

ECEN474: (Analog) VLSI Circuit Design

Fall 2010

Lecture 11: Frequency Response (cont.)



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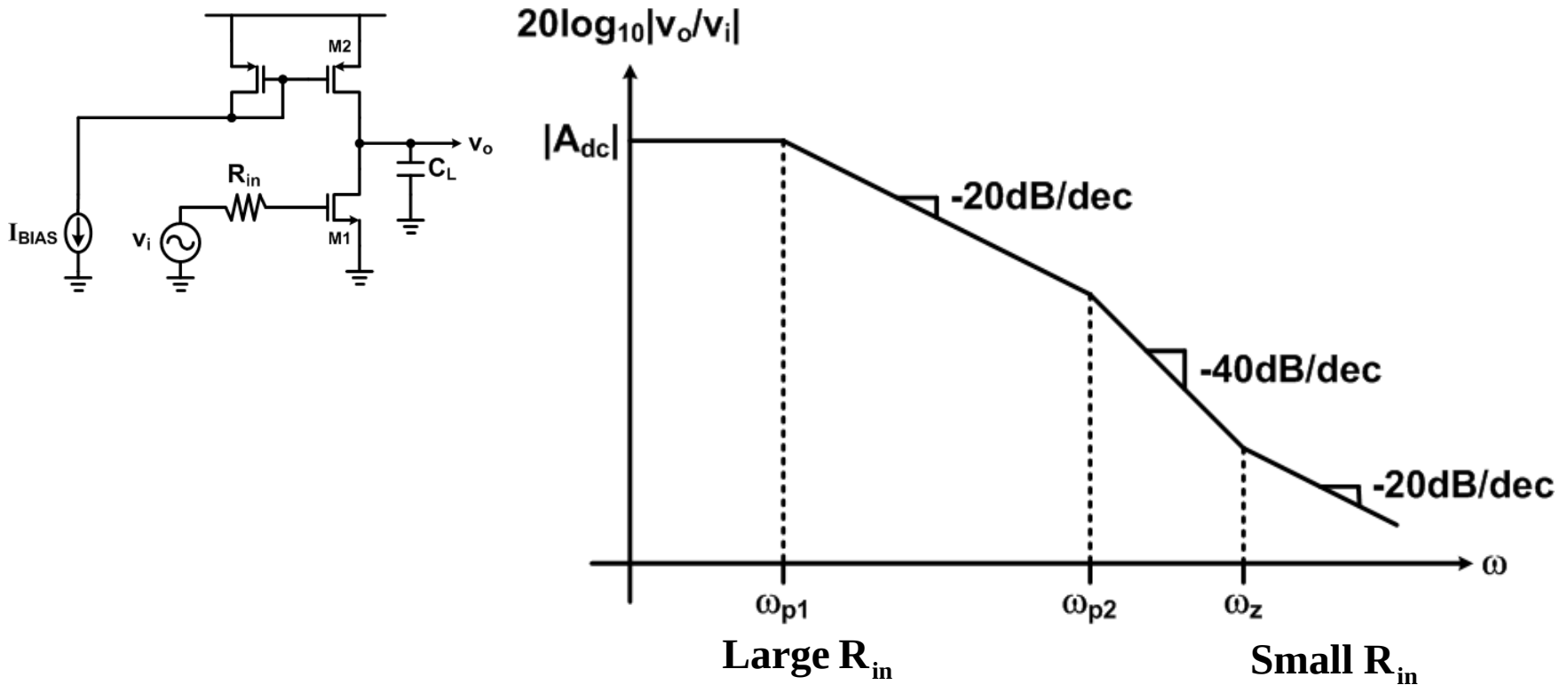
Announcements

- HW3 due Monday Oct 11 9:10AM
 - Posted on website with additional notes
- Reading
 - Johns/Martin 3.1-3.8, 3.11

Agenda

- Common-Source Amp Input Impedance
- Common-Drain Amp Frequency Response
- Differential Pairs

Common-Source Amp Frequency Response

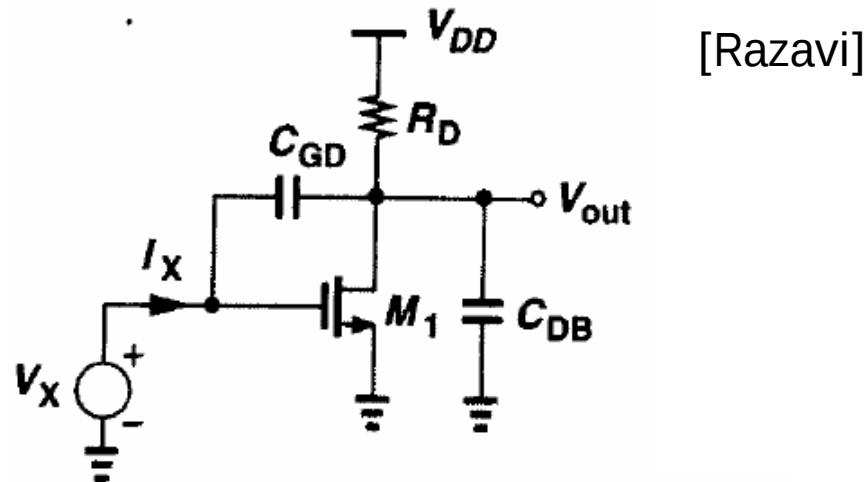


$$A_{dc} = -g_m r_o \quad \omega_z = \frac{g_{m1}}{C_{gd1}}$$

$$\omega_{p1} = -\frac{1}{R_{in} [C_{gs1} + C_{gd1} (1 + g_{m1} r_o)]} \quad \omega_{p1} = -\frac{1}{r_o (C_{gd1} + C_o)}$$

$$\omega_{p2} \cong -\frac{g_{m1} C_{gd1}}{C_{gd1} C_{gs1} + C_{gs1} C_o + C_{gd1} C_o} \quad \omega_{p2} \cong -\frac{1}{R_{in} (C_{gs1} + C_{gd1})}$$

Common-Source Amp Input Impedance



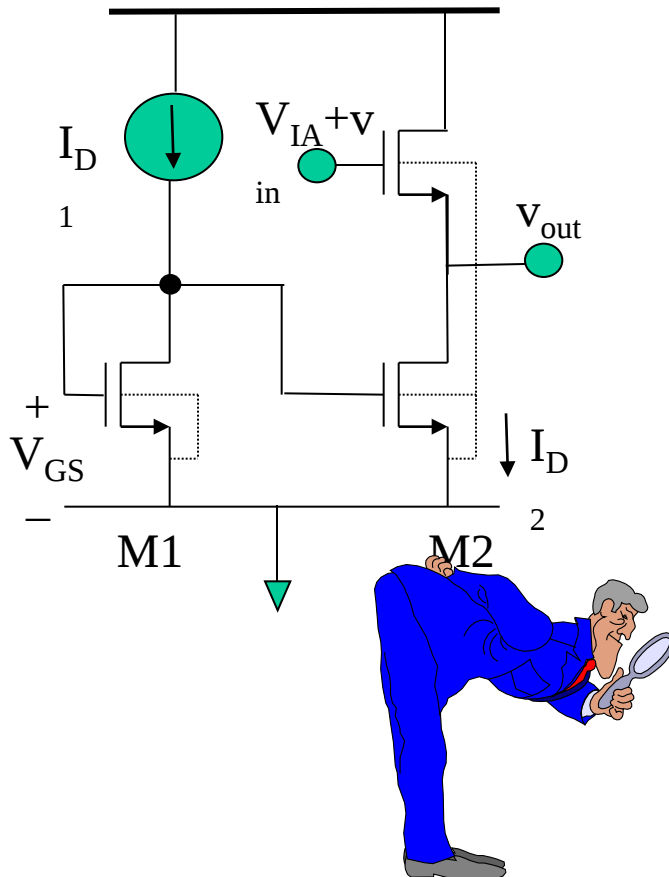
Neglecting Output Cap:
$$Z_{in} = \frac{1}{[C_{GS} + (1 + g_m R_D)C_{GD}]s}$$

Input impedance is purely capacitive ($C_{gs} + \text{Miller } C_{gd}$)

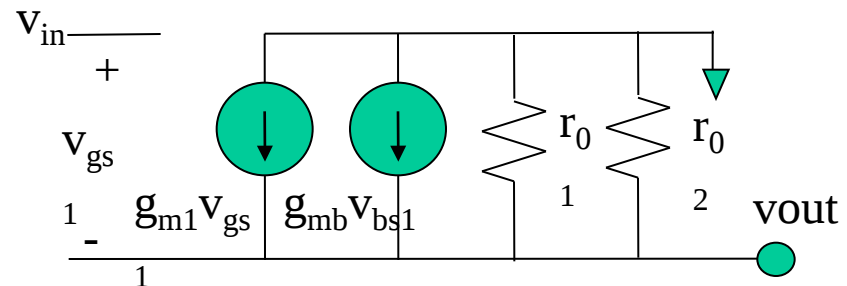
Considering Output Cap:
$$\frac{V_X}{I_X} = \frac{1 + R_D(C_{GD} + C_{DB})s}{C_{GD}s(1 + g_m R_D + R_D C_{DB}s)}$$

Low frequency is capacitive, but then impedance experiences a zero followed by a second pole

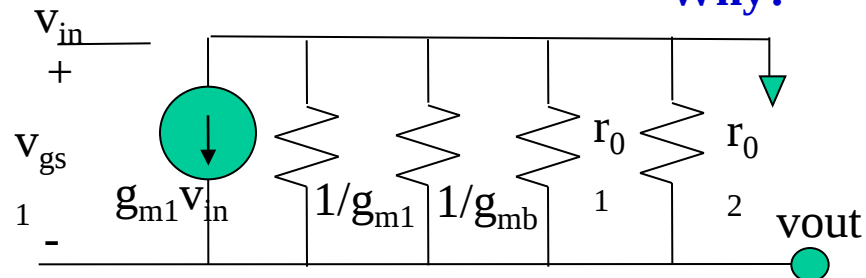
Small signal analysis: Common-drain (source follower) amplifier



Small signal equivalent circuit



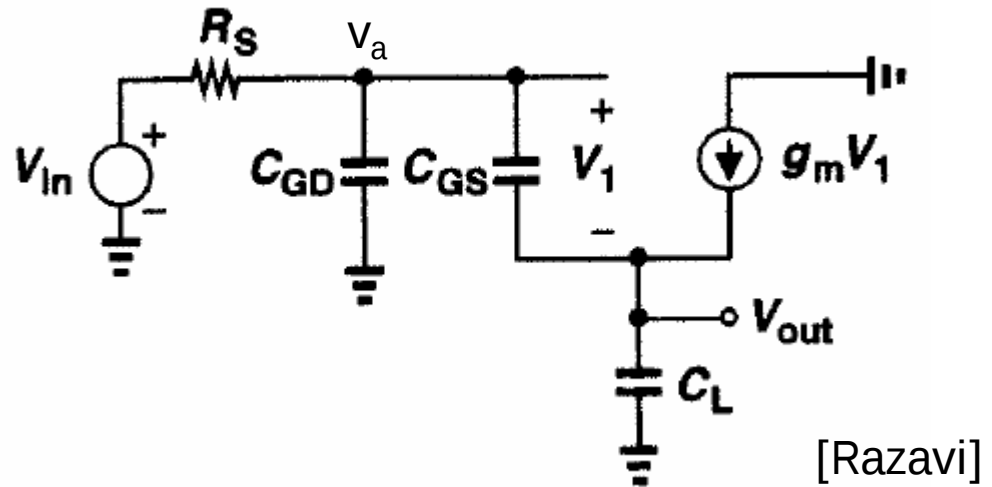
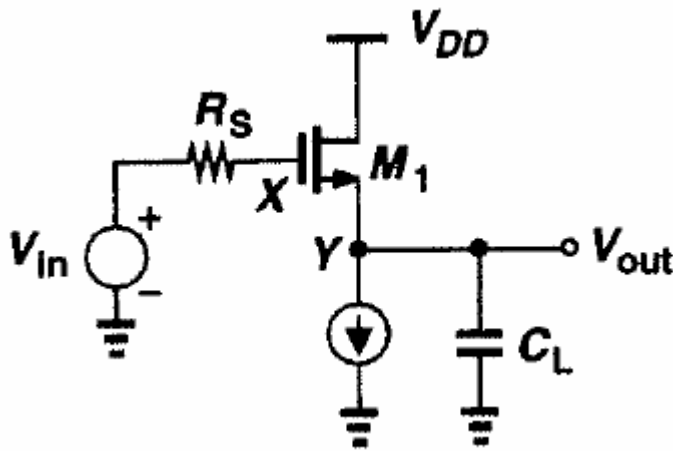
How this is done?
Why?



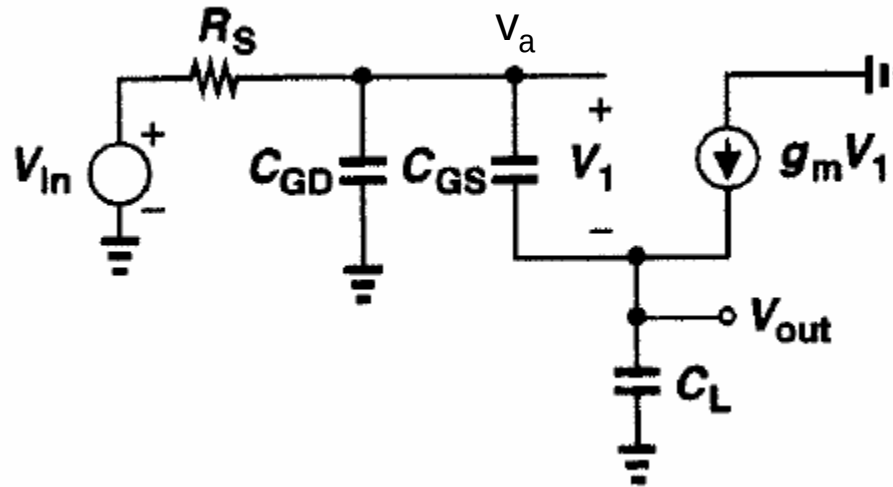
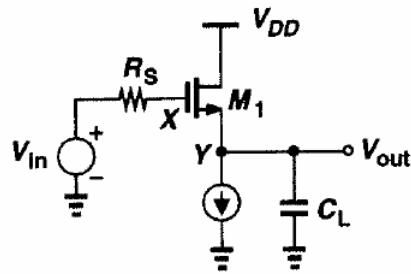
$$\frac{v_{out}}{v_{in}} = \frac{g_{m1}}{g_{m1} + g_{mb} + g_{o1} + g_{o2}}$$

Common-Drain Amplifier: High Frequency Response

- Simplifying the schematic a bit for SSA
 - Ideal current source load and neglecting transistor r_o and g_{mb} (i.e. $\lambda=\gamma=0$)
 - Will result in an optimistic DC gain estimate



Common-Drain Amplifier: High Frequency Response



[Razavi]

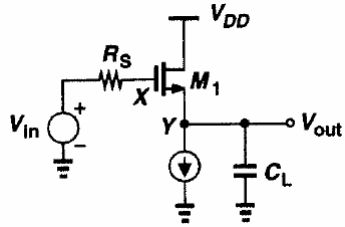
$$\text{KCL @ Node } v_a : (v_a - v_i)G_S + v_a s C_{gd} + (v_a - v_o)s C_{gs} = 0$$

$$\text{KCL @ Node } v_o : (v_o - v_a)s C_{gs} - g_m (v_a - v_o) + v_o s C_L = 0$$

After some algebra:

$$\frac{V_{out}}{V_{in}}(s) = \frac{g_m + C_{GS}s}{R_S(C_{GS}C_L + C_{GS}C_{GD} + C_{GD}C_L)s^2 + (g_m R_S C_{GD} + C_L + C_{GS})s + g_m}$$

Common-Drain Amplifier: High Frequency Response



$$\frac{V_{out}}{V_{in}}(s) = \frac{g_m + C_{GS}s}{R_S(C_{GS}C_L + C_{GS}C_{GD} + C_{GD}C_L)s^2 + (g_m R_S C_{GD} + C_L + C_{GS})s + g_m}$$

- From this simplified transfer function:

$$A_{dc} = \frac{g_m}{g_m} = 1 \quad \text{(Optimistic)}$$

$$\text{Exact } A_{dc} = \frac{g_m}{g_m + g_o + g_{mb}}$$

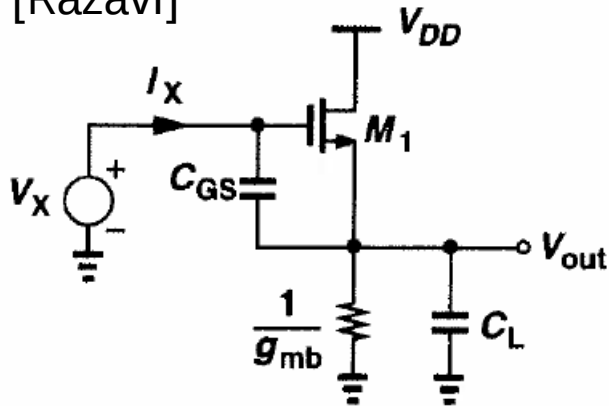
$$\omega_z = -\frac{g_m}{C_{gs}}$$

2 poles, If we assume that they are spaced far apart :

$$\omega_{p1} \approx \frac{g_m}{g_m R_S C_{GD} + C_L + C_{GS}} = \frac{1}{R_S C_{GD} + \frac{C_L + C_{GS}}{g_m}}$$

Common-Drain Amp Input Impedance

[Razavi]



$$Z_{in} = \frac{1}{C_{GS}s} + \left(1 + \frac{g_m}{C_{GS}s}\right) \frac{1}{g_{mb} + C_L s}$$

Low Frequency: $Z_{in} \approx \frac{1}{C_{GS}s} \left(1 + \frac{g_m}{g_{mb}}\right) + \frac{1}{g_{mb}}$

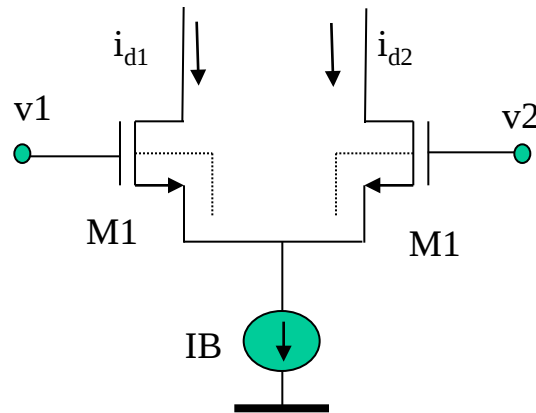
Equivalent to a series capacitive term $C_{gs} \left(\frac{g_{mb}}{g_m + g_{mb}} \right)$ and resistive term $\frac{1}{g_{mb}}$

High Frequency: $Z_{in} \approx \frac{1}{C_{GS}s} + \frac{1}{C_L s} + \frac{g_m}{C_{GS} C_L s^2}$

Series combination of C_{gs} and C_L and a negative resistance term $\left(-\frac{g_m}{C_{gs} C_L \omega^2} \right)$

The negative resistance term can be utilized in oscillator design

Differential Pair: Linear range is limited to $2 V_{DSAT}$



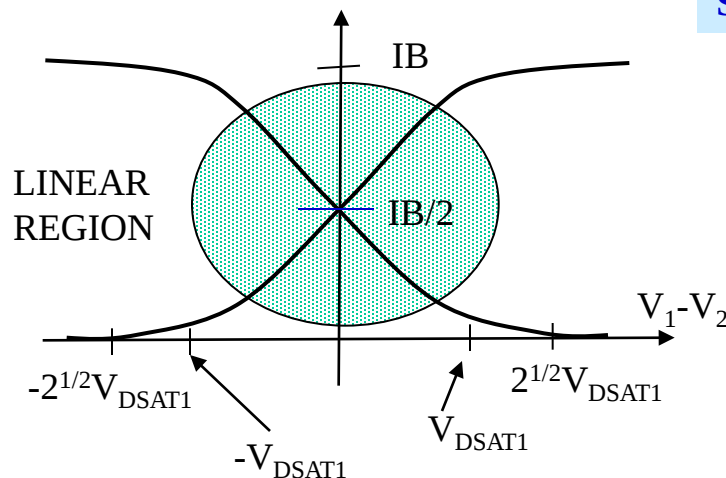
If both transistors are saturated and IB is ideal ($r_{IB} = \infty$)

$$i_{d1} + i_{d2} = I_B$$

$$i_{d1} = \frac{\mu_n C_{OX}}{2} \frac{W}{L} (V_{gs1} - V_T)^2$$

$$i_{d2} = \frac{\mu_n C_{OX}}{2} \frac{W}{L} (V_{gs2} - V_T)^2$$

Solving these equations $\Rightarrow$ Valid for $|v_1 - v_2| < 2^{1/2} V_{DSAT1}$

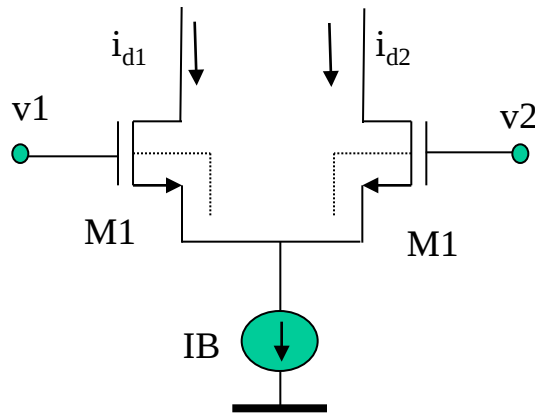


$$i_{d1} = \frac{I_B}{2} + \frac{g_{m1}(v_1 - v_2)}{2} \sqrt{1 - \left(\frac{v_1 - v_2}{2V_{DSAT1}} \right)^2}$$

$$i_{d2} = \frac{I_B}{2} - \frac{g_{m1}(v_1 - v_2)}{2} \sqrt{1 - \left(\frac{v_1 - v_2}{2V_{DSAT1}} \right)^2}$$



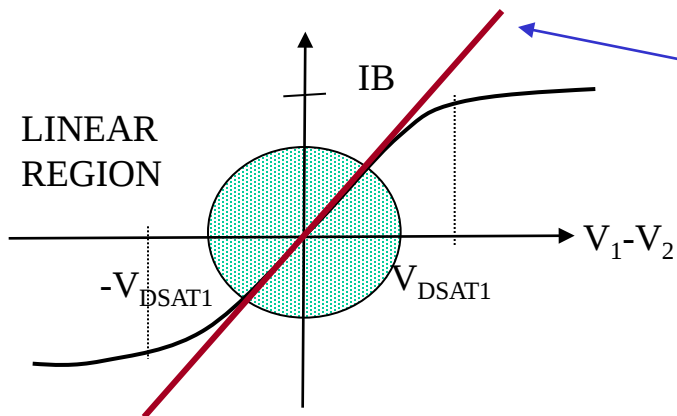
Differential Pair



The diff pair is a nonlinear circuit

$$i_{d1} - i_{d2} = g_{m1} (v_1 - v_2) \underbrace{\sqrt{1 - \left(\frac{v_1 - v_2}{2V_{DSAT1}} \right)^2}}_{\text{Non-linear term}}$$

If $v_d = v_1 - v_2 < V_{DSAT1} \Rightarrow$

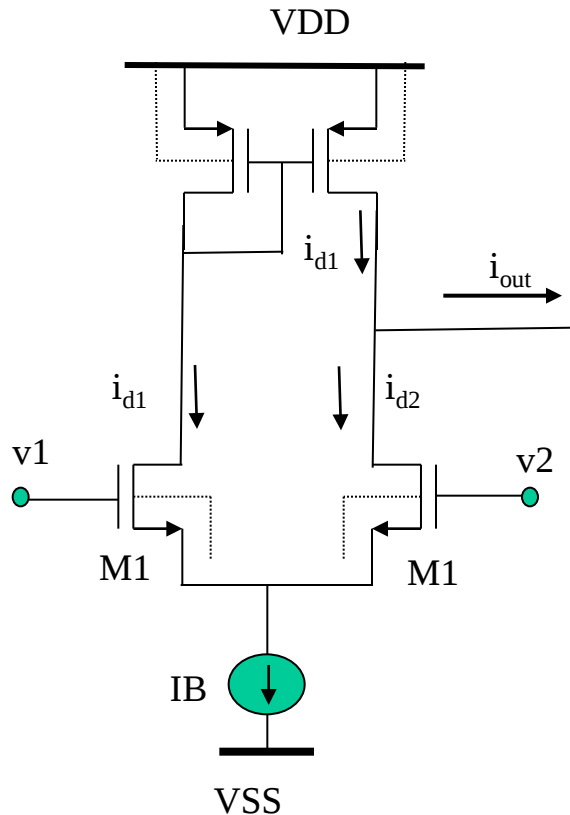


$$i_{d1} - i_{d2} = \sqrt{\mu_n C_{OX} \frac{W}{L} I_B} (v_1 - v_2)$$

Note:

**Linear range increases for large V_{DSAT1}
 V_{GS} is also increased (limited by VSS)**

Basic Operational Transconductance Amplifier



DESIGN CONSIDERATIONS:

$$\triangleright V_d = v_1 - v_2 < V_{DSAT}$$

$$\triangleright v_{1,2} - V_{SS} > V_{GS1} + V_{DSATB}$$

For small signals, ignoring the capacitors:

$$i_{out} = \sqrt{\mu_n C_{OX} \frac{W}{L} I_B} (v_1 - v_2)$$

or

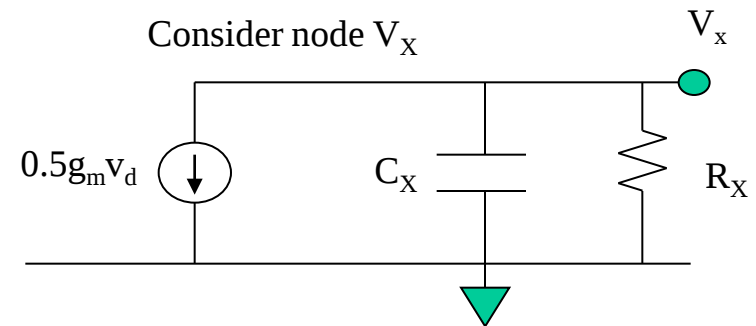
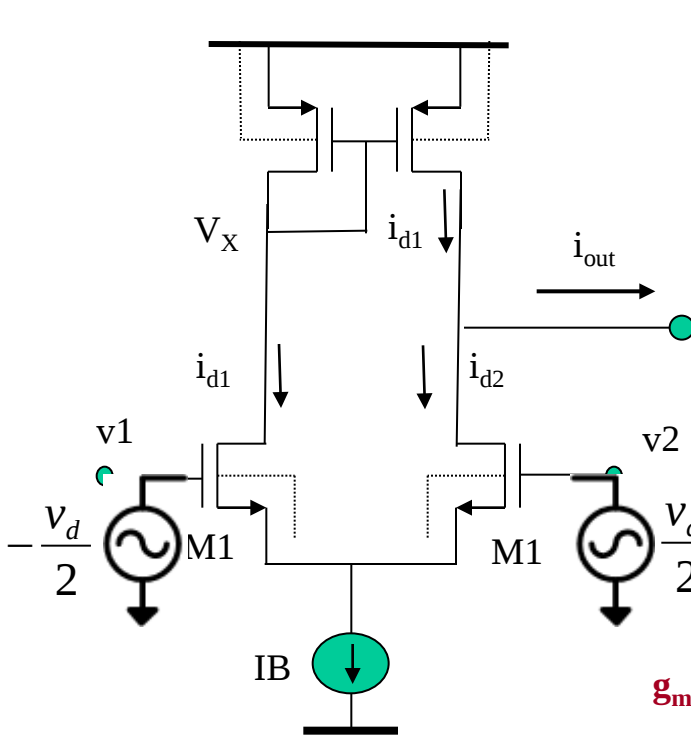
$$i_{out} = g_m (v_1 - v_2) \quad \text{Sensitive to differential signals}$$

$$v_{out} = g_m r_{out} (v_1 - v_2)$$

$$r_{out} = r_{o1} \parallel r_{op}$$

For an ideal current source and ignoring the effects of g_{mb} , and transistor mismatches, then $i_{out}=0$ for $v_1=v_2 \implies$ rejection to common-mode (noise) signals present at the input!

Frequency Response



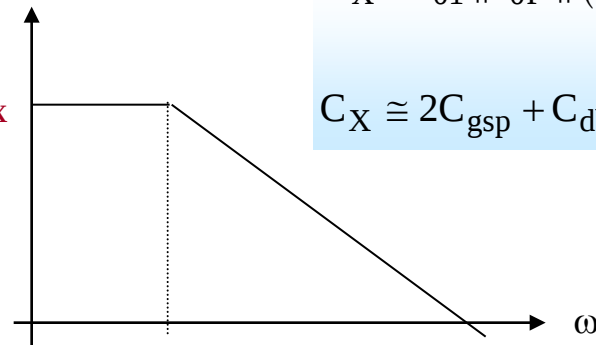
$$V_X = -\frac{0.5g_m R_X}{1 + sR_X C_X} V_d$$

$$R_X = r_{o1} \parallel r_{o2} \parallel (1/g_{mp})$$

$$C_X \cong 2C_{gsp} + C_{dbp} + (1 + \text{miller factor})C_{dgp} + C_{dbn}$$

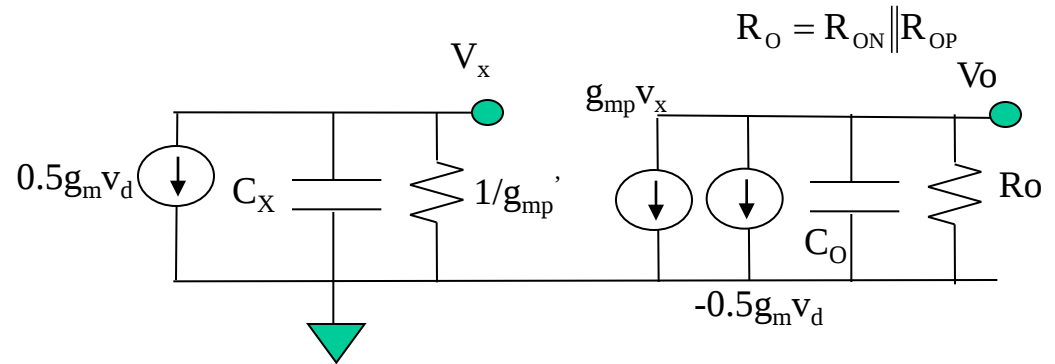
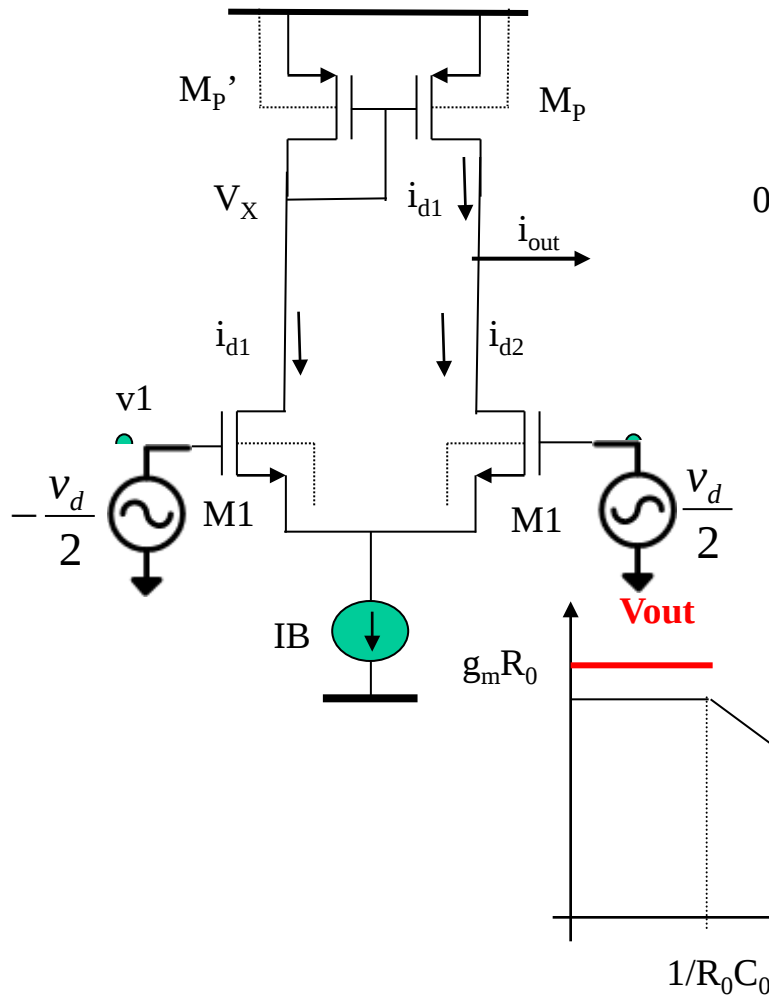
Magnitude

$g_m R_X$



$1/R_X C_X$

Low Frequency Response

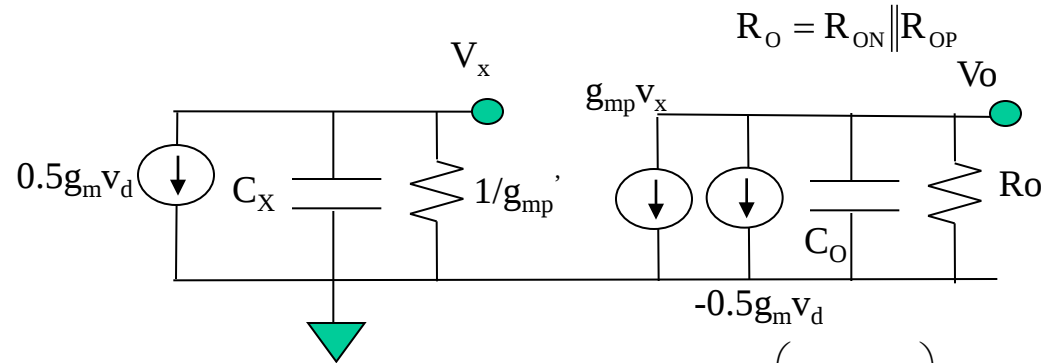
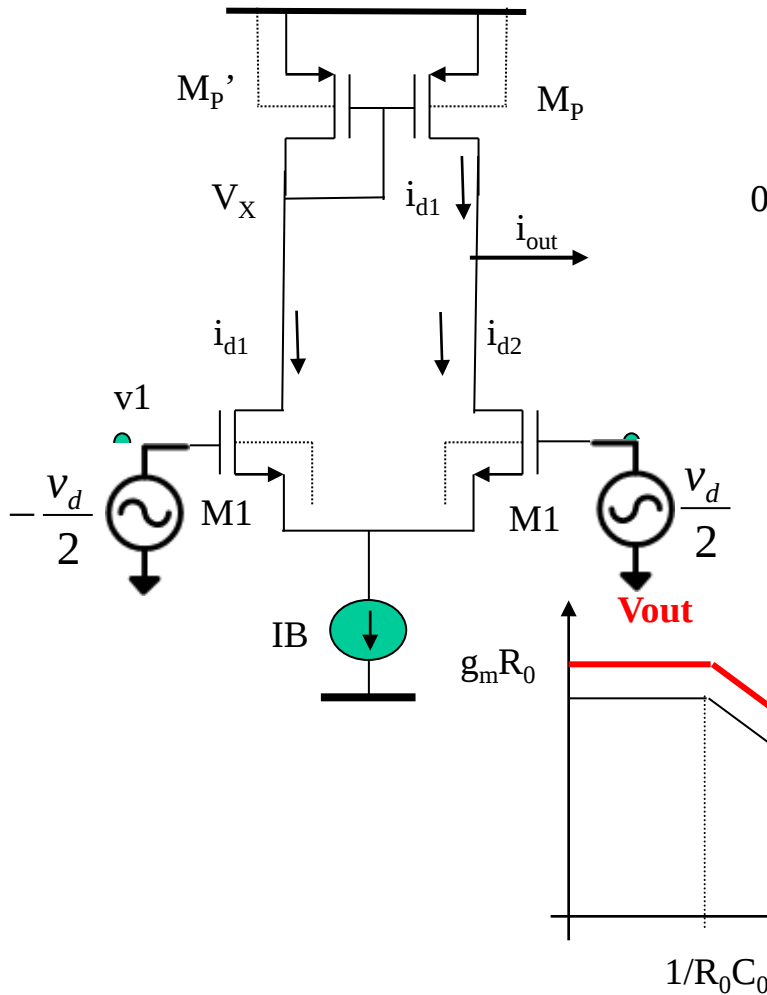


$$v_o = -g_m \left(\frac{v_d}{2} \right) R_o - g_m \left(-\frac{v_d}{2} \right) R_x (-g_{mp} R_o)$$

$$R_x \approx \frac{1}{g_{mp}}$$

$$v_o = -g_m v_d R_o$$

Frequency Response



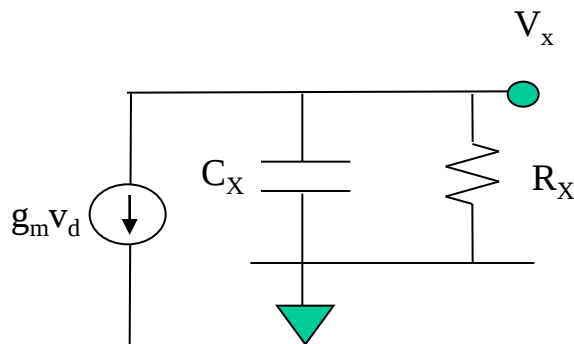
$$v_o = -g_m \left(\frac{v_d}{2} \right) \frac{R_o}{1 + sR_o C_o} - g_m \left(\frac{v_d}{2} \right) \left(\frac{1/g_{mp}}{1 + s \frac{C_x}{g_{mp}}} \right) \frac{g_{mp} R_o}{1 + sR_o C_o}$$

$$v_o = -g_m R_o \left(\frac{v_d}{2} \right) \frac{1}{1 + sR_o C_o} \left[1 + \frac{1}{1 + s \frac{C_x}{g_{mp}}} \right]$$

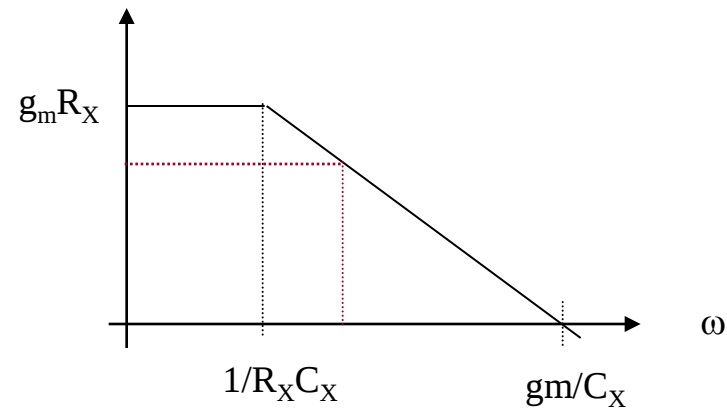
$$v_o = -g_m R_o \left(\frac{v_d}{2} \right) \frac{1}{1 + sR_o C_o} \left[\frac{2 + s \frac{C_x}{g_{mp}}}{1 + s \frac{C_x}{g_{mp}}} \right]$$

Frequency Response

Poles are associated with both resistors and capacitors



$$V_x = \frac{g_m R_x}{1 + s R_x C_x} V_d$$



IMPORTANT REMARKS !!!!

- DC-GAIN IS PROPORTIONAL TO R_x
- POLE FREQUENCY IS PROPORTIONAL TO $1/C_x R_x$
- GAIN-BANDWIDTH PRODUCT ($=g_m/C_x$) IS CONSTANT

TRADEOFF BETWEEN GAIN AND BANDWIDTH

Next Time

- Single-Stage Amplifiers (cont.)
 - Common-Gate
 - Cascode Stage
- Noise