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EECS140
Analog Circuit Design

# Lectures on FREQUENCY RESPONSE



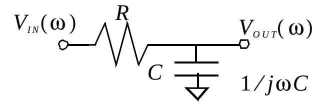


## Bode Plots

FR-1

Solve impedance network transfer function.

$$H(\omega) = \frac{V_{OUT}(\omega)}{V_{IN}(\omega)}$$ ( H(ω) , $V_{out}(\omega)$ & $V_{in}(\omega)$ are phasors )




$$H(\omega) = \frac{V_{OUT}(\omega)}{V_{IN}(\omega)} = \frac{1/j\omega C}{R + 1/j\omega C}$$

$$H(\omega) = \frac{1/j\omega C}{1 + j\omega RC}$$

Convert H(ω) to polar coordinates, |H(ω)| < θ

$$|H(\omega)| = [H(\omega)(H^*(\omega))]^{\frac{1}{2}}$$

$$\theta = \text{atan}\left\{\frac{I_m\{H(\omega)\}}{R_e\{H(\omega)\}}\right\}$$

$$IF \;\; H(\omega) = \frac{N(\omega)}{D(\omega)} \;\; then$$

$$R_e \cdot \{H(\omega)\} = R_e \cdot \{N(\omega) \cdot D^*(\omega)\}$$

$$I_M \cdot \{H(\omega)\} = I_M \cdot \{N(\omega) \cdot D^*(\omega)\}$$





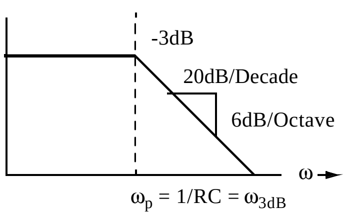
## Bode Plots (Cont.)

FR-2

$$(H(\omega) \cdot H^*(\omega))^{1/2} = \left(\frac{1}{1 + j\omega RC}\right) \cdot \left(\frac{1}{1 - j\omega RC}\right)$$

$$= \left(\frac{1}{1 + (\omega RC)^2}\right)^{1/2} = \left[\frac{1}{1 + \left(\frac{\omega}{\omega_{3dB}}\right)^2}\right]^{1/2}$$

Bode Plot Magnitude $|H(\omega)|_{dB} = 20 \cdot \log |H(\omega)|$




$\omega \gg \omega_{3dB}$

$$|H(\omega)| \approx \left[\frac{1}{\left(\frac{\omega}{\omega_{3dB}}\right)^2}\right]^{1/2} = \frac{\omega_{3dB}}{\omega}$$

6dB/Octave - drops by 2 every time frequency doubles





## Bode Plots (Cont.)

FR-3

$$H(\omega) = \frac{1}{1 + j\frac{\omega}{\omega_{3dB}}} = |H(\omega)| \cdot \exp(j\theta(\omega))$$

$$H(\omega) = \frac{1}{1 + j\frac{\omega}{\omega_{3dB}}} \cdot \frac{\left(1 - j\frac{\omega}{\omega_{3dB}}\right)}{1 - j\frac{\omega}{\omega_{3dB}}}$$

$$= \frac{1 - j\frac{\omega}{\omega_{3dB}}}{1 + \left(\frac{\omega}{\omega_{3dB}}\right)^2}$$

$$\theta(\omega) = \text{atan}\left\{\frac{I_m H(\omega)}{R_e H(\omega)}\right\}$$

## Bode Plots (Cont.)

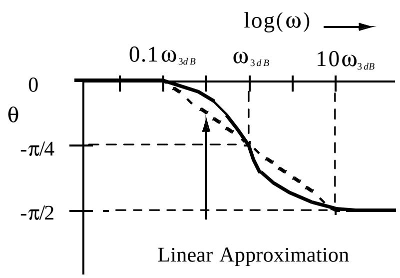
FR-4

$$Re\{H(\omega)\} = \frac{1}{1 + \left(\frac{\omega}{\omega_{3dB}}\right)^2}$$

$$Im\{H(\omega)\} = \frac{-\left(\frac{\omega}{\omega_{3dB}}\right)}{1 + \left(\frac{\omega}{\omega_{3dB}}\right)^2}$$

$$\theta(\omega) = arc\tan\left\{-\frac{\omega}{\omega_{3dB}}\right\}$$

$$= -arc\tan\left\{\frac{\omega}{\omega_{3dB}}\right\}$$

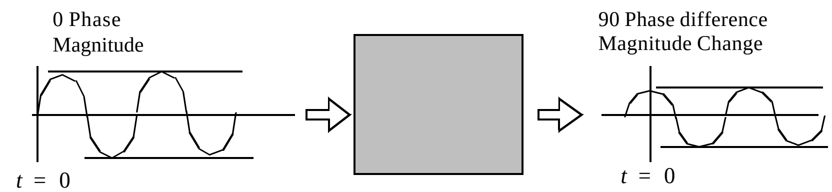


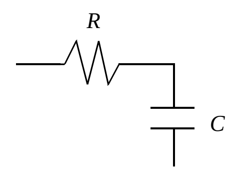





## Bode Plots (Cont.)

FR-5




$$H(\omega) = \frac{1}{1 + j\omega RC}$$

$$|H(\omega)| = (H(\omega) \cdot H^*(\omega))^{1/2}$$



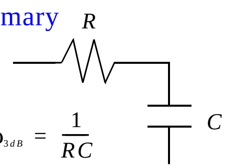


## Bode Plots (Cont.)

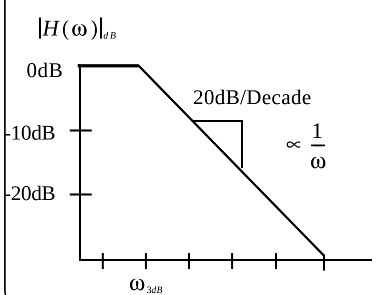
FR-6

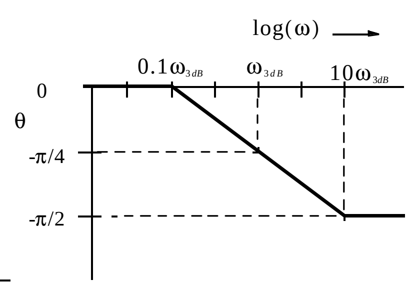
### 1 Pole Summary

$$H(\omega) = \frac{1}{1 + j\frac{\omega}{\omega_{3dB}}}$$




$$\omega_{3dB} = \frac{1}{RC}$$



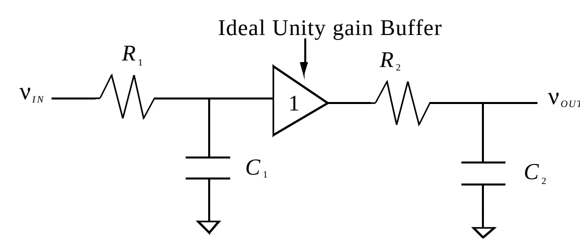





## Bode Plots (Cont.)

FR-7

### 2 Poles



## Bode Plots (Cont.)

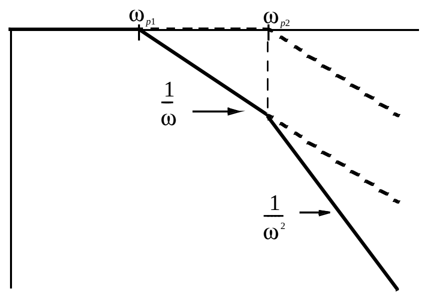
FR-8

Two Poles:

$$H(\omega) = \left(\frac{1}{1+j\frac{\omega}{\omega_{p1}}}\right)\cdot\left(\frac{1}{1+j\frac{\omega}{\omega_{p2}}}\right) = H_{\omega_{p1}}(\omega)\cdot H_{\omega_{p2}}(\omega)$$

$$20\cdot\log|H(\omega)| = 20\cdot\log(|H_{\omega_{p1}}(\omega)|\cdot|H_{\omega_{p2}}(\omega)|)$$

$$= 20\cdot\log|H_{\omega_{p1}}(\omega)| + 20\cdot\log|H_{\omega_{p2}}(\omega)|$$








## Bode Plots (Cont.)

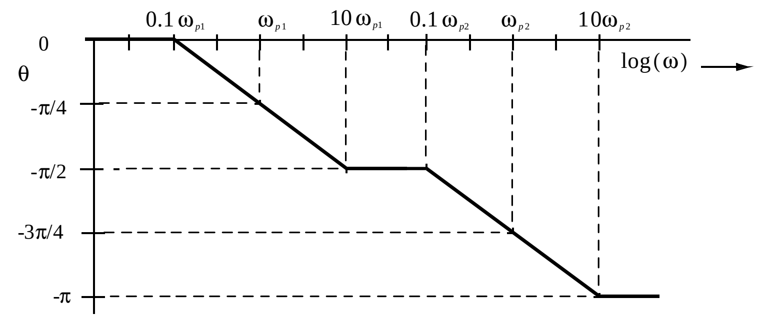
FR-9

$$H(\omega) = [|H_{\omega_{p1}}|\cdot\exp(j\theta_{\omega_{p1}})]\cdot[|H_{\omega_{p2}}|\cdot\exp(j\theta_{\omega_{p2}})]$$

$$= |H_{\omega_{p1}}|\cdot|H_{\omega_{p2}}|\cdot\exp(j[\theta_{\omega_{p1}}+\theta_{\omega_{p2}}])$$

$$= |H(\omega)|\cdot\exp(j\theta(\omega))$$

$$\theta(\omega) = \theta_{\omega_{p1}} + \theta_{\omega_{p2}}$$

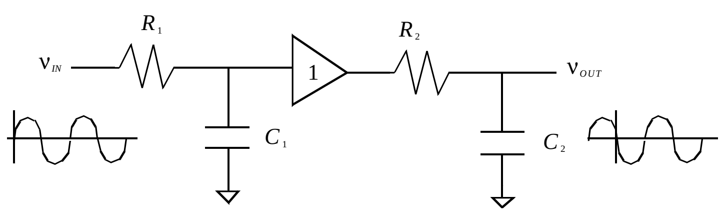


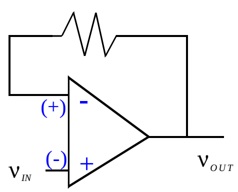





## Bode Plots (Cont.)

FR-10




If we have 180 degree phase shift we have a problem.

The negative feedback will turn into positive feedback.

Can’t have positive feedback in a loop with gain > 1

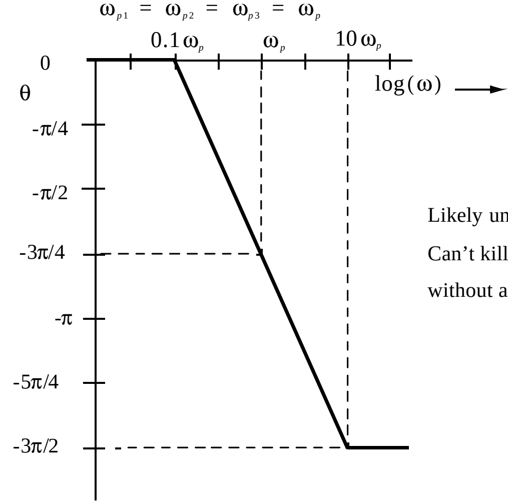




## Bode Plots (Cont.)

FR-11

$\omega_{p1} = \omega_{p2} = \omega_{p3} = \omega_p$




3 poles on top of each other

Likely unstable circuit

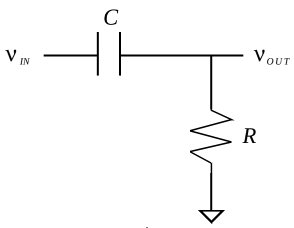
Can’t kill gain here

without adding phase shift.

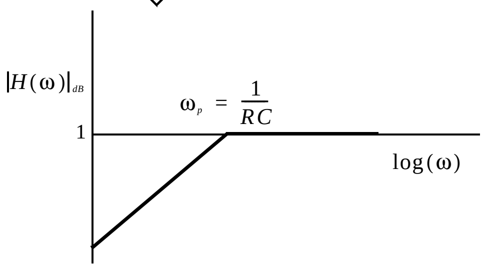
## Bode Plots (Cont.)

FR-12

Zero at zero frequency, pole at 1/RC




$$\frac{R}{R+\frac{1}{j\omega C}} = \frac{j\omega RC}{1+j\omega RC} = \frac{j\omega RC}{1+j\frac{\omega}{\frac{1}{RC}}}$$





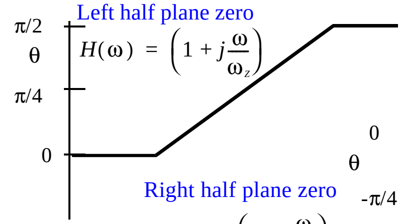



## Single Zero at $\omega_z$

FR-13

Left half plane zero

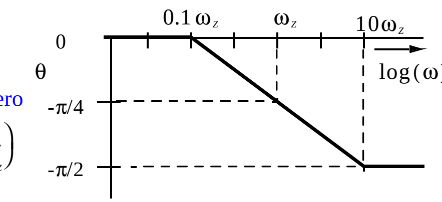
$$H(\omega) = \left(1 + j\frac{\omega}{\omega_z}\right)$$

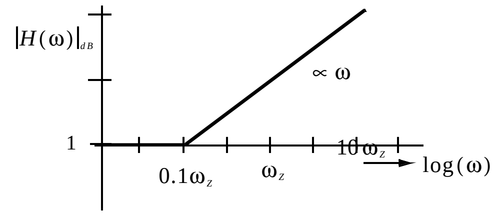



Right half plane zero

$$H(\omega) = \left(1 - j\frac{\omega}{\omega_z}\right)$$

$$\theta = \arctan\left(\frac{\omega}{\omega_z}\right)$$




For both:

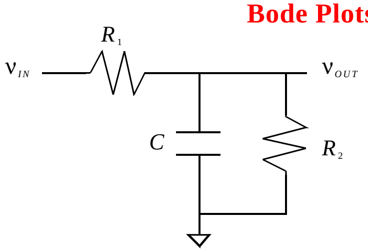
$$|H(\omega)| = \left(1 + \left(\frac{\omega}{\omega_z}\right)^2\right)^{1/2}$$





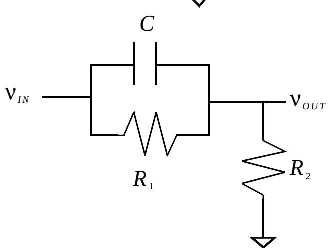
FR-14

## Bode Plots (Cont.)




1 Pole

$$H(\omega) = \left(\frac{R_2}{R_1+R_2}\right)\cdot\frac{1}{1+j\omega(R_1 \parallel R_2)C}$$




1 Pole, 1 Zero

$$H(\omega) = \left(\frac{R_2}{R_1+R_2}\right)\cdot\frac{1+j\omega R_1 C}{1+j\omega(R_1 \parallel R_2)C}$$

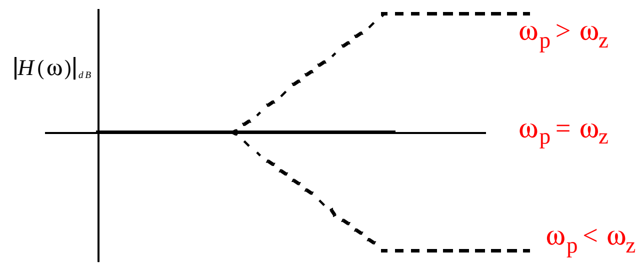




FR-15

## Bode Plots (Cont.)

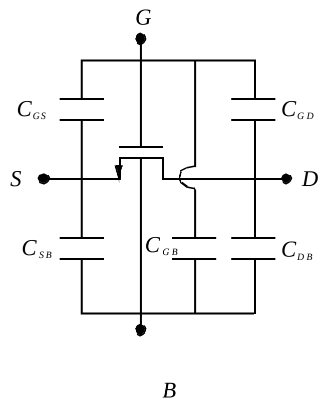
1 Pole, 1 Zero




$$H(\omega) = \frac{1+j\frac{\omega}{\omega_z}}{1+j\frac{\omega}{\omega_p}}$$

## Capacitances

FR-16




$$C_{ox} = \frac{\varepsilon_{SiO_2}}{t_{ox}} = 0.1\frac{fF}{\mu^2} = 10^{-4}\frac{F}{m^2}$$

$$CGSO = 5\times10^{-10}\frac{F}{m}$$

$$CGDO = 5\times10^{-10}\frac{F}{m}$$

$$CGBO = 4\times10^{-10}\frac{F}{m}$$

$$CJ = 10^{-4}\frac{F}{m^2}$$

$$PB = \phi_B = 0.8V$$



EECS140 ANALOG CIRCUIT DESIGN LECTURES ON FREQUENCY RESPONSE

## Capacitances (Cont.)

FR-17

**Sat :**

$$C_{GS} = \frac{2}{3}\cdot C_{ox}\cdot L\cdot W + CGSO\cdot W$$

$$C_{GD} = CGDO\cdot W$$

$$C_{SB} = \frac{CJ\cdot AS}{\left(1+\frac{V_{BS}}{PB}\right)^{MJ}} + \frac{CJSW\cdot PS}{\left(1+\frac{V_{BS}}{PB}\right)^{MJSW}}$$

$$C_{GB} = CGBO\cdot L$$

**Linear :**

$$C_{GS} = \frac{C_{ox}\cdot L\cdot W}{2} + CGSO\cdot W$$

$$C_{GD} = \frac{C_{ox}\cdot L\cdot W}{2} + CGDO\cdot W$$

(similar for $C_{DB}$ )

$MJ = \frac{1}{2}$ (default)

$MJSW = 3$ (default)

$PS$ = Perimeter of Source

$AS$ = Area of Source

$CGBO \equiv$ Capacitance of gate to bulk overlap

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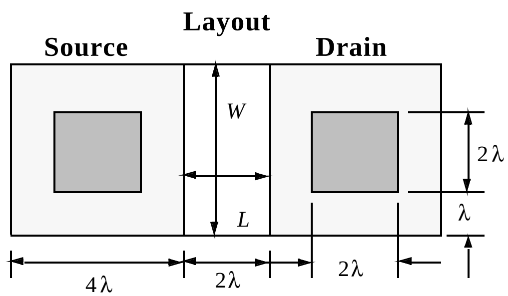
EECS140 ANALOG CIRCUIT DESIGN LECTURES ON FREQUENCY RESPONSE

## Capacitances (Cont.)

FR-18




(Minimum size device, W/L = 2)

Area of Source $= AS = 4\lambda\cdot W$

Area of Drain $= AD = AS$

Perimeter of Source $= PS = 8\lambda + W$

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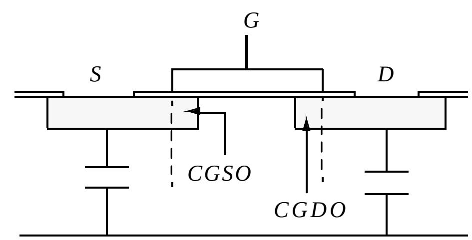
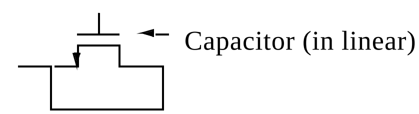
## Capacitances (Cont.)

FR-19

M1 1 2 3 4 NMOS L=2u W=2u
\+ AS=4p AD=4p PS=6u PD=6u

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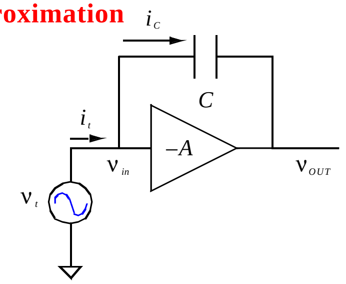
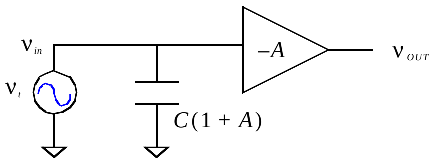
## Miller Approximation

FR-20




$$v_{OUT} = -A \cdot v_{in}$$

$$i_C = C \cdot \frac{d}{dt}(v_{in} - v_{OUT}) = C \cdot \frac{d}{dt}(v_{in} + A \cdot v_{OUT}) = C \cdot (1 + A) \cdot \frac{dv_{in}}{dt}$$

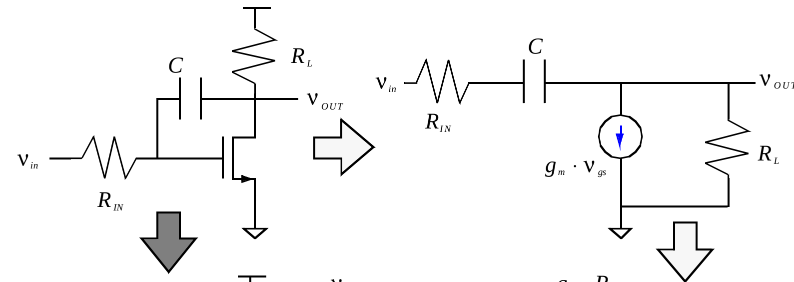




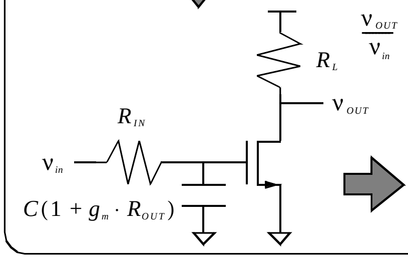



## Miller Approximation (Cont.)

FR-21




$$\frac{v_{OUT}}{v_{in}} = \frac{g_m \cdot R_{OUT}}{1 + j\omega[\underbrace{R_{IN}C(1 + g_m \cdot R_{OUT})}_{C_{MILLER}} + R_{OUT}C]}$$



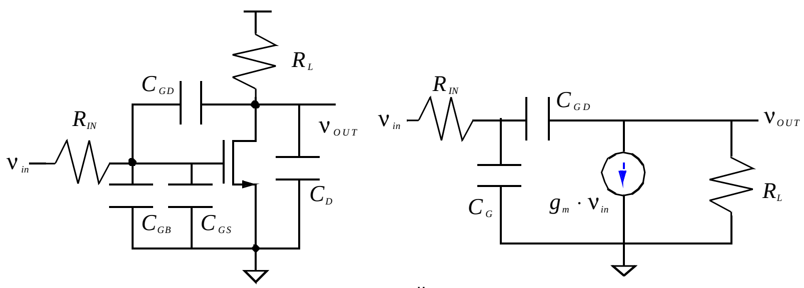

$$\omega_p = \frac{1}{R_{IN}C(1 + g_m \cdot R_{OUT})}$$





## Inverter

FR-22




$$R_{OUT} = R_L \parallel r_o$$

$$C_G = C_{GB} + C_{GS}$$

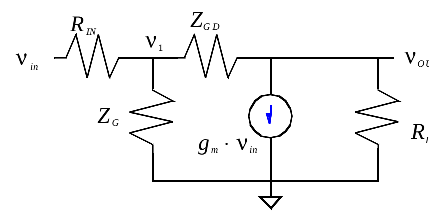
$C_D$ ignored (not usually possible)





## Inverter (Cont.)

FR-23




$$\frac{v_1 - v_{in}}{R_{IN}} + \frac{v_1}{Z_G} + \frac{v_1 - v_{OUT}}{Z_{GD}} = 0$$

$$\frac{v_{OUT}}{v_{in}} = -g_m \cdot R_{OUT} \cdot \frac{\left(1 - \frac{C_{GD}}{g_m}\right)}{1 + j\omega\{[C_{GD}(1 + g_m \cdot R_L) + C_G] \cdot R_{IN} + R_L C_{GD}\} - \omega^2 R_{OUT} R_{IN} C_G C_{GD}}$$

$$= \frac{\left(1 - j\omega\frac{C_{GD}}{g_m}\right)}{\left(1 + j\frac{\omega}{\omega_{p1}}\right) \cdot \left(1 + j\frac{\omega}{\omega_{p2}}\right)} = \frac{\left(1 - j\omega\frac{C_{GD}}{g_m}\right)}{1 + j\omega\left(\frac{1}{\omega_{p1}} + \frac{1}{\omega_{p2}}\right) - \omega^2 \frac{1}{\omega_{p1}} \frac{1}{\omega_{p2}}}$$

# Inverter (Cont.)

FR-24

$$\omega_{p1} = -\frac{1}{R_{IN}\cdot[C_G + \underbrace{C_{GD}(1+g_m R_{OUT})}_{C_{MILLER}}] + R_L C_{GD}}$$

$$\omega_{p2} = -\frac{1}{R_{OUT}C_{GD}} - \frac{1}{\left(R_{OUT}\,\|\,R_{IN}\,\|\,\frac{1}{g_m}\right)C_G}$$

$$\omega_Z = \frac{g_m}{C_{GD}}$$

$$H(\omega) = \frac{\left(1 + j\frac{\omega}{\omega_Z}\right)}{\left(1 + j\frac{\omega}{\omega_{p1}}\right)\cdot\left(1 + j\frac{\omega}{\omega_{p2}}\right)}$$





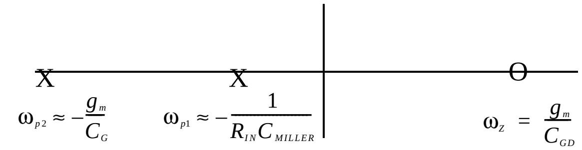
# Inverter (Cont.)

FR-25

$$H(\omega) = \frac{\left(1 + j\frac{\omega}{\omega_Z}\right)}{\left(1 + j\frac{\omega}{\omega_{p1}}\right)\cdot\left(1 + j\frac{\omega}{\omega_{p2}}\right)}$$

$$H(s) = \frac{\left(1 - \frac{s}{s_Z}\right)}{\left(1 - \frac{s}{s_{p1}}\right)\cdot\left(1 - \frac{s}{s_{p2}}\right)}$$

$$s_Z = -j\omega_Z$$
$$s_{p1} = -j\omega_{p1}$$
$$s_{p2} = -j\omega_{p2}$$

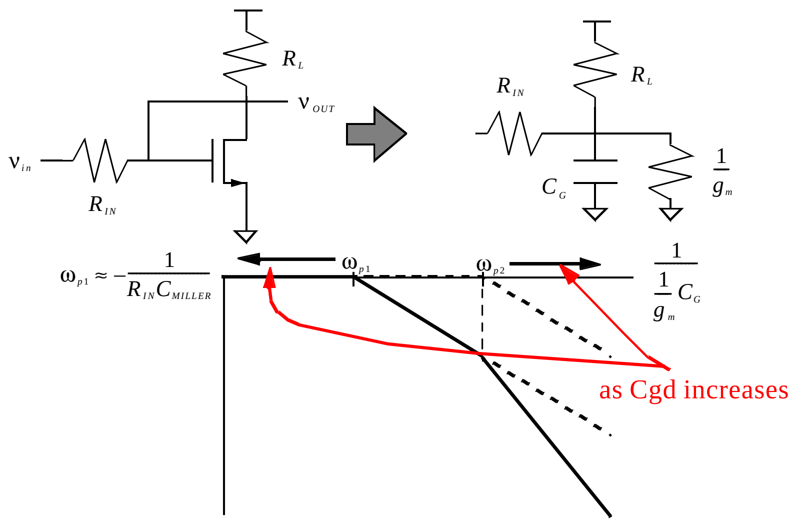







# Inverter (Cont.)

FR-26

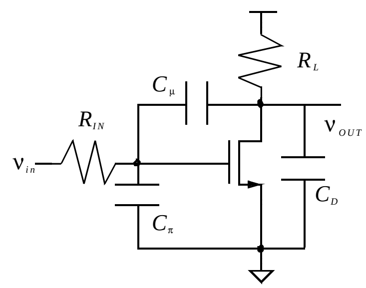







# Inverter (Cont.)

FR-27



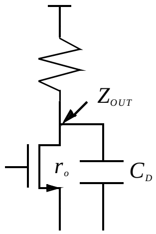

$$R_{OUT} = R_L\,\|\,r_o$$

## Case 1 (Miller Capacitance not important) :

$$R_{IN}C_\pi,\ R_{OUT}C_D \gg R_{IN}\cdot\underbrace{(1+g_m R_{OUT})C_\mu}_{C_{MILLER}}$$

$$\omega_{p1} = \frac{1}{R_{IN}C_\pi} \qquad \omega_{p2} = \frac{1}{R_{OUT}C_D}$$

## Inverter (Cont.) FR-28




$$Z_{OUT} = R_L \parallel r_o \parallel \frac{1}{j\omega C_D}$$

$$= R_{OUT} \parallel \frac{1}{j\omega C_D}$$

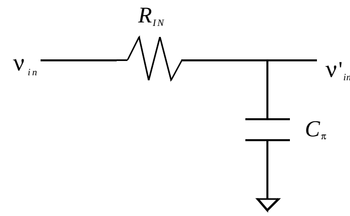
$$A_v = -g_m \cdot Z_{OUT} = -g_m \cdot \frac{\frac{R_{OUT}}{j\omega C_D}}{R_{OUT} + \frac{1}{j\omega C_D}} = -g_m \cdot \frac{R_{OUT}}{1 + j\omega R_{OUT} C_D}$$

$$\omega_p = \frac{1}{R_{OUT} C_D}$$





## Inverter (Cont.) FR-29




$$\frac{v_{in}'}{v_{in}} = \frac{\frac{1}{j\omega C_\pi}}{R_{IN} + \frac{1}{j\omega C_\pi}} = \frac{1}{1 + j\omega R_{IN} C_\pi}$$

$$\omega_p = \frac{1}{R_{IN} C_\pi}$$





## Inverter (Cont.) FR-30

**Case 2 (Large Cd) :**

$$R_{OUT} C_D \gg R_{IN}(1 + g_m R_{OUT}) C_\mu, R_{IN} C_\pi$$

$$\omega_{p1} = \frac{1}{R_{OUT} C_D} \qquad \omega_{p2} = \frac{1}{R_{IN}(C_\pi + C_\mu)}$$

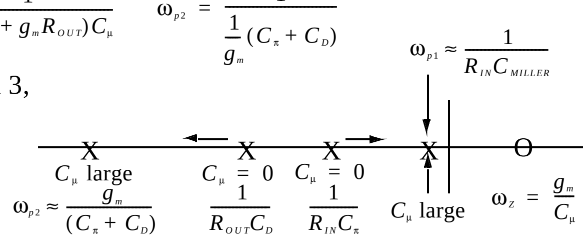
**Case 3 (Large Cμ) :**

$$R_{IN}(1 + g_m R_{OUT}) C_\mu \gg R_{OUT} C_D, R_{IN} C_\pi$$

$$\omega_{p1} = \frac{1}{R_{IN}(1 + g_m R_{OUT}) C_\mu} \qquad \omega_{p2} = \frac{1}{\frac{1}{g_m}(C_\pi + C_D)}$$

For case 2 and 3,

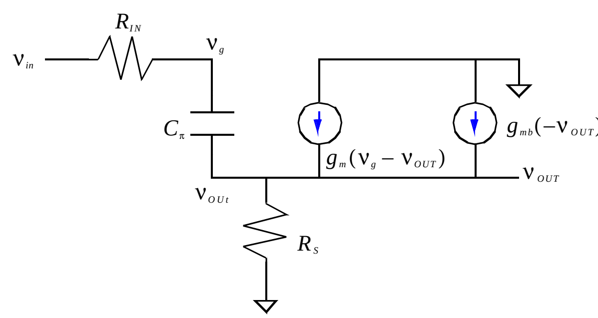
$$\omega_{ZERO} = \frac{g_m}{C_\mu}$$








## Source Follower FR-31




$$v_g = \left(\frac{1}{1 + j\omega R_{IN} C_\pi}\right) \cdot (v_{in} - v_{OUT}) + v_{OUT}$$

$$\frac{v_{OUT}}{R_S} = \frac{v_g - v_{OUT}}{\frac{1}{j\omega C_\pi}} + g_m \cdot v_g - (1 + \chi) \cdot g_m \cdot v_{OUT}$$

## Source Follower (Cont.)

FR-32

$$v_{OUT}\cdot\left(\frac{1}{R_s}+(1+\chi)\cdot g_m+j\omega C_\pi\right) = (j\omega C_\pi + g_m)\cdot v_g$$

$$\frac{v_{OUT}}{v_{in}} = \frac{g_m R_s}{1+(1+\chi)\cdot g_m R_s}\cdot\left[\frac{\left(1+j\omega\frac{C_\pi}{g_m}\right)}{1+j\omega R_{IN}\underbrace{\frac{C_\pi(1+\chi\cdot g_m R_s)}{1+(1+\chi)g_m R_s}}_{1-A}}\right]$$

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

$$\omega_p = \frac{1}{R_{IN}C_\pi(1-A)} \qquad A_v = \frac{g_m R_s}{1+(1+\chi)g_m R_s}$$

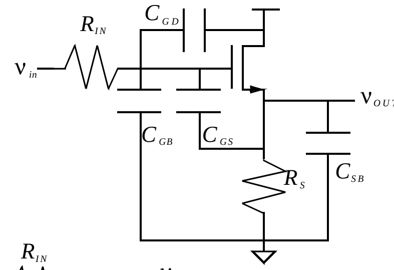
$$A = \frac{g_m R_s}{1+(1+\chi)g_m R_s}$$



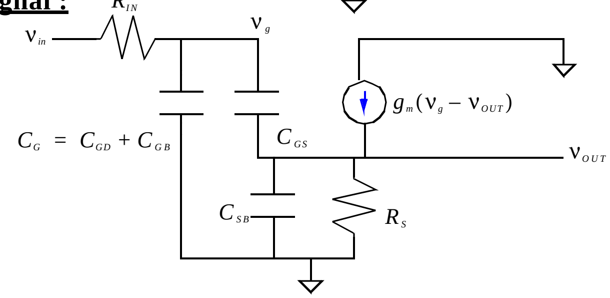


FR-33

## Source Follower again with $C_{SB}$




**Small Signal :**








## Source Follower (Cont.)

FR-34

$$\frac{v_{in}-v_G}{R_{IN}} = v_G\cdot j\omega C_G + (v_G - v_{OUT})\cdot j\omega C_{GS}$$

$$(v_G - v_{OUT})\cdot j\omega C_{GS} - g_m(v_G - v_{OUT}) = \frac{v_{OUT}}{R_S} + v_{OUT}\cdot j\omega C_{SB}$$

$$\frac{v_{OUT}}{v_{in}} = \frac{\frac{g_m R_S}{1+g_m R_S}\cdot\left[1+j\omega\frac{C_{GS}}{g_m}\right]}{1+j\omega\left[R_{IN}C_G+\frac{R_{IN}C_{GS}}{1+g_m R_S}+\frac{R_S(C_{GS}+C_{SB})}{1+g_m R_S}\right]-\omega^2 R_S R_{IN}\left[\frac{C_{GS}C_G + C_{SB}(C_G+C_{GS})}{1+g_m R_S}\right]}$$

let denominator $= \left(1+j\frac{\omega}{p_1}\right)\cdot\left(1+j\frac{\omega}{p_2}\right)$

$$= 1+j\omega\left(\frac{1}{p_1}+\frac{1}{p_2}\right)-\frac{\omega^2}{p_1 p_2}$$





## Source Follower (Cont.)

FR-35

for $p_1$ and $p_2$ widely separated, if we assume that $p_1$ is the dominant pole,

$$\frac{1}{p_1} \gg \frac{1}{p_2}$$

$$p_1 = \frac{1}{R_{IN}C_G+\frac{R_{IN}C_{GS}}{1+g_m R_S}+\frac{R_S(C_{GS}+C_{SB})}{1+g_m R_S}} = \frac{1}{R_{IN}C_G+\frac{R_{IN}C_{GS}}{1+g_m R_S}+R_O(C_{GS}+C_{SB})}$$

where,

$$R_O = \frac{1}{g_m}\parallel R_S$$

thus,

$$p_2 = \frac{R_{IN}C_G+\frac{R_{IN}C_{GS}}{1+g_m R_S}+R_O(C_{GS}+C_{SB})}{R_O R_{IN}[C_{GS}C_G + C_{SB}C_G + C_{SB}C_{GS}]}$$

## Source Follower (Cont.)

FR-36

2 limiting cases,

**Case 1 :**

$$R_{IN}\left(C_G + \frac{C_{GS}}{1 + g_m R_S}\right) \gg R_O(C_{GS} + C_{SB})$$

$$\text{Miller cap} = C_{GS} \cdot (1 - A)$$

$$A = \frac{g_m R_S}{1 + g_m R_S}$$

$$\omega_{p1} = \frac{1}{R_{IN}\left(C_G + \frac{C_{GS}}{1 + g_m R_S}\right)}$$

$$1 - A = 1 - \frac{g_m R_S}{1 + g_m R_S} = \frac{1}{1 + g_m R_S}$$

**Case 2 :**

$$R_O(C_{GS} + C_{SB}) \gg R_{IN}\left(C_G + \frac{C_{GS}}{1 + g_m R_S}\right)$$

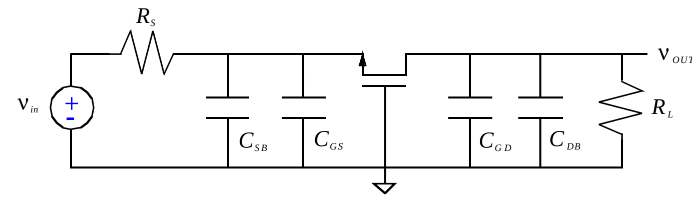
$$\omega_{p1} = \frac{1}{R_O(C_{GS} + C_{SB})}$$



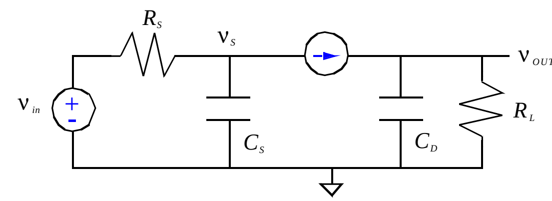


## Common Gate

FR-37




assume $r_o \to \infty$








## Common Gate (Cont.)

FR-38

$$\text{KCL@ } v_s \qquad \frac{v_{in} - v_s}{R_s} = v_s \cdot j\omega C_s + g_m v_s$$

$$\text{KCL@ } v_{OUT} \qquad g_m v_s = v_{OUT} \cdot j\omega C_D + \frac{v_{OUT}}{R_L}$$

$$\frac{v_{OUT}}{v_{in}} = \frac{\frac{g_m R_L}{1 + g_m R_S}}{(1 + j\omega R_L C_D) \cdot \left(1 + j\omega \frac{R_S C_S}{1 + g_m R_S}\right)}$$

no zeros, poles @

$$p_1 = \frac{1}{R_L C_D}$$

$$p_2 = \frac{1}{\frac{R_S}{1 + g_m R_S} C_S} = \frac{1}{\left(R_S \parallel \frac{1}{g_m}\right) C_S}$$





## Common Gate (Cont.)

FR-39

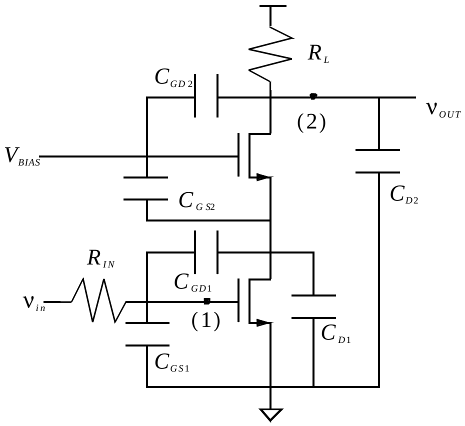
$$@ \; v_{OUT} \to R_{eq} = R_L, \quad C_{eq} = C_D \quad \Rightarrow \quad p_1 = \frac{1}{R_{eq} C_{eq}} = \frac{1}{R_L C_D}$$

$$@ \; v_s \to R_{eq} = R_S \parallel \frac{1}{g_m}, \quad C_{eq} = C_S \quad \Rightarrow \quad p_2 = \frac{1}{R_{eq} C_{eq}} = \frac{1}{\left(R_S \parallel \frac{1}{g_m}\right) C_S}$$

Since all caps go to ground, finding poles reduces to finding Req’s and Ceq’s at the nodes.

FR-40

## Cascode - reduces the Miller probelm








FR-41

## Cascode (Cont.)

If we assume that $R_s$ is very large, then,

At (1) :

$$R_{eq} = R_s$$

$$C_{eq} = C_{GS1} + C_{GD1} \cdot (1 - A) \qquad p_1 = \frac{1}{R_{eq} C_{eq}}$$

$$A = -g_m \cdot \frac{1}{g_m} = -1$$

$$C_{eq} = C_{GS1} + 2 \cdot C_{GD1}$$

At (2) :

$$R_{eq} = R_L \| r_o \leftarrow \text{large}$$

$$C_{eq} = C_{GD2} + C_{D2} \qquad p_2 = \frac{1}{R_{eq} C_{eq}}$$

No large Miller multiplication of a capacitance!





FR-42

## Zero Value Time Constant Analysis

General case of dominant pole approximation. Use this technique for complex circuits where we can't identify node with large $R_{eq}$ and $C_{eq}$.

**Strategy :**

1) Set all caps $C_j=0$ except for $C_i$

2) Find resistance seen by $C_i$

3) Calculate $R_i C_i$ for all caps

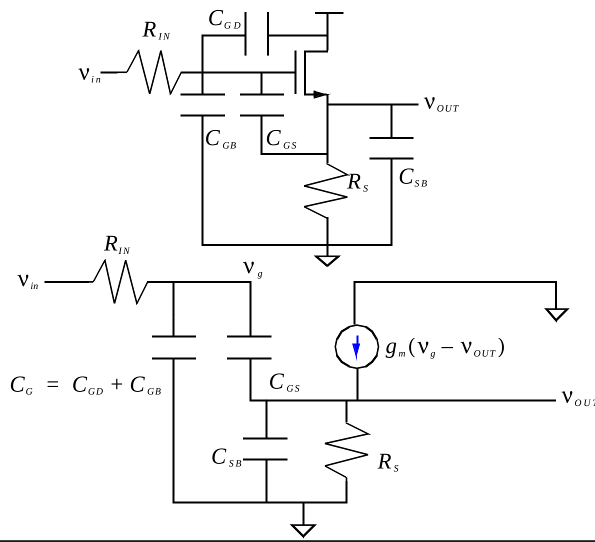
4) $\omega_{3dB} = \frac{1}{\sum R_i C_i}$





FR-43

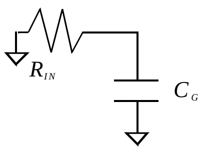
## ZVTC with Source Follower



# ZVTC with Source Follower



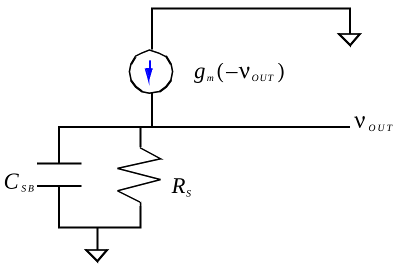
$C_1$ :




$R_1 = R_{IN}$

$C_1 = C_G$

$C_2$ :




$R_2 = R_S \| \frac{1}{g_m}$

$C_2 = C_{SB}$

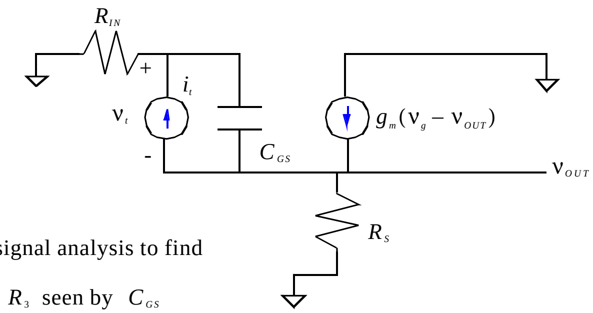




# ZVTC with Source Follower (Cont.)



$C_3$ :




do small signal analysis to find

$\frac{v_t}{i_t} = R_3$ seen by $C_{GS}$

$R_3 = R_o + \frac{R_{IN}}{1 + g_m R_S}$ where $R_o = R_S \| \frac{1}{g_m}$ $\qquad C_3 = C_{GS}$

hence,

$$\omega_{3dB} = \frac{1}{R_1 C_1 + R_2 C_2 + R_3 C_3} = \frac{1}{R_{IN} C_G + R_o C_{SB} + \left(R_o + \frac{R_{IN}}{1 + g_m R_S}\right) C_{GS}}$$