Gain: → note that $v_{sb} = V_{out}$ ⇒



$\therefore R_{eq} = \frac{V_x}{I_x} = \frac{V_x}{g_s V_x} = \frac{1}{g_s}$

→ Can redraw as:



→ KCL @ V_{out}: $g_m(V_{in}-V_{out}) = \frac{V_{out}}{R_S}$

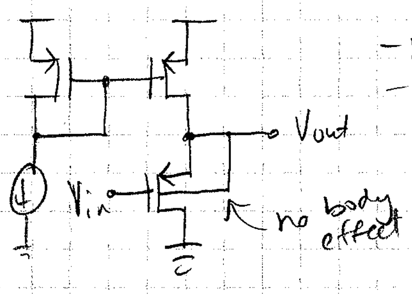
Solve to find: $A_v = \frac{V_{out}}{V_{in}} = \frac{g_m R_S}{1+g_m R_S} = \frac{g_m}{g_m + g_s + 1/r_{ds_1} + 1/r_{ds_2}}$

Notes: • Usually $g_m \gg \frac{1}{r_{ds_1}}, \frac{1}{r_{ds_2}}$ $\Rightarrow$ $\boxed{A_v \approx \frac{g_m}{g_m+g_s}}$

• Usually $g_s \approx \frac{g_m}{5}$, leading to voltage gains from 0.8–0.9.

• We could get a gain of 1 if we could force $v_{sb}=0$.

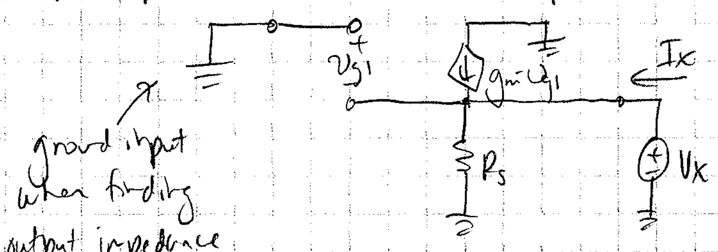
→ Can do this in a pmos by setting the bulk (well) potential to the output voltage (source), then $v_{sb} = V_{out} - V_{out} = 0$



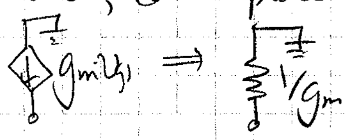
– now $A_v \approx 1$

– can only do this in an nmos if we have a triple well process

Output impedance: – Start with simplified model



– for same reasons as with g_s source, can replace



$\Rightarrow$ This leads to $R_{out} = \frac{V_x}{I_x} = R_s \| \frac{1}{g_m} = \frac{1}{g_m} \| \frac{1}{g_s} \| r_{ds1} \| r_{ds2}$

→ Can make this low if we make g_m high. $\boxed{R_{out} \approx \frac{1}{g_m} \| \frac{1}{g_s}}$

Frequency Effects [Section 3.11]

→ 3.11 covers frequency response of all the subcircuits we have discussed
- we will discuss only the Common-Source Amplifier
- refer to the text for others as needed

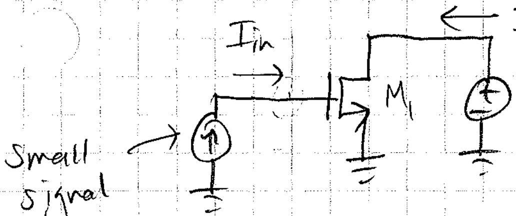
Aside: Why do transistors get faster with each successive generation?

→ Speed of transistors is commonly characterized by their maximum useful operating frequency, or unity gain frequency (f_T)

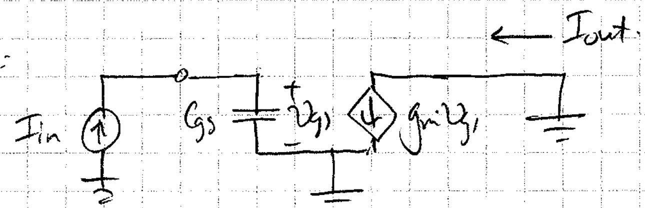
<u>Unity Gain Frequency</u> (f_T): frequency at which a transistor has unity current gain (small signal)

Let's derive this quantity, using the simplest small signal model:

(Biasing for gate not shown)



<u>Small signal:</u>



$$v_{gs} = \frac{I_{in}}{j\omega \cdot C_{gs}}, \quad I_{out} = g_m \cdot v_{gs} = \frac{g_m \cdot I_{in}}{j\omega \cdot C_{gs}} \Rightarrow \frac{I_{out}}{I_{in}} = \frac{g_m}{j\omega \cdot C_{gs}}$$

$$\therefore \text{Set } \left|\frac{I_{out}}{I_{in}}\right| = 1 \Rightarrow 1 = \frac{g_m}{\omega \cdot C_{gs}} \quad \therefore \boxed{\omega_T \cong \frac{g_m}{C_{gs}}}$$

Now, $g_m = \mu_n C_{ox}\left(\frac{W}{L}\right) \cdot V_{eff}$, $C_{gs} \approx \frac{2}{3} \cdot W \cdot L \cdot C_{ox}$

$$\text{So, } \omega_T = \frac{\mu_n \cancel{C_{ox}}(\cancel{W}/L) \cdot V_{eff}}{2/3 \cdot \cancel{W} \cdot L \cdot \cancel{C_{ox}}} = \frac{3 \mu_n V_{eff}}{2 \cdot L^2} \quad \alpha \quad \frac{1}{L^2}$$

→ So, as minimum L goes down with each successive generation, unity gain frequency goes up

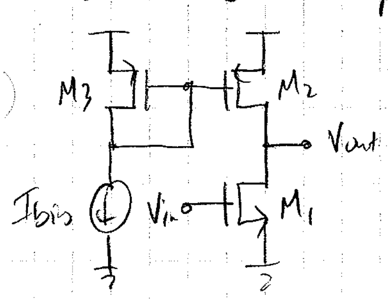
<u>Example</u>: Foundries are currently fabricating in 45 nm technology, how much increase in f_T can be expected by moving to 32 nm?

$$\omega_{T,32} = \frac{\omega_{T,45}}{\left(\frac{32}{45}\right)^2} = 1.98 \cdot \omega_{T,45}$$

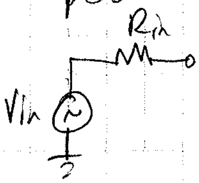
→ So, max. operating freq. will almost double

- many other factors at play, but this gives a rough idea of performance gains with successive generations.

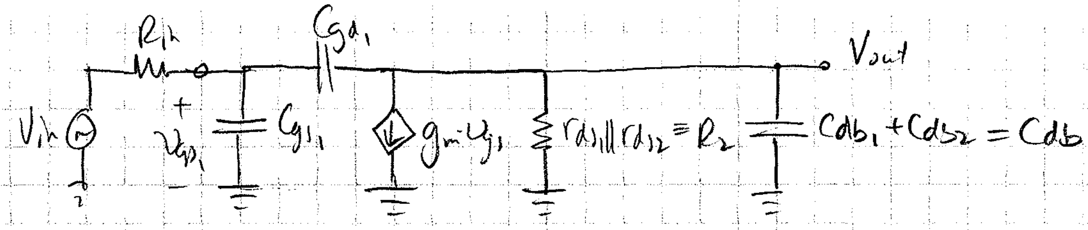
<u>Common-Source Amplifier Frequency Response</u> [3.11]



- Assume V_{in} is driven by a voltage source with output impedance of R_{in}



Small signal model:



Notes: • C_{sb} not included since source & bulk are both grounded
• In a real design we would also have the input impedance of the next stage at the drain (eg. C_{gs} of next stage)

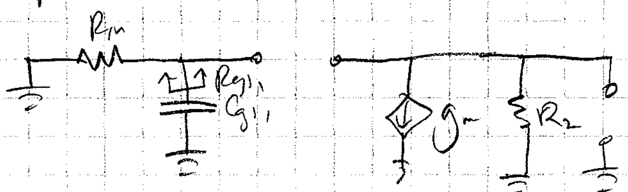
→ We are often interested in the 3-db frequency, the frequency where the voltage gain $\frac{V_{out}}{V_{in}}$ is 3-db lower than the low frequency value.

– could set up nodal equations and solve (tedious!!)

→ Instead let's use method of <u>open-circuit time constants</u> to get an estimate of the 3-db frequency.

– ground input, find time constant associated with each capacitor

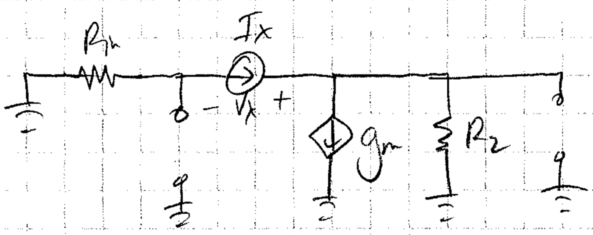
C_{gs_1}:



$R_{gs_1} = R_{in}$

$\tau_{gs_1} = C_{gs_1} \cdot R_{in}$

C_{gd_1}:

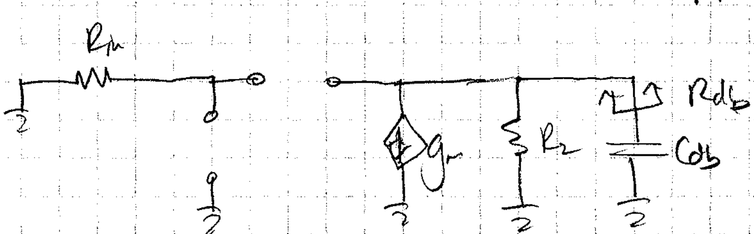


$R_{gd_1} = \frac{V_x}{I_x}$ (solve using KCL)

$= R_{in}(1 + g_{m_1} R_2) + R_2$

$\therefore \tau_{gd_1} = C_{gd_1} \cdot R_{in}(1 + g_{m_1} R_2) + C_{gd_1} R_2$

C_{db}:



$R_{db} = R_2$

$\therefore \tau_{db} = R_2 \cdot C_{db}$

Now: $$\omega_{3db} \approx \frac{1}{\tau_{gs} + \tau_{gd} + \tau_{ds}}$$

$$= \frac{1}{R_{in} \cdot C_{gs_1} + R_{in} \cdot C_{gd_1}(1 + g_{m_1} R_2) + C_{gd_1} \cdot R_2 + C_{db} \cdot R_2} \quad (*)$$

→ Typically the last two terms can be neglected, leading to:

5

(**) $\boxed{\omega_{3dB} \approx \dfrac{1}{R_{in} \cdot C_{gs_1} + R_{in} \cdot C_{gd_1} (1 + g_{m_1} \cdot R_2)}}$ (in radians!!!)

Miller Effect ($A = g_{m_1} R_2$)

→ Note that the impact of C_{gd_1} is increased by the Miller effect, so it will be more significant for higher gain.

→ Let's compare the accuracy of this approximation with simulation results from Cadence...

- get small signal parameters from DC simulation → print dc operating points
- estimate f_{3dB}: from (*): 256 MHz
  from (**): 283 MHz (10% difference from ignoring the last two terms)
- now use AC simulation to check: (explain why $R_{in} = 50\,k\Omega$)
  - f_{3dB} from AC = 157 MHz

→ This is a better result, lower than from analytical since simulator solves full equations & takes into account more poles

→ Analytical result was off by 63%. (could be worse)

Notes: Analysis is not useful for accurately predicting performance, more useful for indicating how performance changes with design variables.

eg. How will reducing width affect f_{3dB}?

$$\omega_{3dB} = \frac{1}{R_{in} \cdot C_{gs_1} + R_{in} \cdot C_{gd_1} (1 + g_{m_1} R_L)}$$

goes down with reducing W ($g_m = \sqrt{\mu_n C_{ox} \frac{W}{L} I_D}$)

goes down ($C_{gd} = W \cdot L_{ov} \cdot C_{ov}$)

goes down ($C_{gs} = \frac{2}{3} \cdot W \cdot L \cdot C_{ox}$)

→ So, reducing width of M_1 will increase f_{3dB}.