11 August 2022

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13 محرم 1444

Analog IC Design

Lecture 09
Frequency Response (2)

Dr. Hesham A. Omran

Integrated Circuits Laboratory (ICL)
Electronics and Electrical Communication Eng. Dept.
Faculty of Engineering
Ain Shams University

Outline

- Recapping previous key results
- Frequency response of CS: Midband, LFR, and HFR (Miller's effect)
- Frequency response of CG: HFR
- Frequency response of cascode: HFR
  - Cascode for gain and cascode for BW
- Frequency response of CD: HFR
  - Frequency domain peaking and time domain ringing
  - Z_{in}: negative resistance and Z_{out}: inductive rise

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MOSFET in Saturation

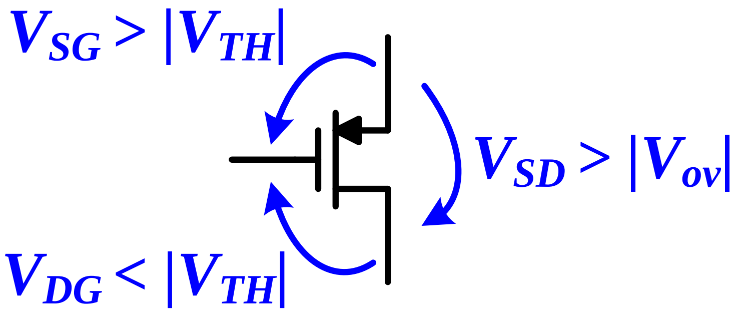
- The channel is pinched off if the difference between the gate and drain voltages is not sufficient to create an inversion layer

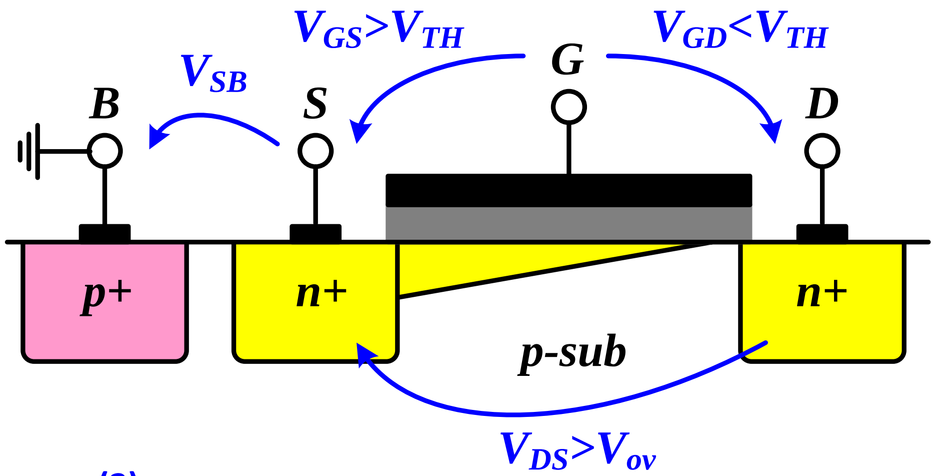
$$V_{GD} \leq V_{TH} \quad OR \quad V_{DS} \geq V_{ov}$$

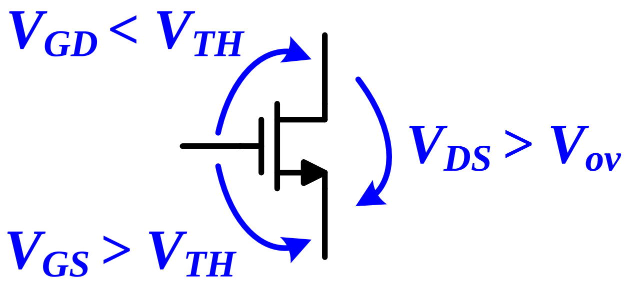
- Square-law (long channel MOS)

$$I_D = \frac{\mu_n C_{ox}}{2}\frac{W}{L} \cdot V_{ov}^2(1 + \lambda V_{DS})$$

$$V_{SB} \uparrow \;\; \Rightarrow \;\; V_{TH} \uparrow$$







Regions of Operation Summary

OFF (Subthreshold)

$V_{GS} < V_{TH}$

ON

$V_{GS} > V_{TH}$

Triode

$V_{DS} < V_{ov}$

Or

$V_{GD} > V_{TH}$

$$I_D = \mu C_{ox}\frac{W}{L}\left(V_{ov}V_{DS} - \frac{V_{DS}^2}{2}\right)$$

Pinch-Off (Saturation)

$V_{DS} \geq V_{ov}$

Or

$V_{GD} \leq V_{TH}$

$$I_D = \frac{\mu C_{ox}}{2}\frac{W}{L}V_{ov}^2(1 + \lambda V_{DS})$$

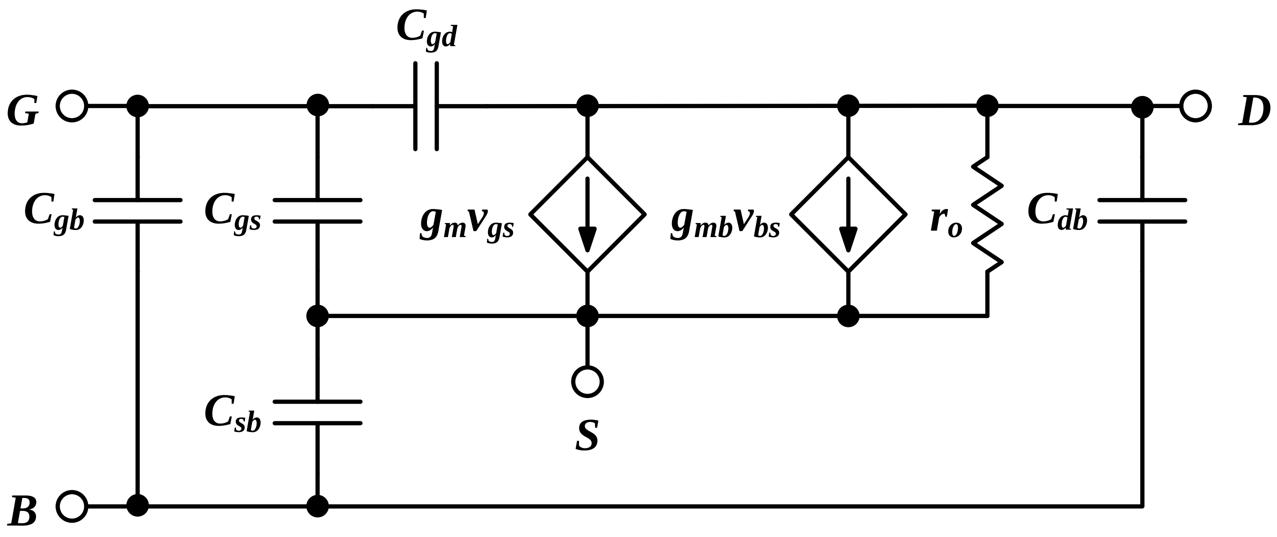
High Frequency Small Signal Model

$$g_m = \frac{\partial I_D}{\partial V_{GS}} = \mu C_{ox}\frac{W}{L}V_{ov} = \sqrt{\mu C_{ox}\frac{W}{L}\cdot 2I_D} = \frac{2I_D}{V_{ov}}$$

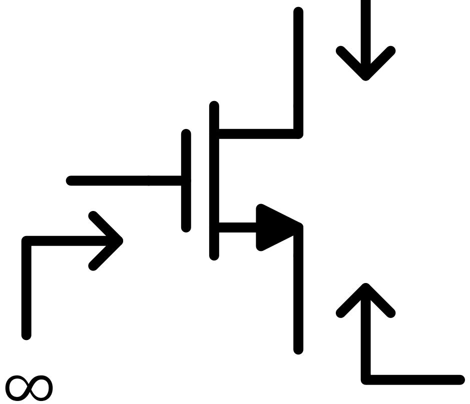
$$g_{mb} = \eta g_m \qquad \eta \approx 0.1 - 0.25$$

$$r_o = \frac{1}{\partial I_D/\partial V_{DS}} = \frac{V_A}{I_D} = \frac{1}{\lambda I_D} \qquad V_A \propto L \leftrightarrow \lambda \propto \frac{1}{L} \qquad V_{DS}\uparrow V_A \uparrow$$

$$C_{gb} \approx 0 \qquad C_{gs} \gg C_{gd} \qquad C_{sb} > C_{db}$$



Rin/out Shortcuts Summary



$r_o[1 + (g_m + g_{mb})R_S]$

H.I.N.

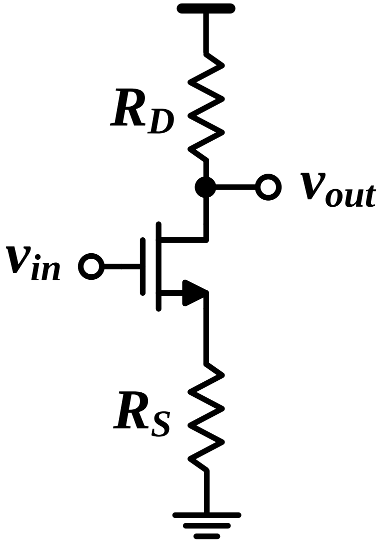
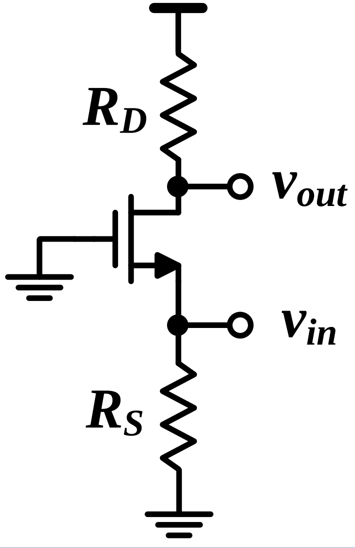
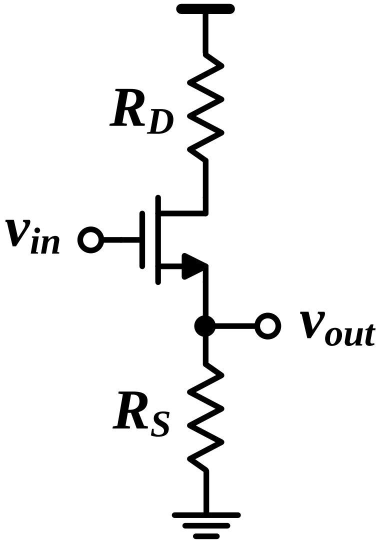
∞

At low frequencies **ONLY**

$$\frac{1}{g_m + g_{mb}}\left(1 + \frac{R_D}{r_o}\right)$$

L.I.N.

Summary of Basic Topologies

	CS	CG	CD (SF)
			
	Voltage & current amplifier	Voltage amplifier Current buffer	Voltage buffer Current amplifier
Rin	∞	$R_S \vert\vert \dfrac{1}{g_m + g_{mb}}\left(1 + \dfrac{R_D}{r_o}\right)$	∞
Rout	$R_D \vert\vert r_o[1 + (g_m + g_{mb})R_S]$	$R_D \vert\vert r_o$	$R_S \vert\vert \dfrac{1}{g_m + g_{mb}}\left(1 + \dfrac{R_D}{r_o}\right)$
Gm	$\dfrac{-g_m}{1 + (g_m + g_{mb})R_S}$	$g_m + g_{mb}$	$\dfrac{g_m}{1 + R_D/r_o}$

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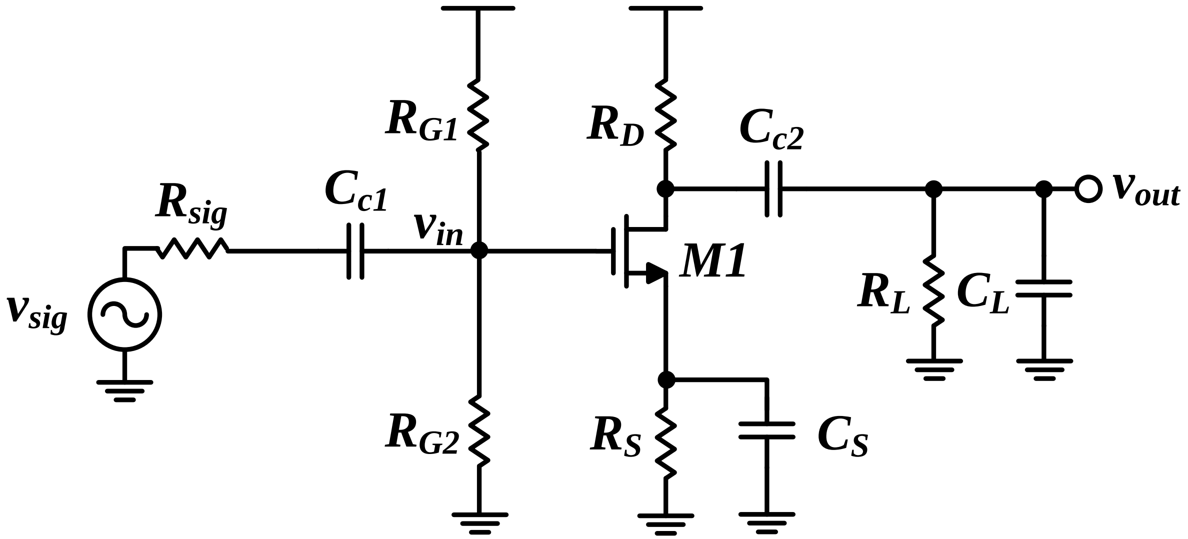
Frequency Response of CS: Midband

$$A_v = \frac{v_{in}}{v_{sig}} \cdot \frac{v_{out}}{v_{in}}$$

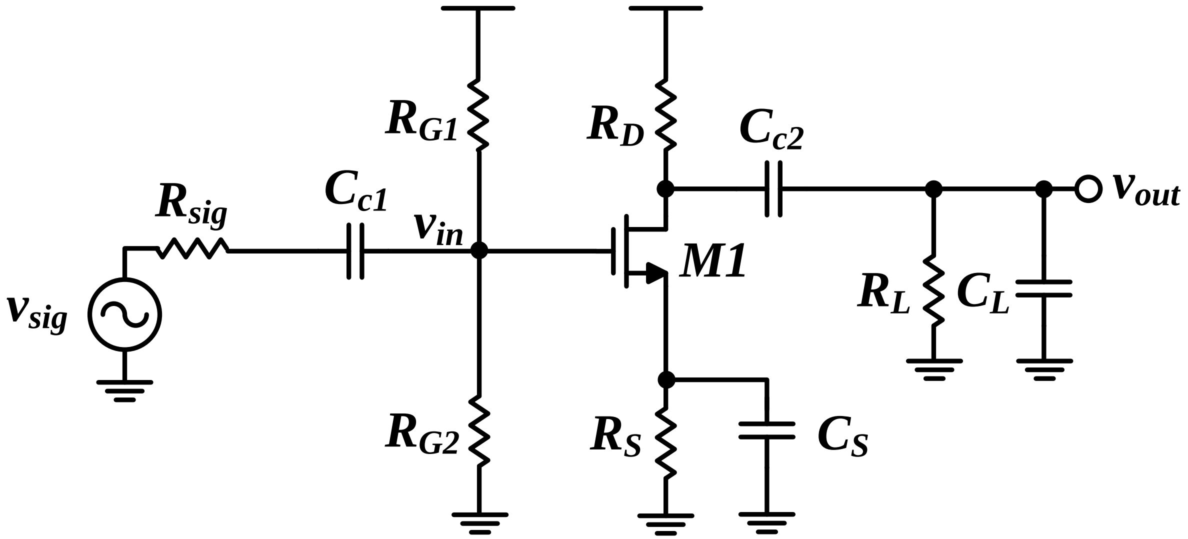
$$\frac{v_{out}}{v_{in}} = G_m R_{out} = -g_m(R_D||R_L||r_o)$$

$$\frac{v_{in}}{v_{sig}} = \frac{R_{in}}{R_{in} + R_{sig}}, R_{in} = R_G = R_{G1}||R_{G2}$$



Frequency Response of CS: LFR

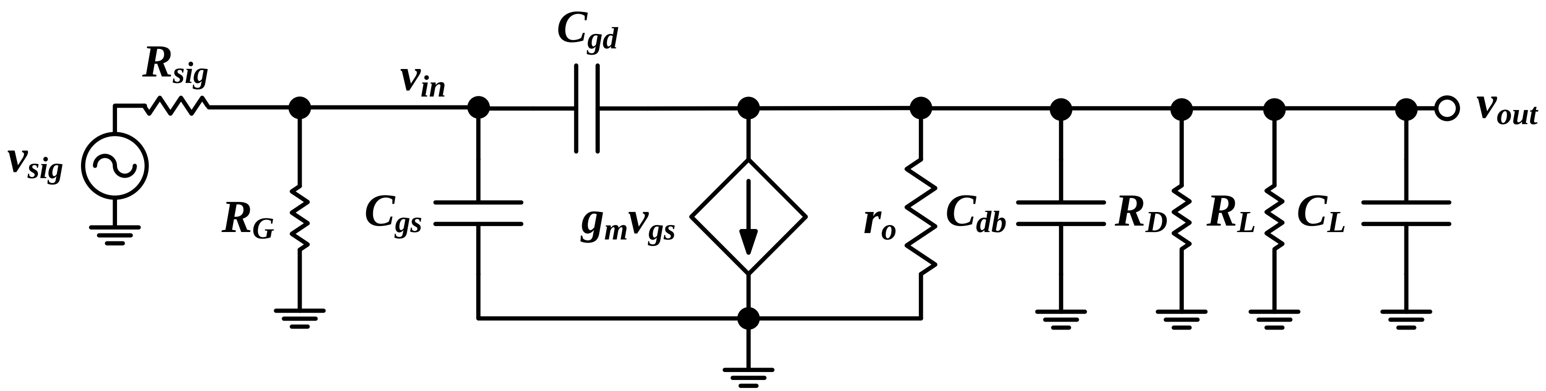
- $C_{C1}: R_{th} = R_{sig} + R_G \rightarrow \omega_{p,C_{C1}} = \frac{1}{(R_{sig}+R_G)C_{C1}}$ & $\omega_{z,C_{C1}} = 0$
- $C_{C2}: R_{th} = R_L + R_D||r_o \rightarrow \omega_{p,C_{C2}} = \frac{1}{(R_L+R_D||r_o)C_{C2}}$ & $\omega_{z,C_{C2}} = 0$
- $C_S: R_{th} = R_S||R_{LFS} \rightarrow \omega_{p,C_S} = \frac{1}{(R_S||R_{LFS})C_S}$ & $\omega_{z,C_S} = \frac{1}{R_S C_S}$
- Usually ω_{p,C_S} is dominant: $\omega_L \approx \omega_{p,C_S}$ (why?)
- Note that for IC amplifiers we usually use direct coupling (no LFR)



CS HFR: (1) Miller's Approx + OCTC

- Break the feedback capacitance $\left(C_{gd}\right)$ using Miller's approx
- Each node is associated with a pole
  - v_{in} node → i/p pole $\left(\omega_{p,in}\right)$
  - v_{out} node → o/p pole $\left(\omega_{p,out}\right)$
- Don't forget the RHP feedforward zero

$$\omega_{z,C_{gd}} = \frac{g_m}{C_{gd}}$$ → Usually $\omega_{z,C_{gd}}$ is very high (why?)



CS HFR: (1) Miller's Approx + OCTC

- i/p pole: **suffers from Miller effect (capacitance multiplication)**

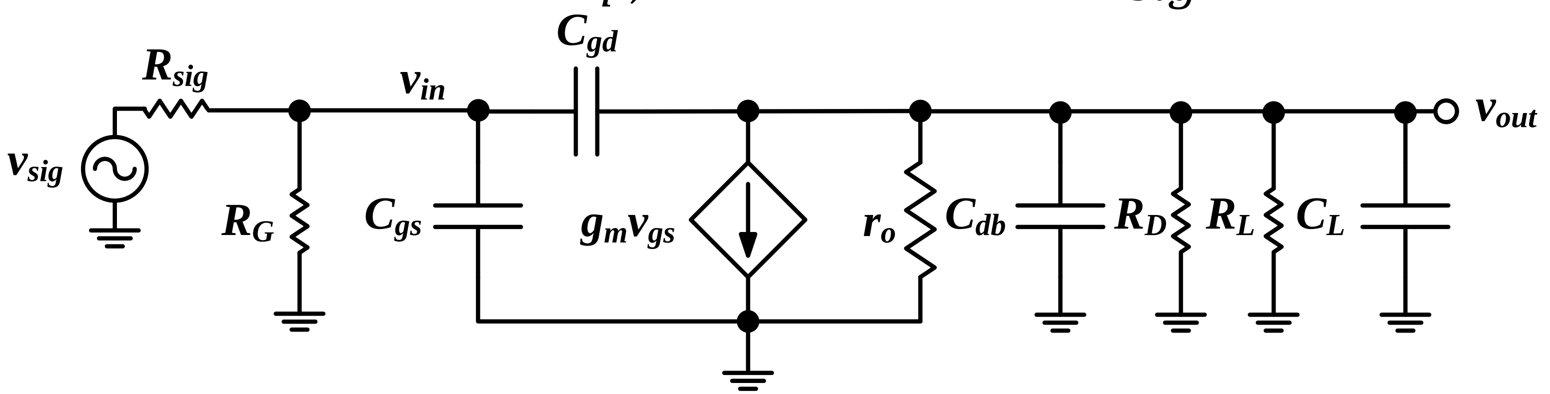
$$R_{th,in} = R_{sig}||R_G = R'_{sig} \rightarrow \omega_{p,in} \approx \frac{1}{R'_{sig}[C_{gs}+\boldsymbol{C_{gd}(1+A_o)}]}$$

$$A_o = \left|\frac{v_{out}}{v_{in}}\right| = g_m R_{out}$$

- o/p pole: $R_{th,out} = R_L||R_D||r_o$

$$\rightarrow \omega_{p,out} \approx \frac{1}{R_{out}\left(C_L+C_{db}+C_{gd}\left(1+\frac{1}{A_o}\right)\right)} \approx \frac{1}{R_{out}(C_{out}+C_{gd})}$$

- Usually i/p pole is dominant: $\omega_H \approx \omega_{p,in}$ (why?), unless R'_{sig} ↓↓



CS HFR: (1) Miller's Approx + OCTC

$$\omega_H \approx \frac{1}{\frac{1}{\omega_{p,in}} + \frac{1}{\omega_{p,out}}} = \frac{1}{R'_{sig}\left[C_{gs} + C_{gd}(1 + g_m R_{out})\right] + R_{out}\left(C_{out} + C_{gd}\right)}$$

- If input pole is dominant (e.g., if $R'_{sig}\uparrow\uparrow$ or $C_L \downarrow\downarrow$)

$$\omega_H \approx \frac{1}{R'_{sig}\left[C_{gs} + C_{gd}(1 + g_m R_{out})\right]} \approx \omega_{p,in}$$

- If output pole is dominant (e.g., if $R'_{sig} \downarrow\downarrow$ or $C_L \uparrow\uparrow$)

$$\omega_H \approx \frac{1}{R_{out}\left(C_{out} + C_{gd}\right)} \approx \omega_{p,out}$$

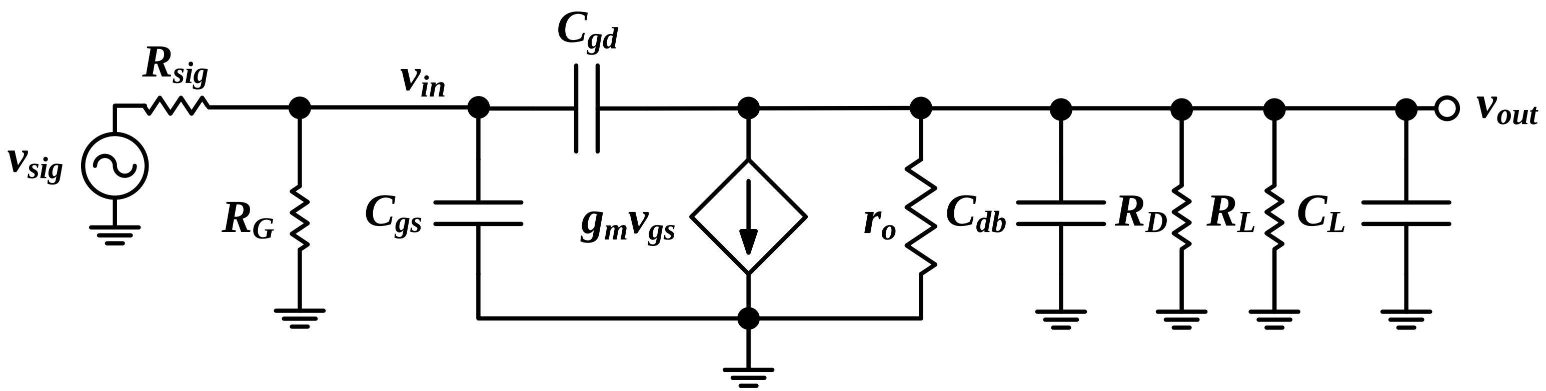
$$GBW = A_v \omega_H = G_m R_{out} \cdot \frac{1}{R_{out}\left(C_{out}+C_{gd}\right)} = \frac{G_m}{C_{out}+C_{gd}}$$

→ independent of R_{out}!

CS HFR: (2) Just OCTC Technique

- $C_{gs}: R_{th,in} = R_{sig}||R_G = R'_{sig} \rightarrow \omega_{p,C_{gs}} = \dfrac{1}{R'_{sig}C_{gs}}$
- $C_{out} = C_L + C_{db}: R_{th} = R_L||R_D||r_o = R_{out} \rightarrow \omega_{p,C_{out}} = \dfrac{1}{R_{out}C_{out}}$
- $C_{gd}: R_{th} = \dfrac{v_x}{i_x} = R'_{sig}(1 + g_m R_{out}) + R_{out} \rightarrow \omega_{p,C_{gd}} = \dfrac{1}{[R'_{sig}(1+g_m R_{out})+R_{out}]C_{gd}}$

$$\omega_H \approx \frac{1}{\frac{1}{\omega_{p,C_{gs}}} + \frac{1}{\omega_{p,C_{out}}} + \frac{1}{\omega_{p,C_{gd}}}} = \frac{1}{R'_{sig}C_{gs} + R_{out}C_{out} + [R'_{sig}(1 + g_m R_{out}) + R_{out}]C_{gd}}$$



CS HFR: (2) Just OCTC Technique

$$\omega_H \approx \frac{1}{R'_{sig}\left[C_{gs} + C_{gd}(1 + g_m R_{out})\right] + R_{out}\left(C_{out} + C_{gd}\right)}$$

- If input pole is dominant (e.g., if R'_{sig} ↑↑ or C_L ↓↓)

$$\omega_H \approx \frac{1}{R'_{sig}\left[C_{gs} + C_{gd}(1 + g_m R_{out})\right]} \approx \omega_{p,in}$$

- If output pole is dominant (e.g., if R'_{sig} ↓↓ or C_L ↑↑)

$$\omega_H \approx \frac{1}{R_{out}\left(C_{out} + C_{gd}\right)} \approx \omega_{p,out}$$

- Same as the expressions obtained from Miller approx

CS HFR: (3) Exact Analysis + Dominant Pole Approx

- Surprisingly, exact analysis gives a quite complex expression
  - See [Johns & Martin 2012] or [Razavi 2017]
- If dominant pole approximation is applied

$$\omega_{pd} \approx \frac{1}{b_1} = \frac{1}{R'_{sig}\left[C_{gs} + C_{gd}(1 + g_m R_{out})\right] + R_{out}\left(C_{out} + C_{gd}\right)}$$

  - Same result as OCTC (both based on same approximation)
- Additionally, dominant pole approx gives an expression for ω_{pnd}

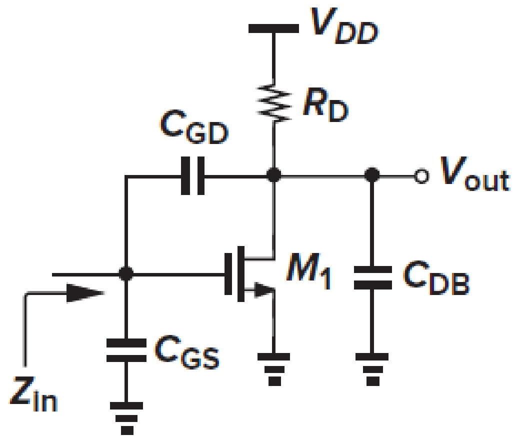
$$\omega_{pnd} \approx \frac{1}{b_2 \omega_{p1}} = \frac{b_1}{b_2} = \frac{g_m C_{gd}}{C_{gd}\left(C_{gs} + C_{out}\right) + C_{gs} C_{out}}$$

  - If a large cap is connected parallel to C_{gd}: $\omega_{pnd} \approx \frac{g_m}{C_{gs}+C_{out}}$
    - Can be derived intuitively without analysis (how?)
    - **We will need this case when we study two-stage OTA**

Frequency Response of CS: Z_{in}

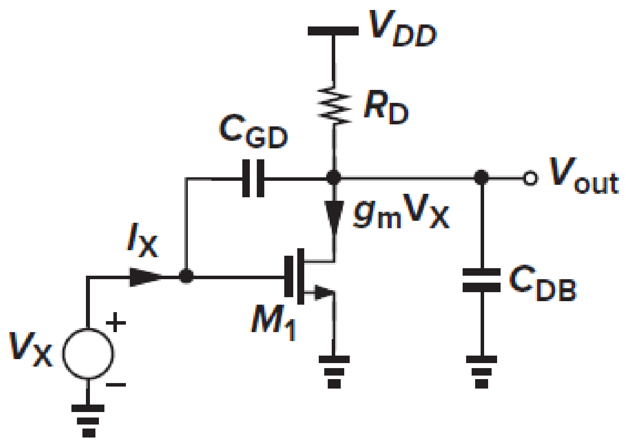
- With Miller approx.

$$Z_{in} = \frac{1}{s\left[C_{gs} + (1 + g_m R_D) C_{gd}\right]}$$



- Exact Analysis (C_{gs} adds in parallel)

$$Z_{in} = \frac{V_X}{I_X} = \frac{1 + sR_D\left(C_{gd} + C_{db}\right)}{sC_{gd}(1 + g_m R_D + sR_D C_{db})}$$



  - Extra pole and zero at high frequency ($\omega_p > \omega_z$)
  - At relatively low frequency the exact solution reduces to Miller approx.

[Razavi, 2017]

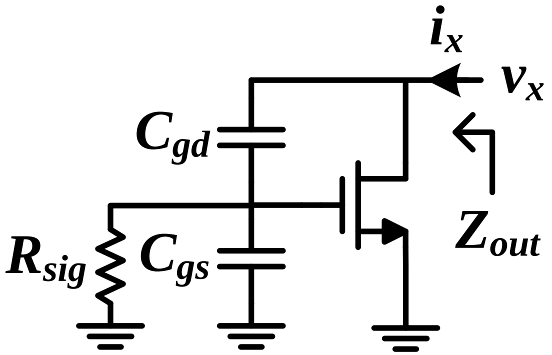
Frequency Response of CS: Z_{out}

- Can we use Miller?

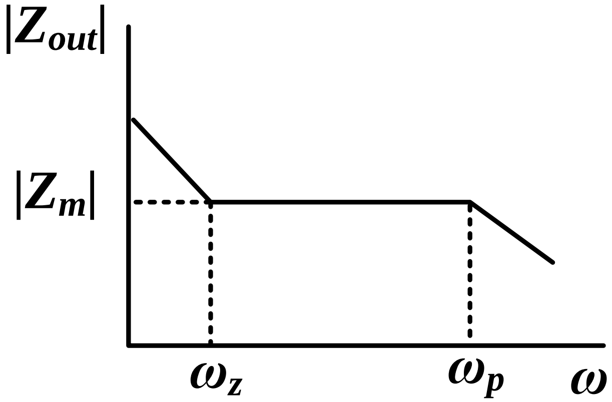
$$i_x = f(v_{gs}) = g_m v_{gs} + \frac{v_{gs}(1 + sR_{sig}C_{gs})}{R_{sig}}$$

$$v_x = f(v_{gs}) = v_{gs} + \frac{v_{gs}(1 + sR_{sig}C_{gs})}{sR_{sig}C_{gd}}$$

$$Z_{out} = \frac{v_x}{i_x} \approx \frac{1 + sR_{sig}(C_{gs} + C_{gd})}{sC_{gd}g_m R_{sig}\left(1 + s\frac{C_{gs}}{g_m}\right)}$$



- r_o and C_{db} add in parallel
- Important special case: If we have a large capacitor parallel to C_{gd}
  - $|Z_m| \approx 1/g_m$ → We will need this case when we study Miller OTA



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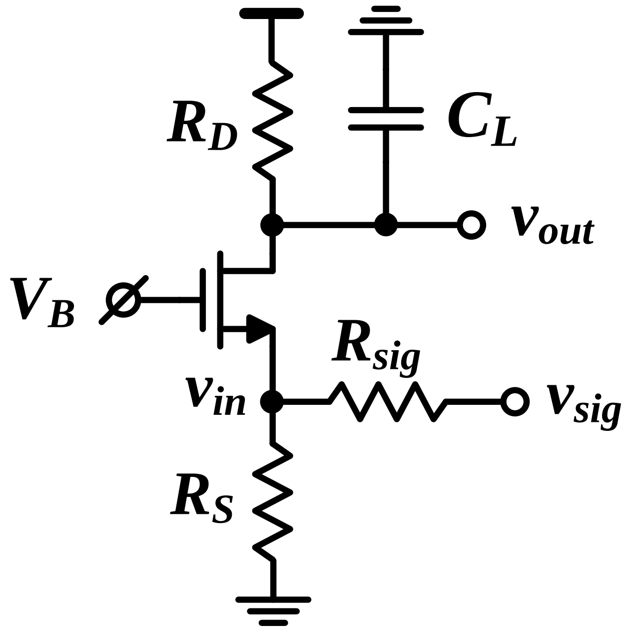
Frequency Response of CG: HFR

- i/p pole: $\omega_{p,in} = \frac{1}{(R_{sig}||R_S||R_{LFS})(C_{gs}+C_{sb})}$
- o/p pole: $\omega_{p,out} = \frac{1}{(R_D||R_{LFD})(C_L+C_{db}+C_{gd})}$
- Usually o/p pole is dominant: $\omega_H \approx \omega_{p,out}$ (why?)
- No FB cap → No Miller effect → $\boldsymbol{BW_{CG} \gg BW_{CS}}$



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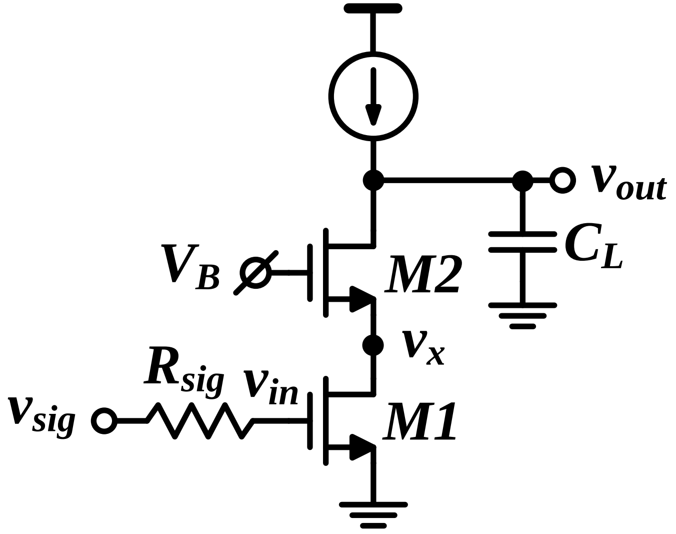
Frequency Response of Cascode: HFR

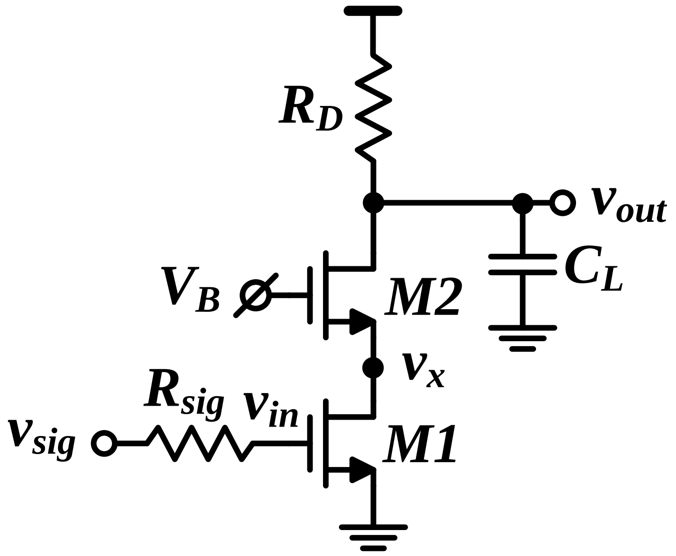
Case 1: BW limited by o/p pole ($R_D \uparrow\uparrow$ $R_{sig} \downarrow\downarrow$) (cascode for gain)

- $A_v = \frac{v_{out}}{v_{sig}} \approx (g_{m1}r_{o1})(g_{m2}r_{o2}) = A_{v,CS} \cdot (g_{m2}r_{o2})$
- $\omega_{p,out} \approx \frac{1}{r_{o1}(g_{m2}r_{o2})(C_L+C_{db2}+C_{gd2})} = \frac{\omega_{p,out,CS}}{g_{m2}r_{o2}}$ → Dominant
- $GBW = A_v\omega_{p,out} = A_{v,CS}\omega_{p,out,CS}$
  $= \frac{G_m}{C_{out}+C_{gd2}}$ → Same as CS!
- $A_{o1} = \left|\frac{v_x}{v_{in}}\right| = g_{m1}(r_{o1}||R_{LFS2}),\ R_{LFS2} = ?$
  - $A_{o1} \ll g_{m1}r_{o1}$ Miller effect reduced
- $\omega_{p,in} = \frac{1}{R_{sig}\left(C_{gs1}+C_{gd1}(1+A_{o1})\right)} = \omega_{p,in,CS}$
- $\omega_{p,x} = \frac{1}{(r_{o1}||R_{LFS2})\left(C_{gs2}+C_{sb2}+C_{db1}+C_{gd1}(1+1/A_{o1})\right)}$



Frequency Response of Cascode: HFR

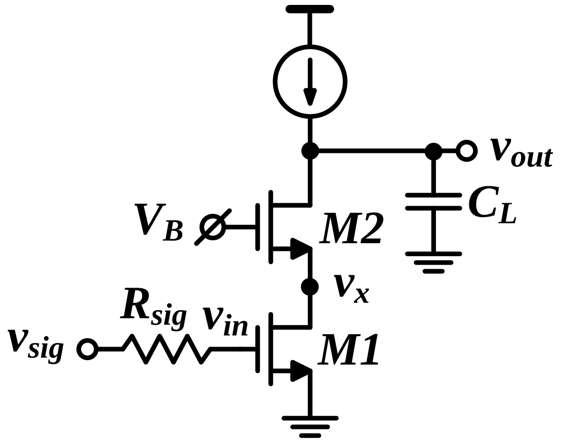
Case 2: BW limited by i/p pole ($R_D \downarrow\downarrow R_{sig} \uparrow\uparrow$) (cascode for BW)



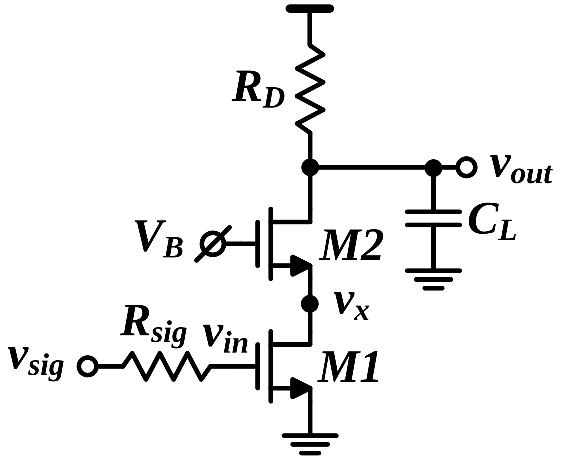
- $A_v = \frac{v_{out}}{v_{sig}} \approx g_{m1} R_D \approx A_{v,CS}$ → Similar to CS!
- $A_{o1} = \left|\frac{v_x}{v_{in}}\right| = g_{m1}(r_{o1} || \frac{1}{g_{m2}}) \approx 1$
- $\omega_{p,in} \approx \frac{1}{R_{sig}(C_{gs1}+2C_{gd1})} > \omega_{p,in,CS}$
  - **Miller effect significantly reduced**
  - **→ BW extension!**
- $\omega_{p,x} \approx \frac{1}{(r_{o1} || \frac{1}{g_{m2}})(C_{gs2}+C_{sb2}+C_{db1}+2C_{gd1})}$
- $\omega_{p,out} \approx \frac{1}{R_D(C_L+C_{db2}+C_{gd2})}$
- $GBW = A_v \omega_{p,in} > GBW$ of CS

Cascode HFR: Recapping

- If BW is limited by o/p pole
  - $GBW = A_v \omega_{p,out} = G_m R_{out} \cdot \frac{1}{R_{out} C_{out}} = \frac{G_m}{C_{out}}$
  - Cascode can be used **to trade gain for bandwidth** by modifying R_{out}
  - But $GBW = A_v \omega_{p,out}$ remain unchanged



- If BW is limited by i/p pole
  - Cascode can provide higher BW (Miller ↓)
  - The gain may be higher as well
  - $GBW = A_v \omega_{p,in}$ increases
  - Also improves reverse isolation (RF LNAs)



- See Example 10.10 in Sedra/Smith 7th ed.

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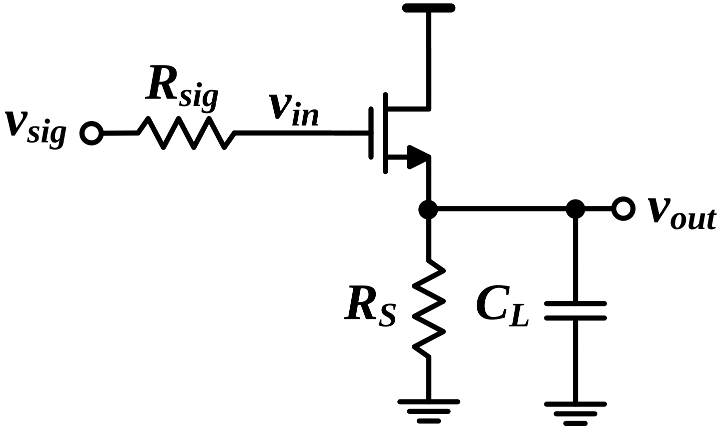
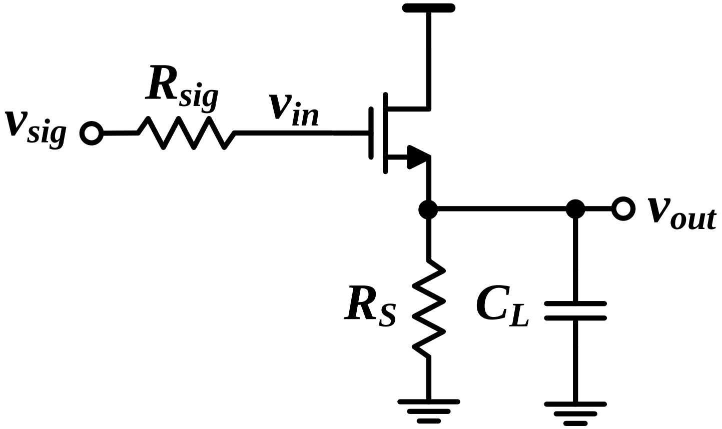
Frequency Response of CD: HFR

- Assume real and widely spaced poles (revisited next slide)
- Apply Miller: Ideally $A_o = v_{out}/v_{in} \approx 1$ → C_{gs} is **bootstrapped**
- i/p pole: $\omega_{p,in} = \frac{1}{R_{sig}\left(C_{gd}+C_{gs}(1-A_o)\right)}$
- o/p pole: $\omega_{p,out} = \frac{1}{(R_S||R_{LFS})\left(C_L+C_{sb}+C_{gs}(1-1/A_o)\right)}$
- Both poles are at high frequency (why?) → Large BW
- Don't forget the LHP feedforward zero: $\omega_z = \frac{g_m}{C_{gs}}$ ↑↑



CD HFR: Why Approximations Fail?

- The two poles are nearby and possibly complex conjugate
- OCTC technique and Miller approx cannot be used ☹



CD HFR: Exact Analysis

- Simple circuit, but exact analysis gives a complex expression!

$$\frac{v_{out}}{v_{sig}} = A_M \frac{1 + s/\omega_z}{\left(1 + \frac{s}{\omega_{p1}}\right)\left(1 + \frac{s}{\omega_{p2}}\right)} = A_M \frac{1 + s/\omega_z}{1 + \left(\frac{1}{\omega_{p1}} + \frac{1}{\omega_{p2}}\right)s + \frac{s^2}{\omega_{p1}\omega_{p2}}}$$

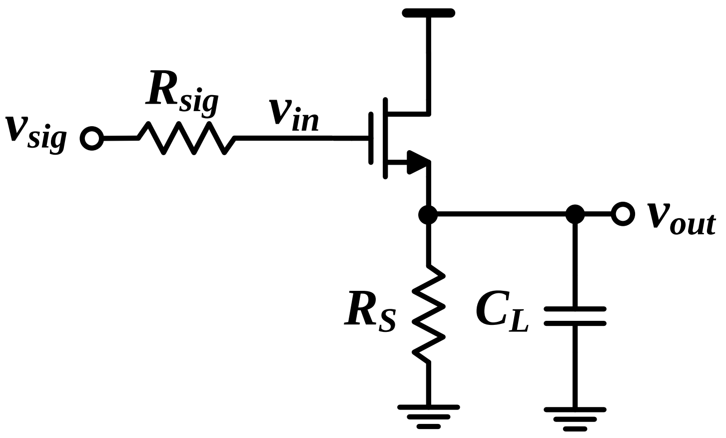
$$= A_M \frac{1 + s/\omega_z}{1 + b_1 s + b_2 s^2} = A_M \frac{1 + s/\omega_z}{1 + \frac{1}{Q}\frac{s}{\omega_o} + \frac{s^2}{\omega_o^2}} = A_M \frac{1 + s/\omega_z}{1 + 2\zeta\frac{s}{\omega_o} + \frac{s^2}{\omega_o^2}}$$

- Special case: R_S ↑↑ (IDC) + CLM and body effect neglected

$$b_1 = C_{gd}R_{sig} + \frac{C_{gs} + C_L}{g_m}$$

$$b_2 = \left(\frac{(C_{gs} + C_{gd})C_L + C_{gs}C_{gd}}{g_m}\right)R_{sig}$$

$$\omega_z = \frac{g_m}{C_{gs}}, \omega_o = \frac{1}{\sqrt{b_2}}, \boldsymbol{Q = \frac{\sqrt{b_2}}{b_1}}$$



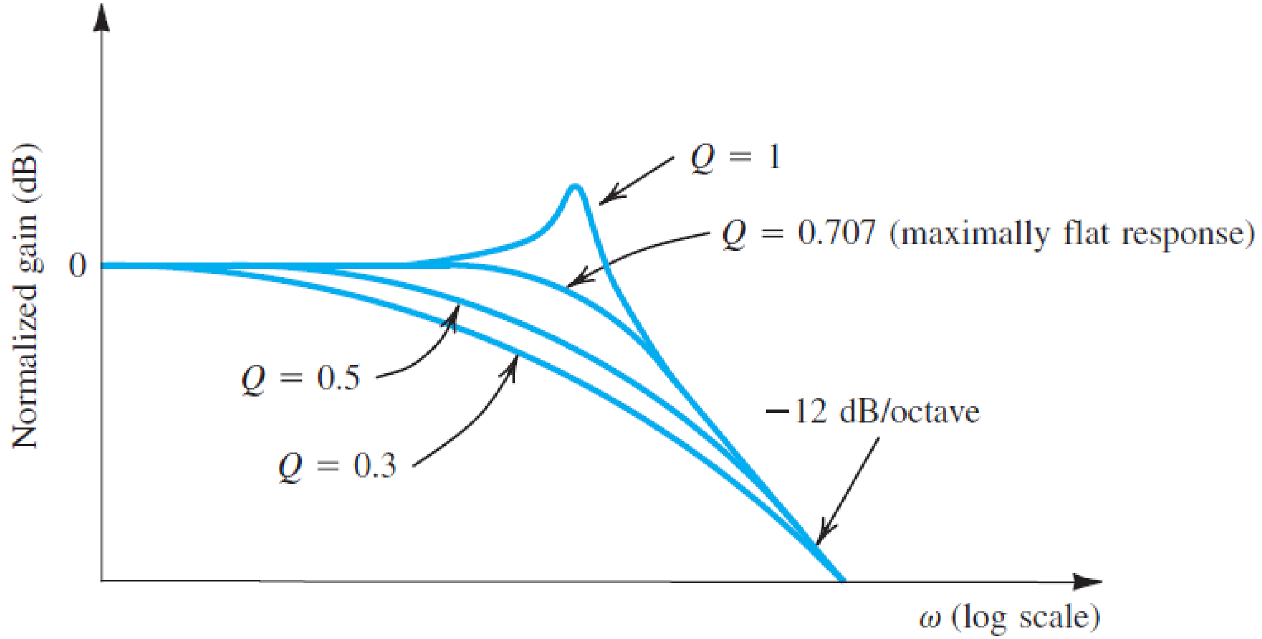
[Sedra/Smith, 2015]

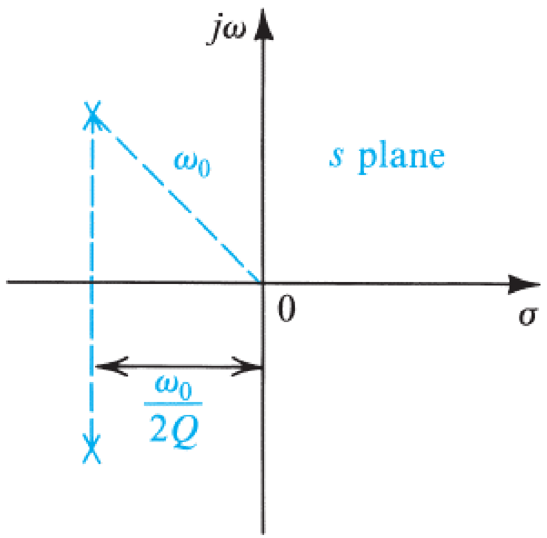
Peaking and Ringing

- $\omega_z \uparrow\uparrow$ is ignored
- $Q > 0.5$ ($\zeta < 1$): Underdamped system (complex conj. poles)
  - Ringing (overshoot) in step response (time domain)

$$\%\ \text{overshoot} = 100\, e^{\frac{-\pi}{\sqrt{4Q^2-1}}}$$

- $Q > \frac{1}{\sqrt{2}} = 0.707$ ($\zeta < 0.707$): Peaking in frequency response





[Sedra/Smith, 2015] & [Johns and Martin, 2012]

Driving Large Capacitive Load

- Special case: R_S ↑↑ (IDC) + CLM and body effect neglected + $\boldsymbol{C_L}$ ↑↑

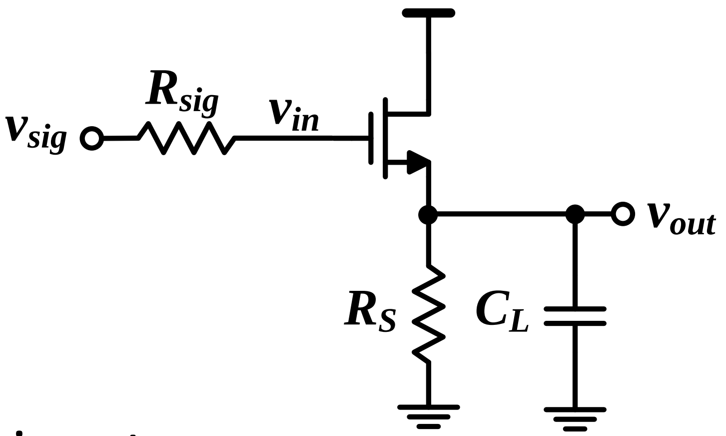
$$b_1 = C_{gd}R_{sig} + \frac{C_{gs} + C_L}{g_m} \approx \frac{C_L}{g_m}$$

$$b_2 = \left(\frac{(C_{gs} + C_{gd})C_L + C_{gs}C_{gd}}{g_m}\right)R_{sig} \approx \frac{(C_{gs} + C_{gd})C_L R_{sig}}{g_m}$$

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

$$\omega_o = \frac{1}{\sqrt{b_2}} \approx \sqrt{\frac{g_m}{(C_{gs} + C_{gd})C_L R_{sig}}}$$

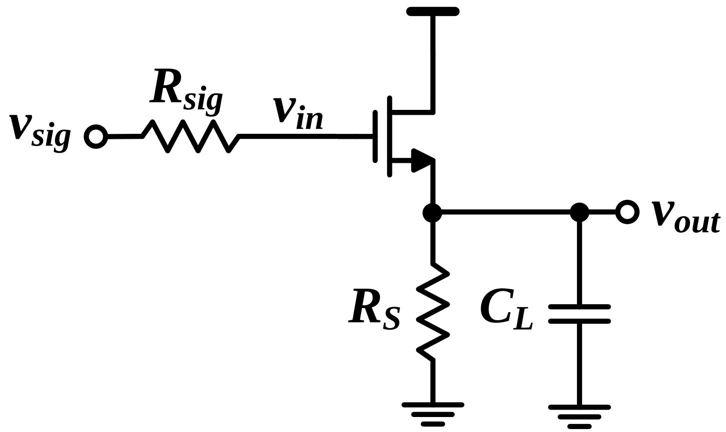
$$Q = \frac{\sqrt{b_2}}{b_1} \approx \sqrt{\frac{g_m(C_{gs} + C_{gd})R_{sig}}{C_L}}$$

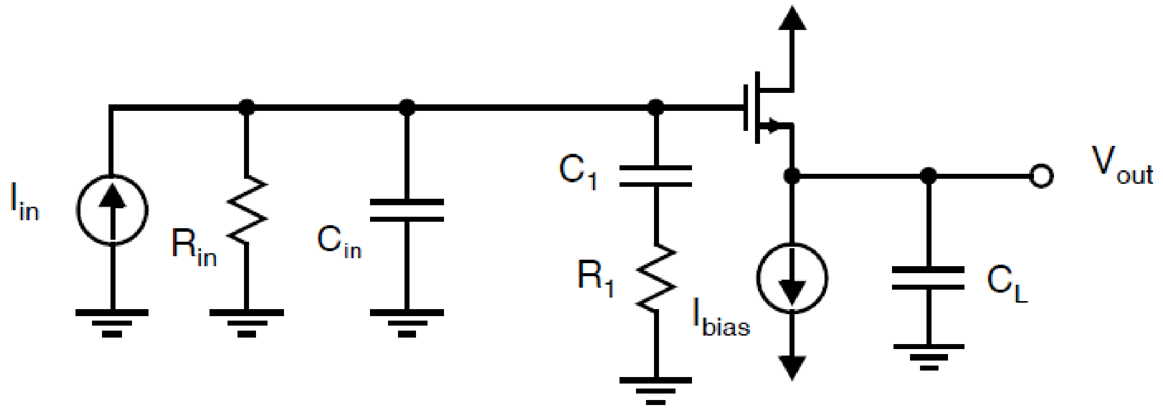


- Increasing C_L eventually decreases Q → $\omega_{p,out}$ becomes dominant

Suppressing the Overshoot

- Space the two poles far apart → single dominant pole
  - Increase C_L (till $Q < 0.5$)
  - Or increase C_{in} (adds to C_{gd}) → but buffer becomes less useful!
- More clever solution
  - A compensation network (R_1 and C_1) can be used to compensate for the negative input impedance and prevent overshoots
  - See [Johns and Martin, 2012] Section 4.4 for more details





[Johns and Martin, 2012]

Z_{in} of CD

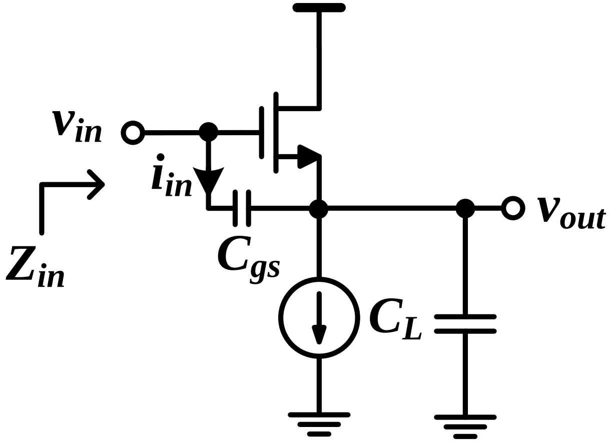
- $v_{gs} = i_{in}/sC_{gs}$
- $v_{in} = i_{in}/sC_{gs} + \left(i_{in} + g_m i_{in}/sC_{gs}\right)(r_o||1/g_{mb}||1/sC_L)$

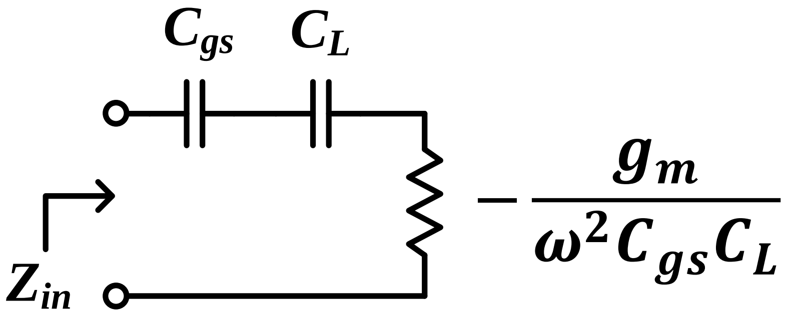
$$Z_{in} = \frac{v_{in}}{i_{in}} = 1/sC_{gs} + \left(1 + g_m/sC_{gs}\right)(r_o||1/g_{mb}||1/sC_L)$$

- If $1/sC_L$ is dominant (e.g., driving large cap load, or @ high freq)

$$Z_{in} \approx \frac{1}{sC_{gs}} + \frac{1}{sC_L} + \frac{g_m}{s^2 C_{gs} C_L} = \frac{1}{j\omega C_{gs}} + \frac{1}{j\omega C_L} - \frac{g_m}{\omega^2 C_{gs} C_L} \rightarrow \text{-ve res!}$$

- Can be used in oscillators, and may make amplifiers unstable!
- Note that C_{gd} shunts Z_{in} at high frequency



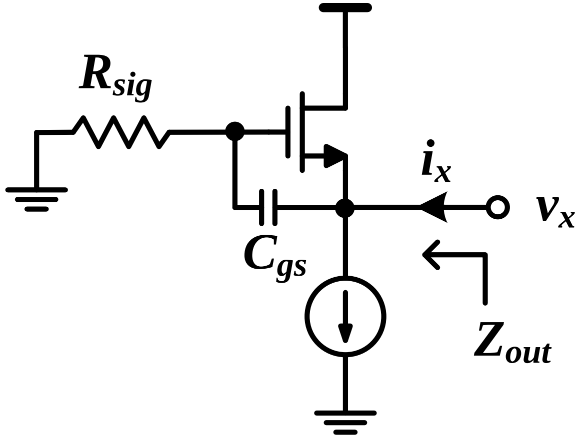


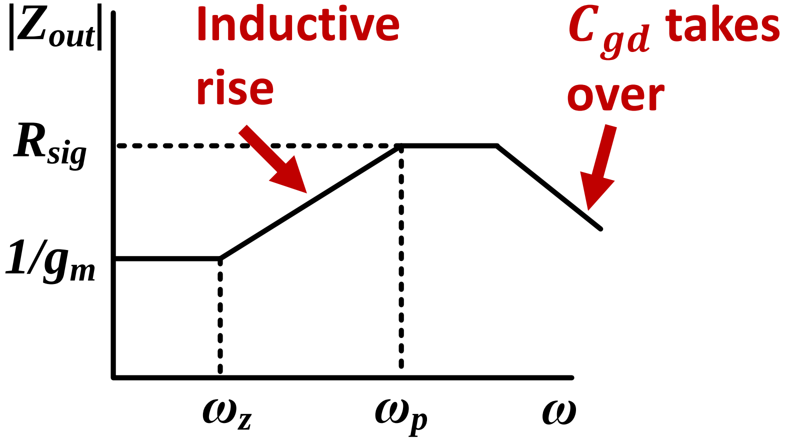
Z_{out} of CD

- $i_x = \frac{v_x}{1/sC_{gs}+R_{sig}} + g_m \cdot \frac{v_x}{1/sC_{gs}+R_{sig}} \cdot \frac{1}{sC_{gs}}$

$$Z_{out} = \frac{v_x}{i_x} = \frac{1}{g_m}\left(\frac{1+sR_{sig}C_{gs}}{1+s\frac{C_{gs}}{g_m}}\right)$$

- By intuition: $\omega \downarrow\downarrow$: $Z_{out} \approx 1/g_m$ and $\omega \uparrow\uparrow$: $Z_{out} \approx R_{sig}$
- Usually $R_{sig} > 1/g_m$(buffer) → inductive rise
- Note that C_{gd} shunts R_{sig} at high frequency ($\approx 1/R_{sig}C_{gd}$)
- Body resistance $(1/g_{mb})$ and r_o add to Z_{out} in parallel





Thank you!

References

- A. Sedra and K. Smith, “Microelectronic Circuits,” Oxford University Press, 7th ed., 2015
- B. Razavi, “Design of Analog CMOS Integrated Circuits,” McGraw-Hill, 2nd ed., 2017
- T. C. Carusone, D. Johns, and K. W. Martin. “Analog Integrated Circuit Design,” Wiley, 2nd ed., 2012

Quiz

- LD = 100 nH, Cgd = 10 fF, gm = 10 mS, w = 10 Gr/s
- Ignore VA and other caps
- Assume Av >> 1
- Rin = ?