EE5321/EE7321
Semiconductor Devices and Circuits

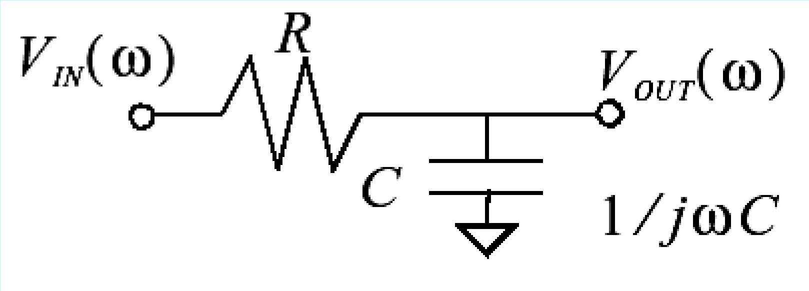
Frequency Response Part1

Impedance network transfer function

- Impedance network transfer function:

$$H(\omega) = \frac{V_{out}(\omega)}{V_{in}(\omega)}$$

where $H(\omega)$, $V_{out}(\omega)$ and $V_{in}(\omega)$ are phasors



$$H(\omega) = \frac{V_{out}(\omega)}{V_{in}(\omega)} = \frac{1/j\omega C}{R + \left(1/j\omega C\right)} = \frac{1}{1 + j\omega RC}$$

$H(\omega)$ in polar coordinates

- $H(\omega)$ is represented by its amplitude and phase
- Amplitude $|H(\omega)|$

$$\left|H(\omega)\right| = \sqrt{H(\omega) \bullet H^*(\omega)}$$

- Phase $\angle\theta$

$$\theta(\omega) = \arctan\left\{\frac{\mathrm{Im}\left[H(\omega)\right]}{\mathrm{Re}\left[H(\omega)\right]}\right\}$$

- If $H(\omega) = N(\omega) / D(\omega)$ then:

$$\mathrm{Re}[H(\omega)] = \mathrm{Re}[N(\omega)\cdot D^*(\omega)]$$

$$\mathrm{Im}[H(\omega)] = \mathrm{Im}[N(\omega)\cdot D^*(\omega)]$$

H(ω) for the RC circuit

- Amplitude

$$\sqrt{H(\omega)\bullet H^{*}(\omega)}=\sqrt{\left(\frac{1}{1+j\,\omega R\,C}\right)\bullet\left(\frac{1}{1-j\,\omega R\,C}\right)}$$

$$\sqrt{H(\omega)\bullet H^{*}(\omega)}=\sqrt{\left(\frac{1}{1+(\omega R\,C)^{2}}\right)}$$

- Amplitude in Decibels $|H(\omega)|_{dB}=20\bullet\log\left[|H(\omega)|\right]$

- For a -3dB reduction on the magnitude

$$-3=20\bullet\log\left[\left|H\left(\omega_{3dB}\right)\right|\right] \Rightarrow \left|H\left(\omega_{3dB}\right)\right|=0.7079$$

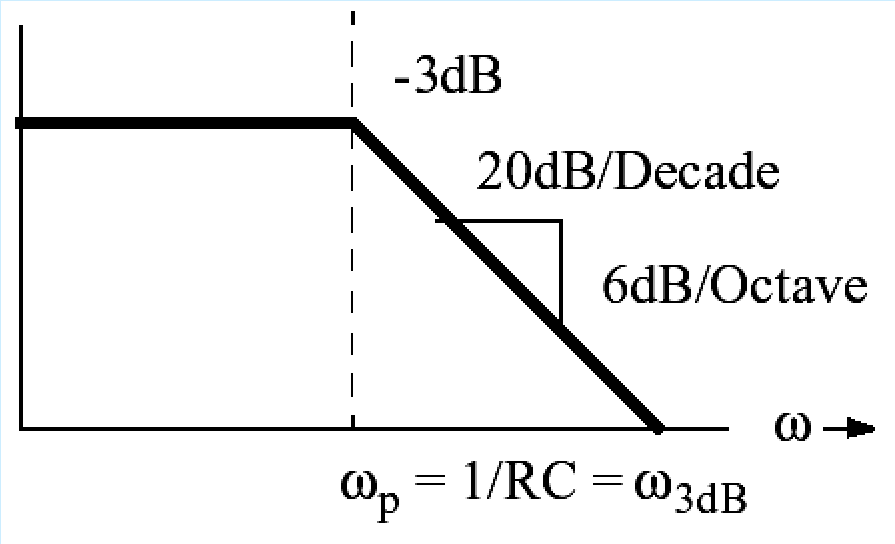
Bode Plot RC circuit – Amplitude

$$|H(\omega_{3dB})| = \sqrt{\left(\frac{1}{1+(\omega_{3dB}\, R\, C)^2}\right)} = 0.7079 \Rightarrow \omega_{3dB} = \omega_p = \frac{1}{R\,C}$$

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

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

$$|H(\omega)| \approx \sqrt{\left(\frac{1}{\left(\frac{\omega}{\omega_{3dB}}\right)^2}\right)}$$



$$\boxed{|H(\omega)| \approx \frac{\omega_{3dB}}{\omega}}$$

Amp drops by 2 when f doubles

Amp drops by 10 every decade

Bode Plot RC circuit - Phase

- $H(\omega)$ phase

$$\theta(\omega) = \arctan\left\{\frac{\mathrm{Im}[H(\omega)]}{\mathrm{Re}[H(\omega)]}\right\}$$

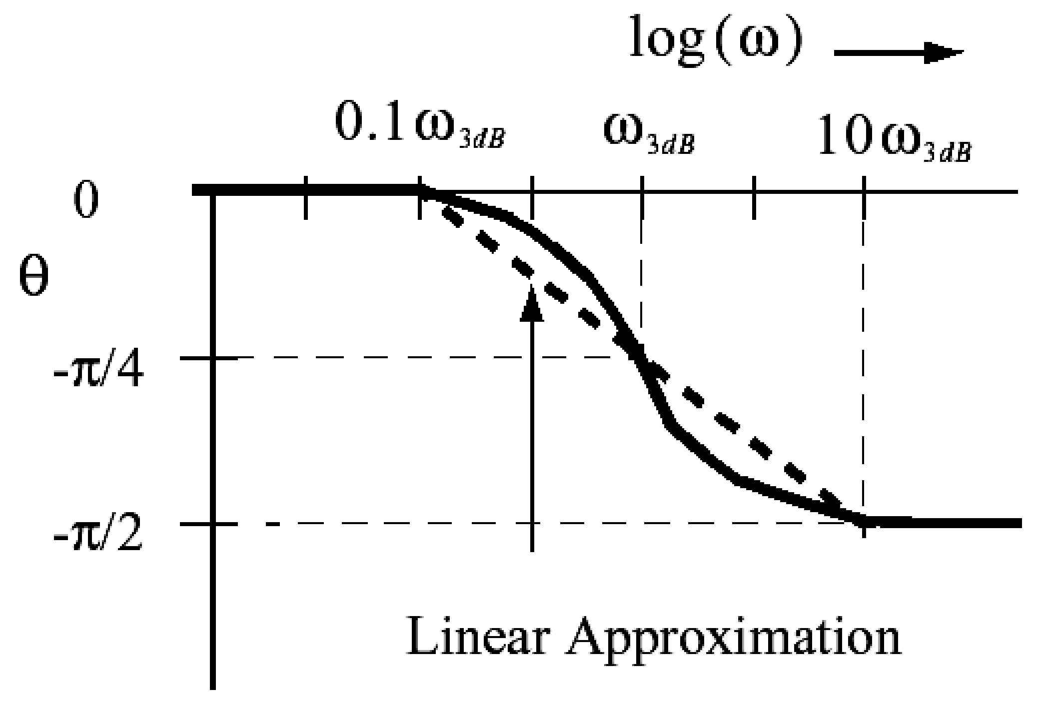
$$H(\omega) = \frac{1}{1 + j\dfrac{\omega}{\omega_{3dB}}} = \frac{1}{1 + j\dfrac{\omega}{\omega_{3dB}}} \bullet \frac{1 - j\dfrac{\omega}{\omega_{3dB}}}{1 - j\dfrac{\omega}{\omega_{3dB}}} = \frac{1 - j\dfrac{\omega}{\omega_{3dB}}}{1 + \left(\dfrac{\omega}{\omega_{3dB}}\right)^2}$$

$$\mathrm{Re}\{H(\omega)\} = \frac{1}{1 + \left(\dfrac{\omega}{\omega_{3dB}}\right)^2} \qquad \mathrm{I}m\{H(\omega)\} = \frac{-\left(\dfrac{\omega}{\omega_{3dB}}\right)}{1 + \left(\dfrac{\omega}{\omega_{3dB}}\right)^2}$$

Bode Plot RC circuit - Phase

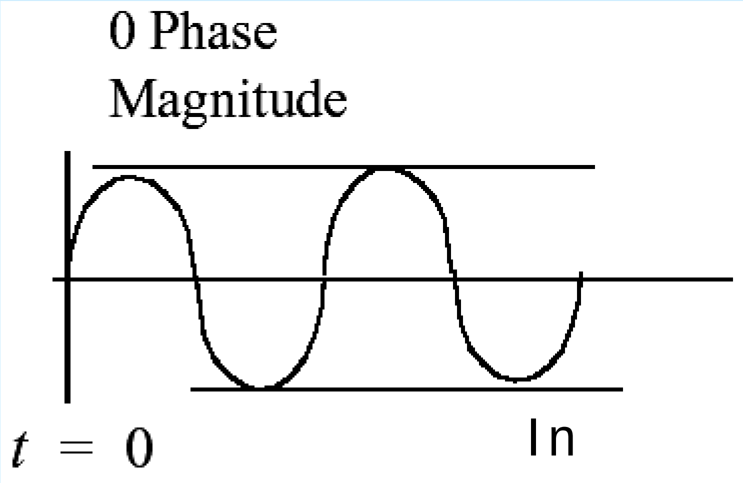
- And the Phase is given by:

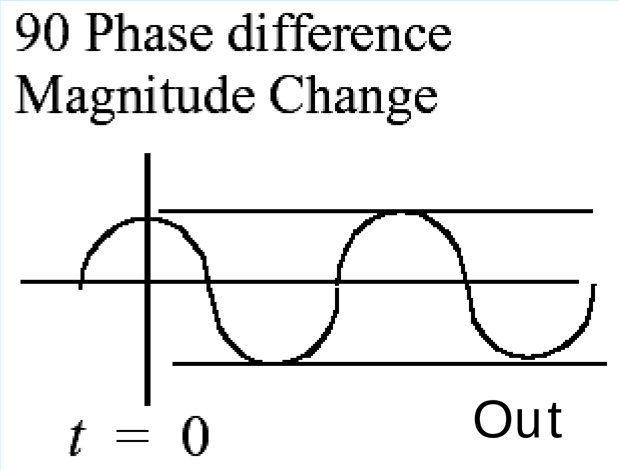
$$\theta(\omega) = \arctan\left\{\frac{\mathrm{Im}[H(\omega)]}{\mathrm{Re}[H(\omega)]}\right\} = \arctan\left\{-\frac{\omega}{\omega_{3dB}}\right\} = -\arctan\left\{\frac{\omega}{\omega_{3dB}}\right\}$$

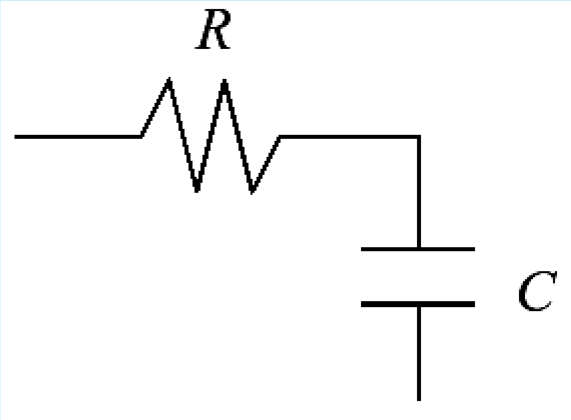


RC circuit – sine wave

- The output wave has amplitude and phase altered by the circuit





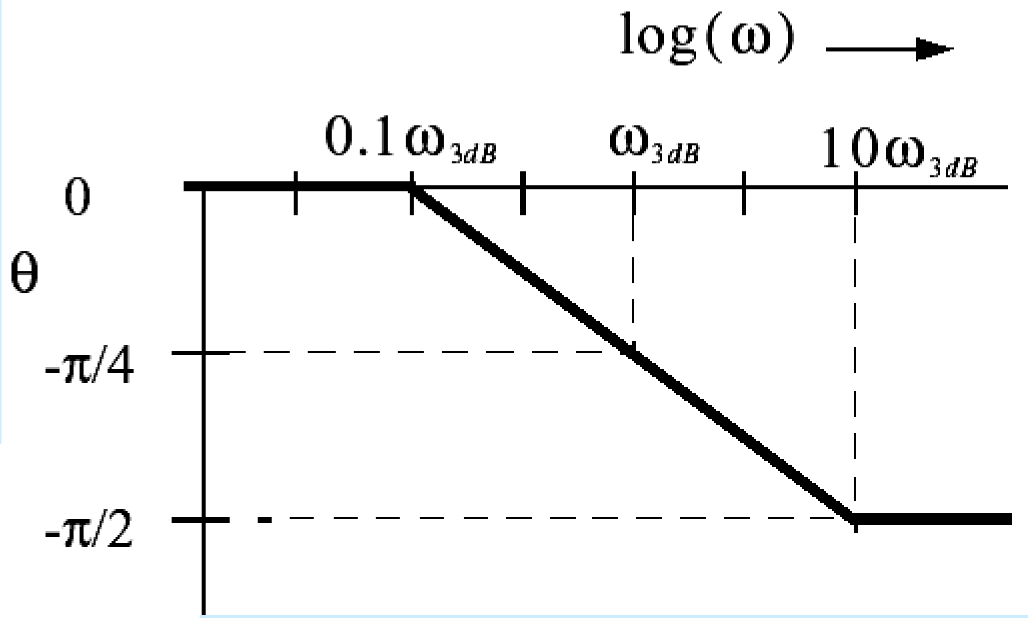


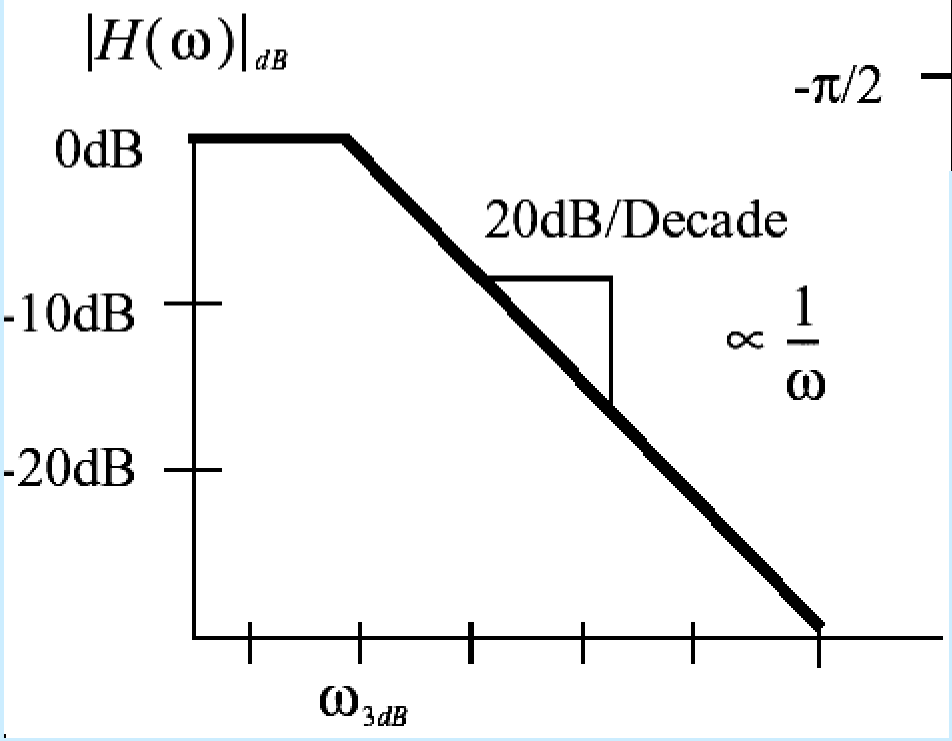
$$H(\omega) = \frac{1}{1 + j\omega RC}$$

Bode Plots – 1 pole

- RC circuit

$$\omega_{3dB} = \omega_p = \frac{1}{R\,C}$$



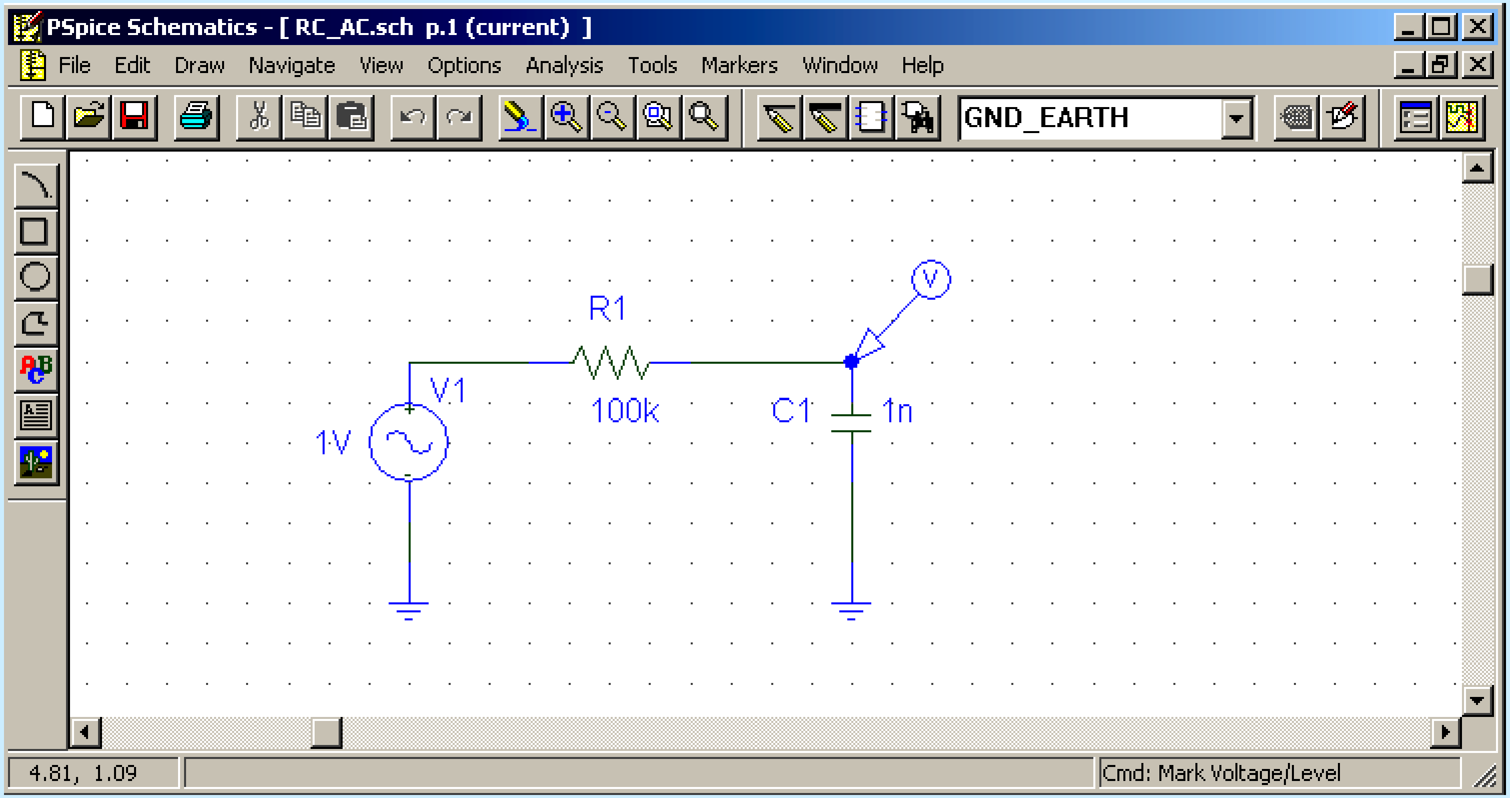


$$\theta(\omega) = \text{-arctan}\left\{\frac{\omega}{\omega_{3dB}}\right\}$$

$$|H(\omega)| \approx \frac{\omega_{3dB}}{\omega}$$

SPICE SIM – RC circuit

- Run AC Sweep with 1V amplitude and freq: 10Hz to 100MHz
- Output DB[V2(C1)/V1(V1)] and P[V2(C1)]



SPICE SIM – RC circuit

- $\omega_p = 1/RC = 10k \;\rightarrow\; f_p = 1.6kHz$

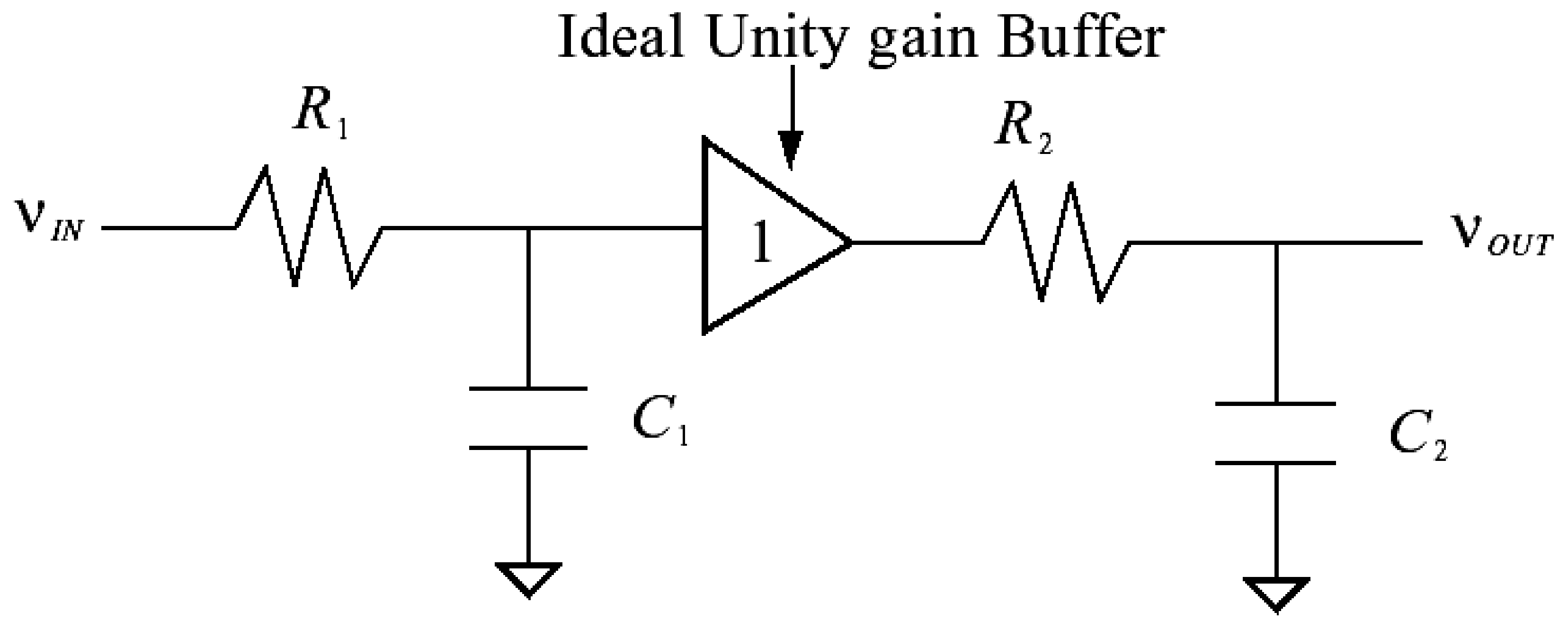
RC circuits in series – 2 poles

- The combination of two RC circuits in series is going to result in 2 poles

$$H(\omega) = \frac{1}{1 + j\dfrac{\omega}{\omega_{p1}}} \bullet \frac{1}{1 + j\dfrac{\omega}{\omega_{p2}}}$$

where: $\omega_{p1} = 1/R_1C_1$ and

$\omega_{p2} = 1/R_2C_2$



RC circuits in series – 2 poles

- Overall transfer function $H(\omega) = H\omega_{p1}(\omega) \bullet H\omega_{p2}(\omega)$

$$H(\omega) = \left[\left|H_{\omega p1}\right| \bullet \exp\left(j\,\theta_{\omega p1}\right)\right] \bullet \left[\left|H_{\omega p2}\right| \bullet \exp\left(j\,\theta_{\omega p2}\right)\right]$$

$$H(\omega) = \left|H_{\omega p1}\right| \bullet \left|H_{\omega p2}\right| \bullet \exp\left(j\left[\theta_{\omega p1} + \theta_{\omega p2}\right]\right)$$

$$H(\omega) = \left|H(\omega)\right| \bullet \exp\left(j\,\theta(\omega)\right)$$

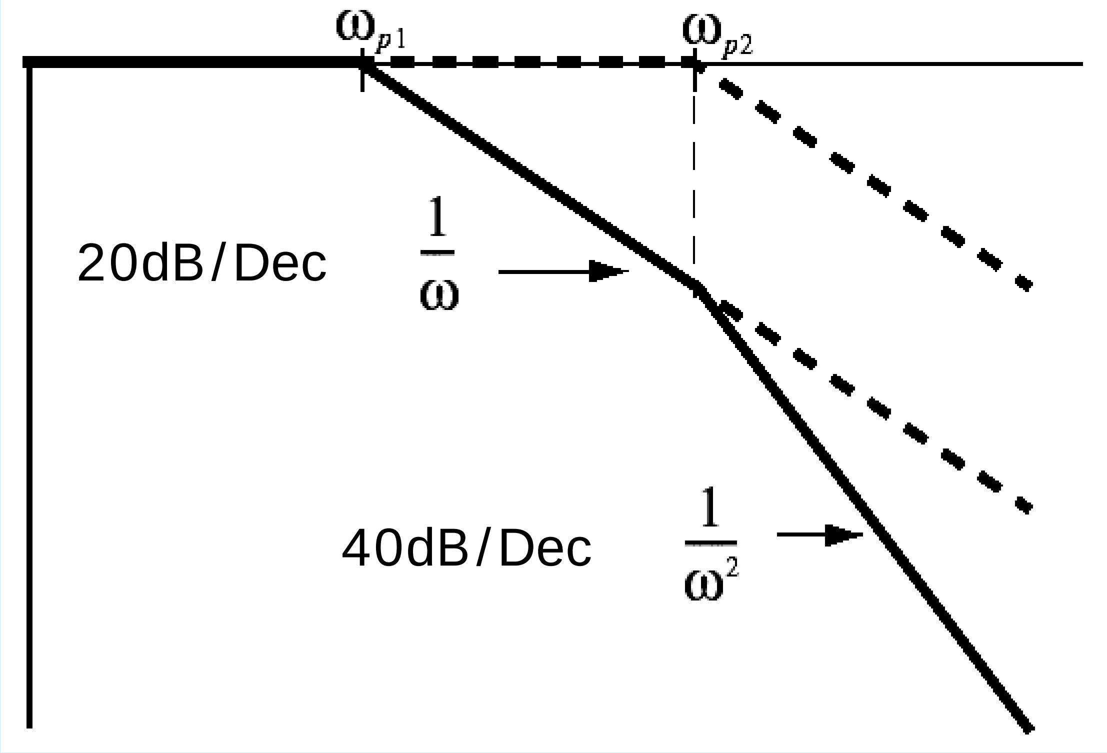
$$\therefore \; \left|H(\omega)\right| = \left|H_{\omega p1}\right| \bullet \left|H_{\omega p2}\right| \text{ and } \theta(\omega) = \theta_{\omega p1} + \theta_{\omega p2}$$

Amplitude Bode Plot – 2 poles

- Second pole "accelerates" the amplitude reduction

$$20 \bullet \log\left\{ \left|H(\omega)\right| \right\} = 20 \bullet \log\left\{ \left|H\left(\omega_{p1}\right)\right| \bullet \left|H\left(\omega_{p2}\right)\right| \right\}$$

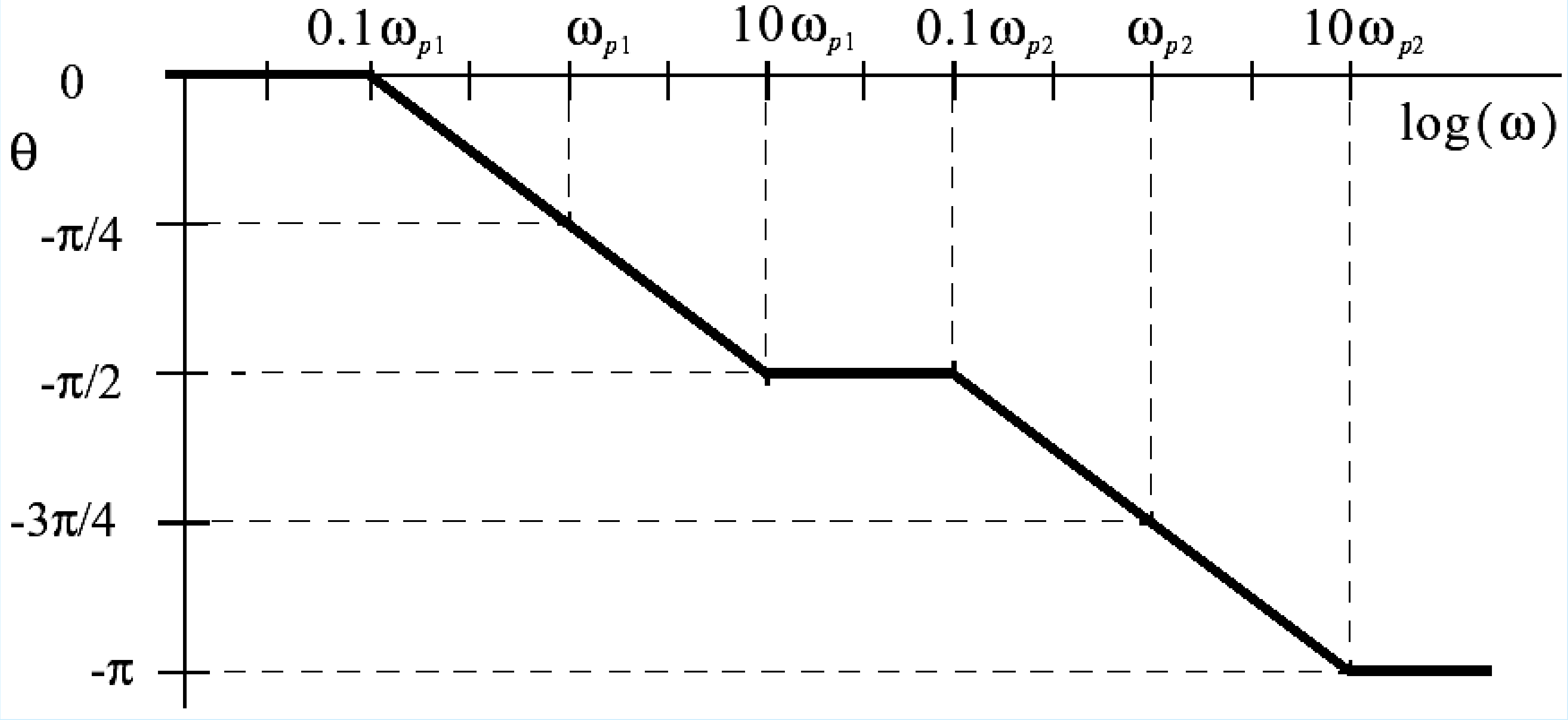
$$20 \bullet \log\left\{ \left|H(\omega)\right| \right\} = 20 \bullet \log\left\{ \left|H\left(\omega_{p1}\right)\right| \right\} + 20 \bullet \log\left\{ \left|H\left(\omega_{p2}\right)\right| \right\}$$



Phase Bode Plot – 2 poles

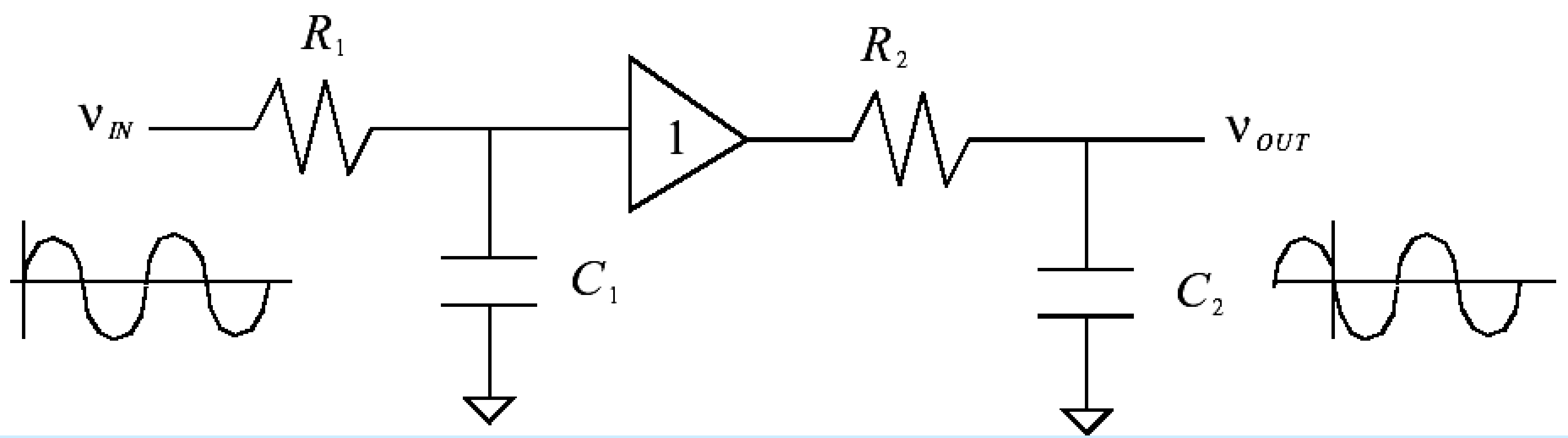
- Second pole adds to the phase shift

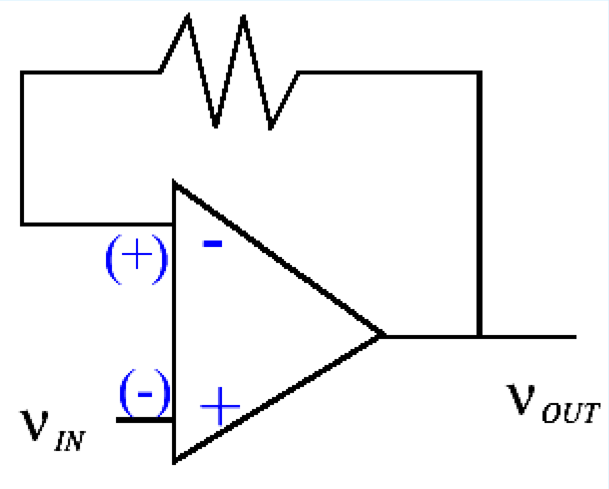
$$\theta(\omega) = \theta_{\omega p1} + \theta_{\omega p2}$$



2 poles circuit – 180° phase shift

- A phase shift of 180° can be a problem

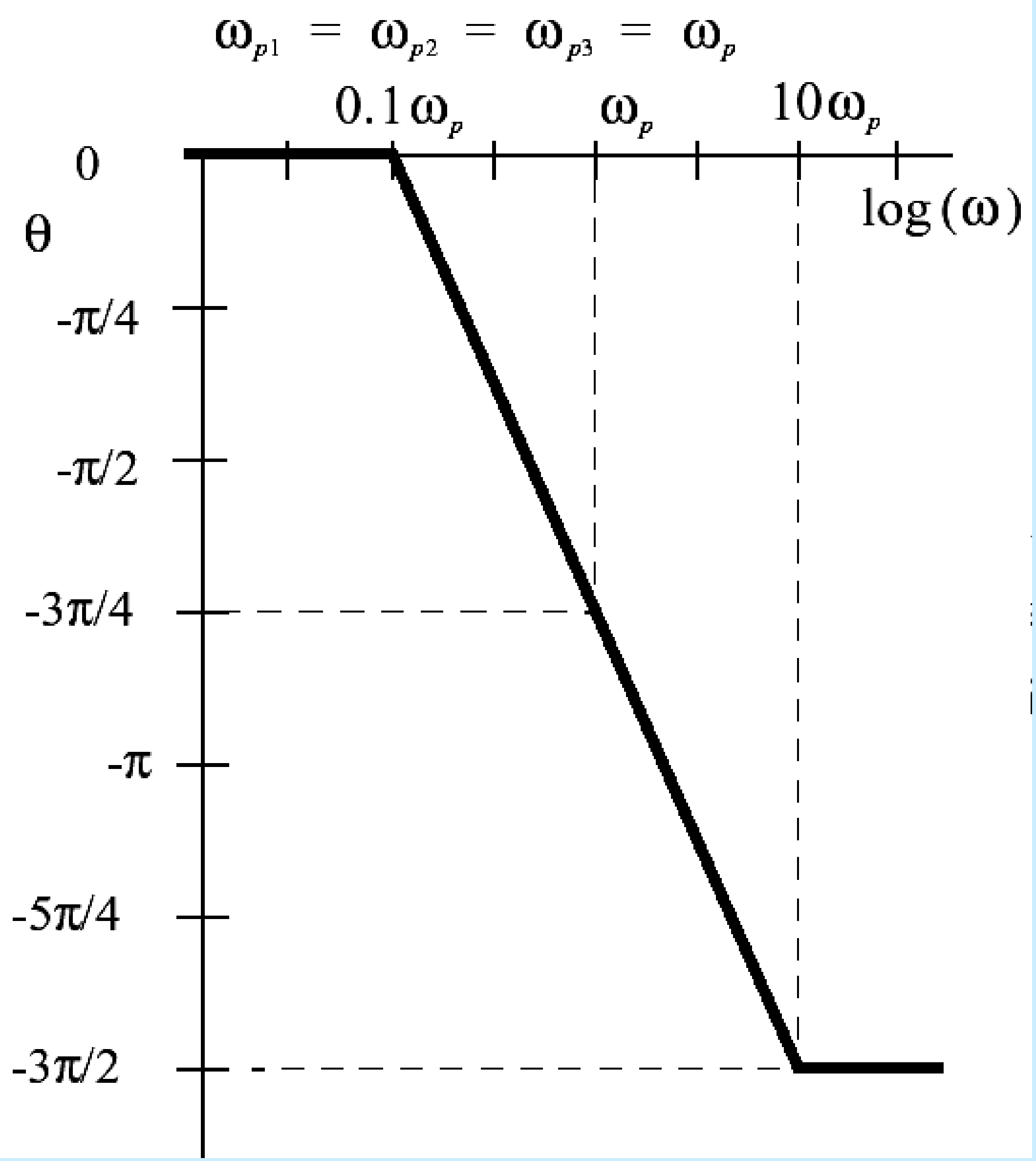




- If in a feedback loop, a 180° phase shift will turn a negative feedback into a positive feedback
- This results in an unstable system if the loop gain is > 1

Bode Plots – 3 Superimposed Poles

- The phase shift is quite “fast” and “strong”
- When used in a feedback loop will probably result in an unstable circuit

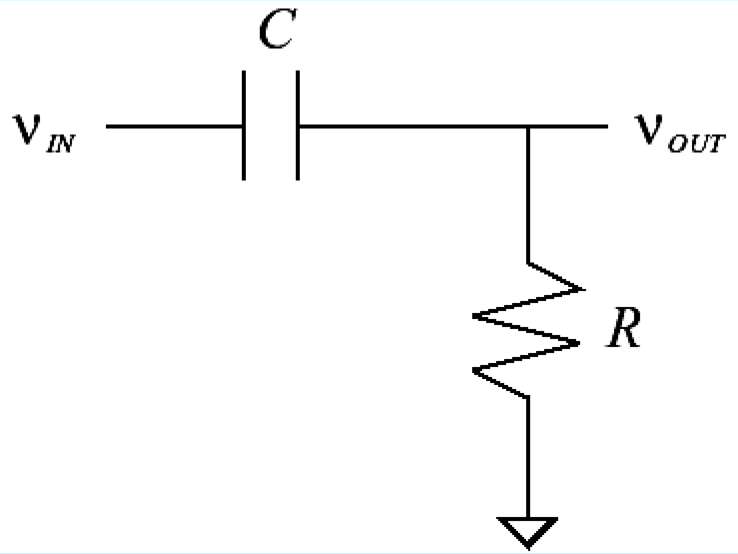


C R circuit – H(ω)

- Circuit has:

  1 Zero at $\omega = 0$

  1 Pole at $\omega = 1/RC$



$$H(\omega) = \frac{V_{out}(\omega)}{V_{in}(\omega)}$$

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

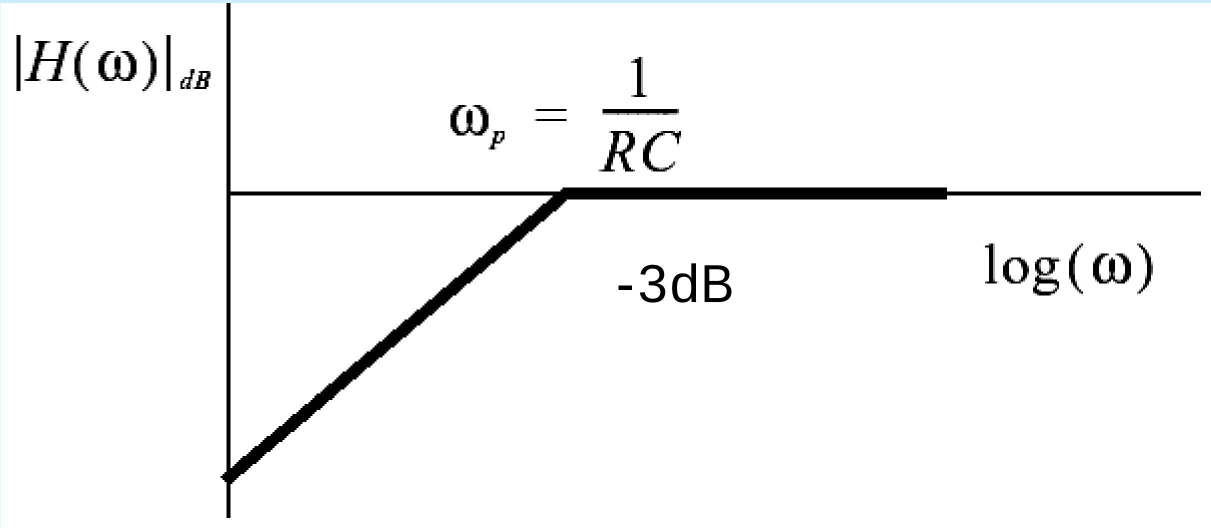
$$|H(\omega)| = \omega RC \bullet \sqrt{\frac{1}{1 + (\omega RC)^2}}$$

C R circuit – Bode plot amplitude

- At $\omega = 0 \rightarrow |H(\omega)| = 0$ and since $\left|H(\omega)\right|_{dB} = 20 \bullet \log\left[\left|H(\omega)\right|\right]$

$$\left|H(\omega)\right|_{dB} = 20 \bullet \log\left(\omega R C \bullet \sqrt{\frac{1}{1+(\omega R C)^2}}\right) \rightarrow -\infty$$

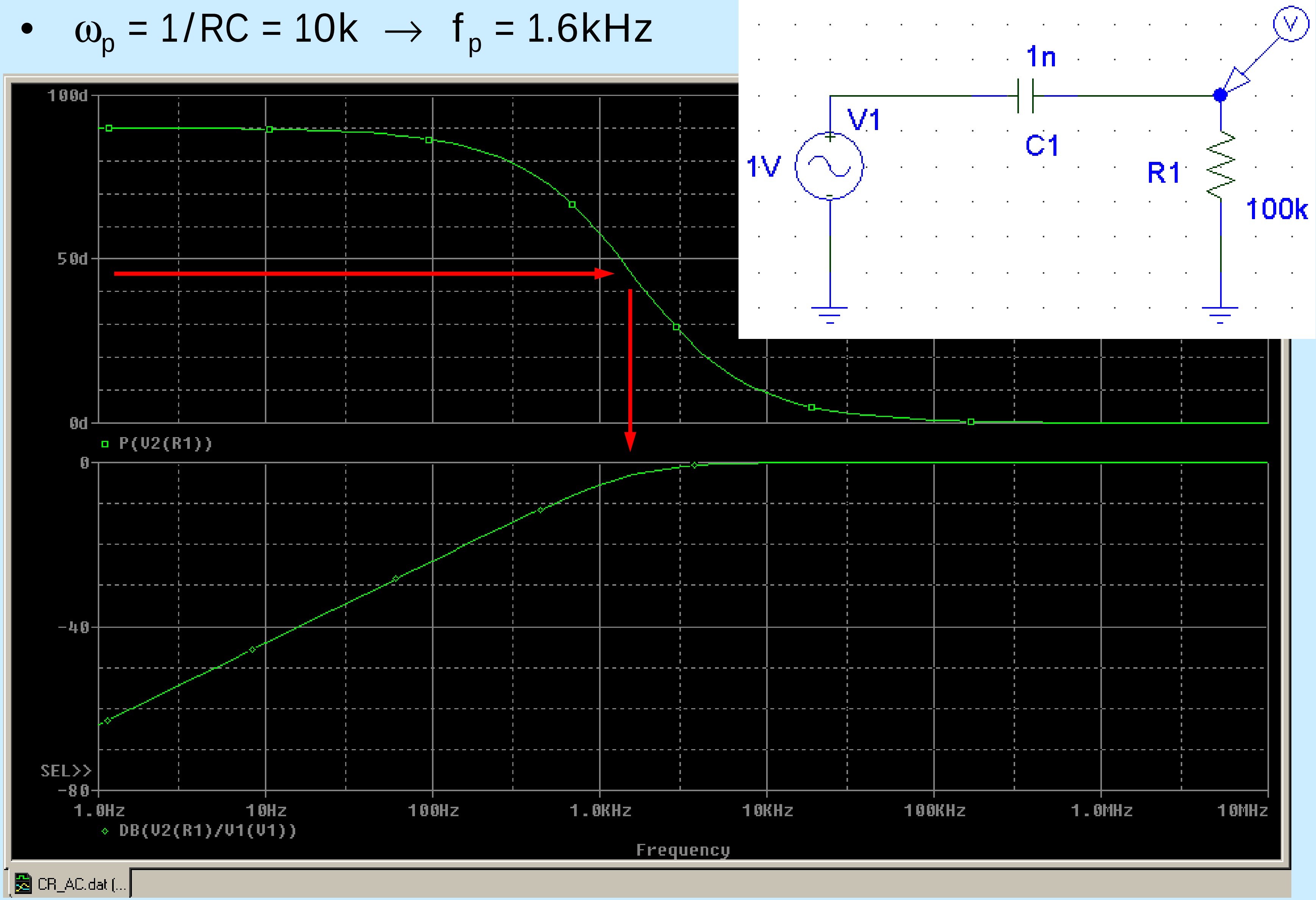
$$\left|H(\omega_p)\right|_{dB} = 20 \bullet \log\left(1 \bullet \sqrt{\frac{1}{1+(1)^2}}\right) = -3\text{dB}$$



$$\left|H(\omega \gg \omega_p)\right|_{dB}$$
$$= 20 \bullet \log(1)$$
$$= 0$$

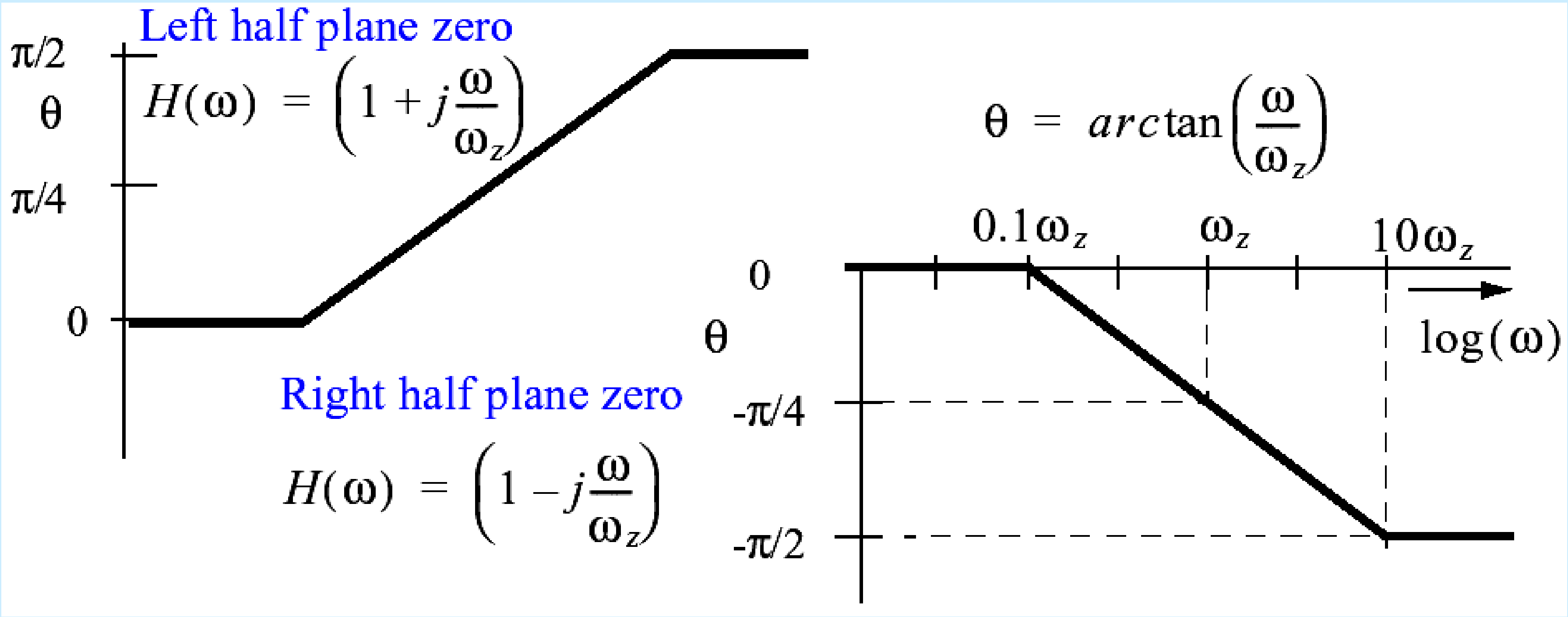
SPICE SIM – C R circuit

- $\omega_p = 1/RC = 10k \rightarrow f_p = 1.6kHz$



Zero's phase response

- The phase response of a Zero depends on which half plane the Zero is located

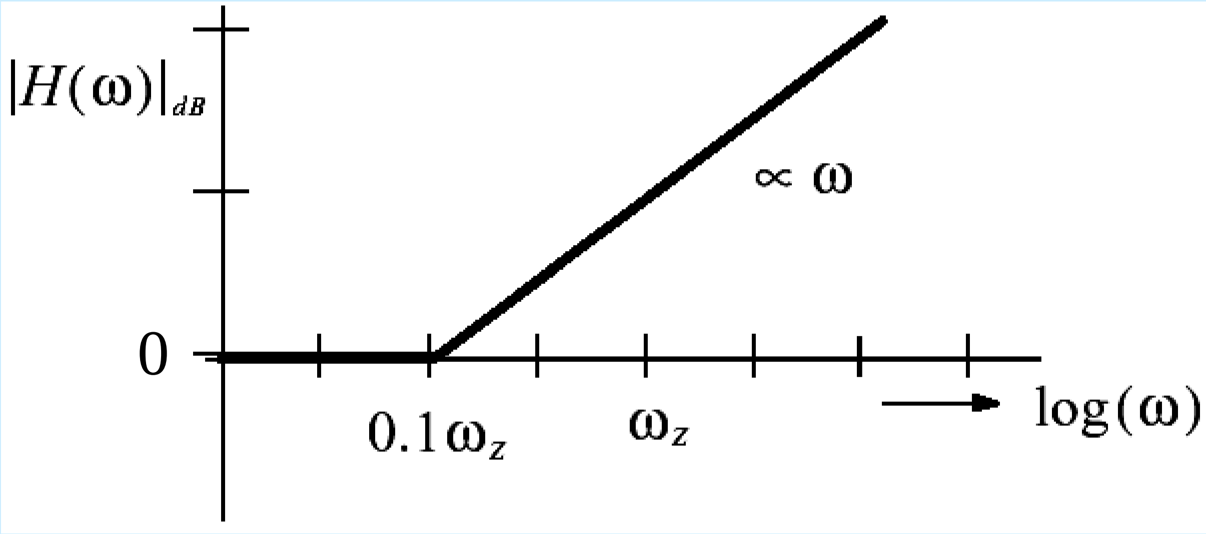


$$H(s) = 1 - \frac{s}{s_z} \qquad s_z = -j\,\omega_z \qquad H(s) = 1 + \frac{s}{s_z}$$

Zero's gain response

- For Zero in either half plane the amplitude response is the same

$$|H(\omega)| = \sqrt{1 + \left(\frac{\omega}{\omega_z}\right)^2} \Rightarrow |H(\omega)|_{dB} = 10 \bullet \log\left(1 + \left(\frac{\omega}{\omega_z}\right)^2\right)$$

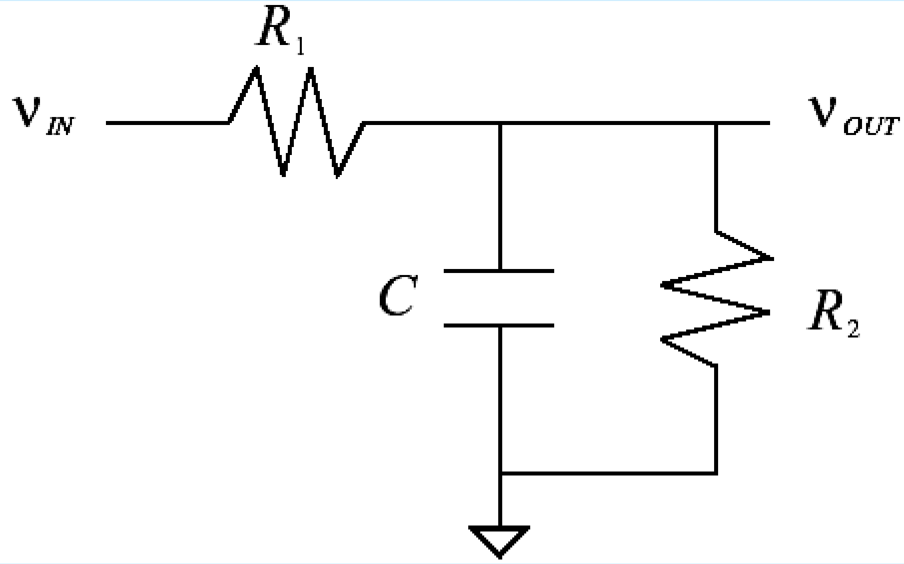


$$|H(\omega >> \omega_z)|_{dB}$$

$$\approx 20 \bullet \log\left(\frac{\omega}{\omega_z}\right)$$

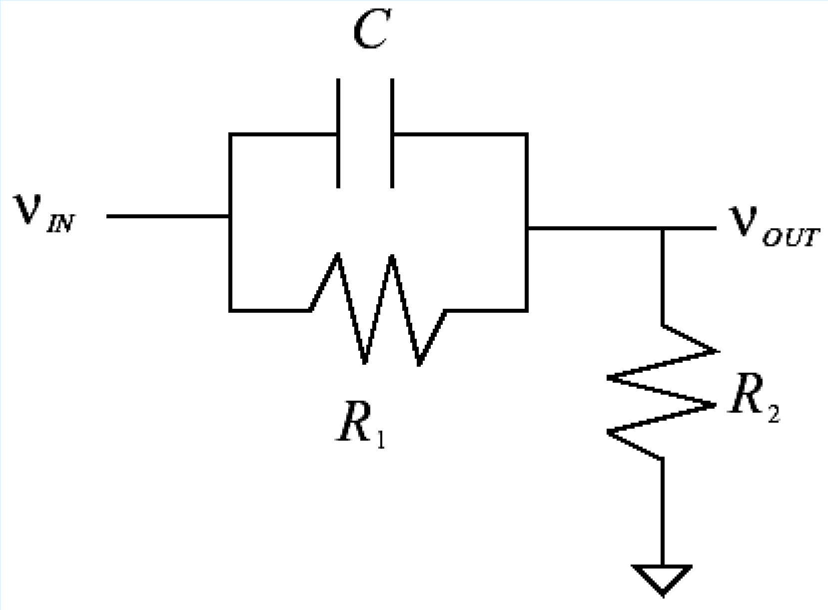
20dB/dec

Transfer function – Other circuits



- 1 Pole

$$H(\omega) = \frac{R_2}{R_1 + R_2} \bullet \frac{1}{1 + j\omega(R_1 \,||\, R_2)C}$$



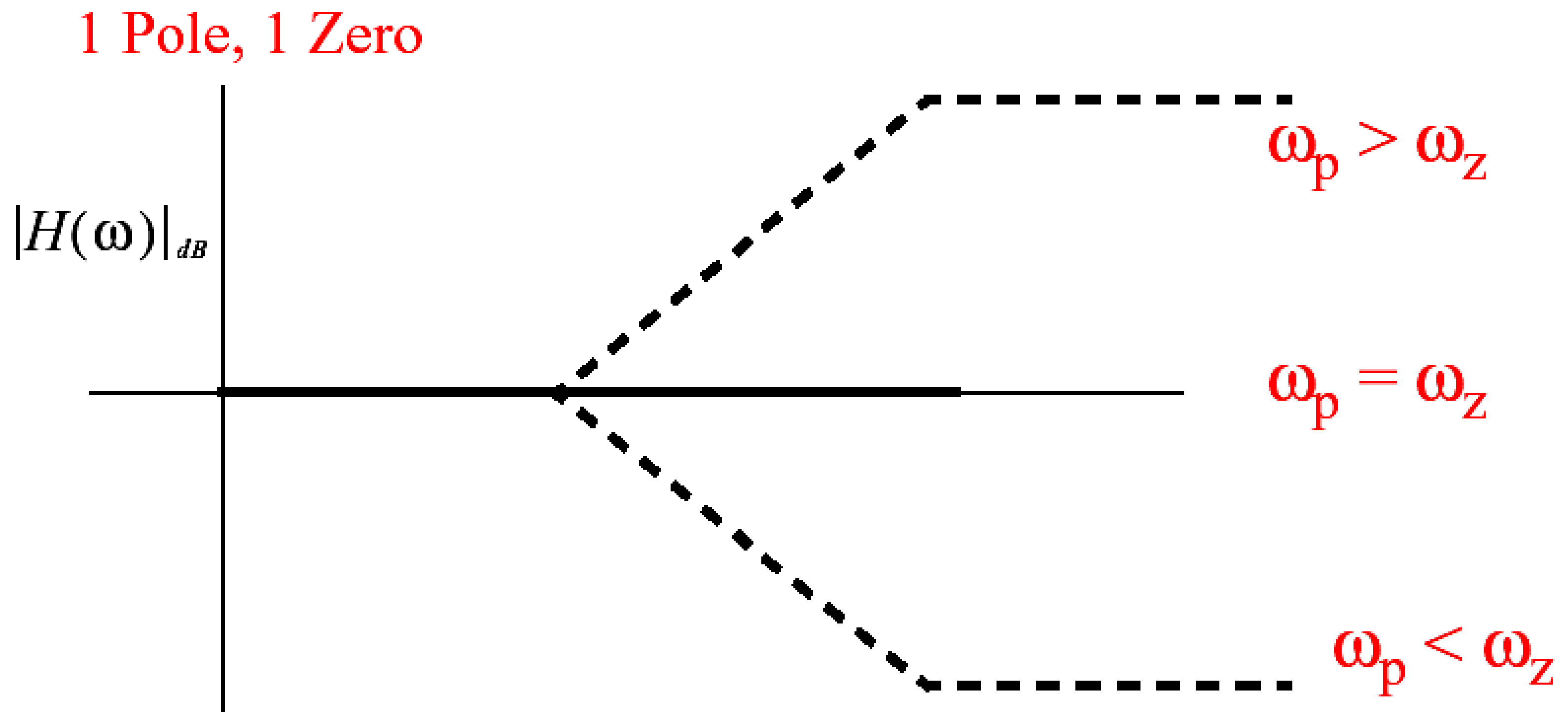
- 1 Pole, 1 Zero

$$H(\omega) = \frac{R_2}{R_1 + R_2} \bullet \frac{1 + j\omega R_1 C}{1 + j\omega(R_1 \,||\, R_2)C}$$

1 Pole, 1 Zero response

- The response depends on the relative location of the Pole and the Zero

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



MOSFET capacitances - circuit

- Specs: tox (Cox), CGSO, CGDO, CGBO, CJ, PB (ϕ_B)

- Typical Values

  Cox = 10^{-4} F/m^2

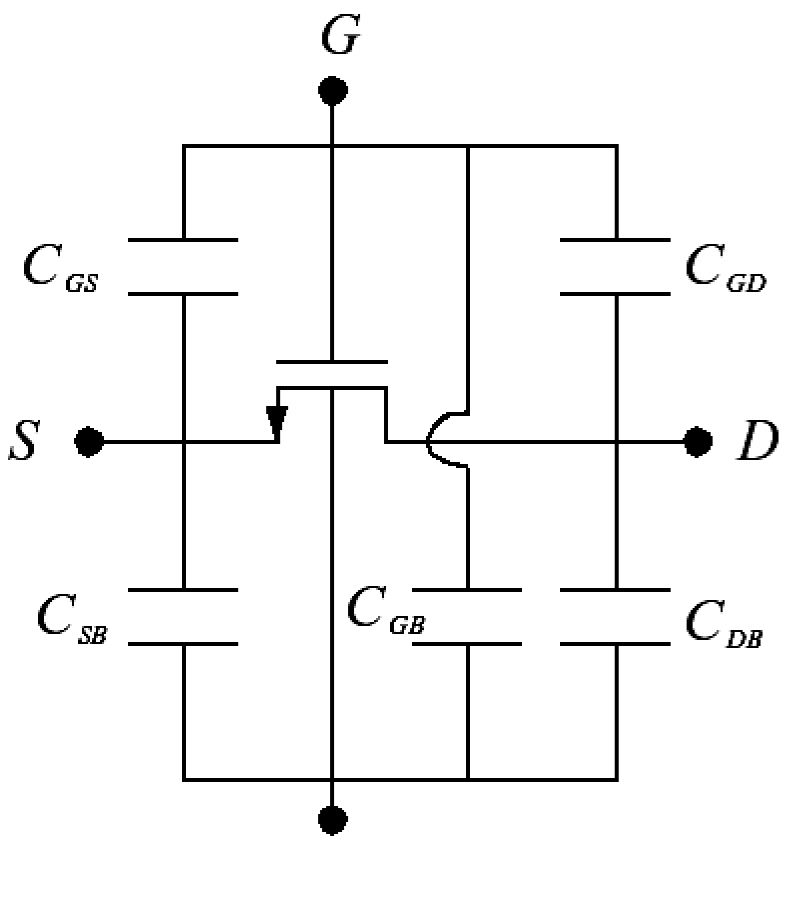
  CGSO = 5×10^{-10} F/m

  CGDO = 5×10^{-10} F/m

  CGBO = 4×10^{-10} F/m

  CJ = 10^{-4} F/m^2

  PB = 0.8 V



MOSFET capacitances - equations

Saturation

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

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

Linear

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

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

with: PS = Perimeter of Source, AS = Area of Source

MJ = ½ (default), MJSW = 3 (default)

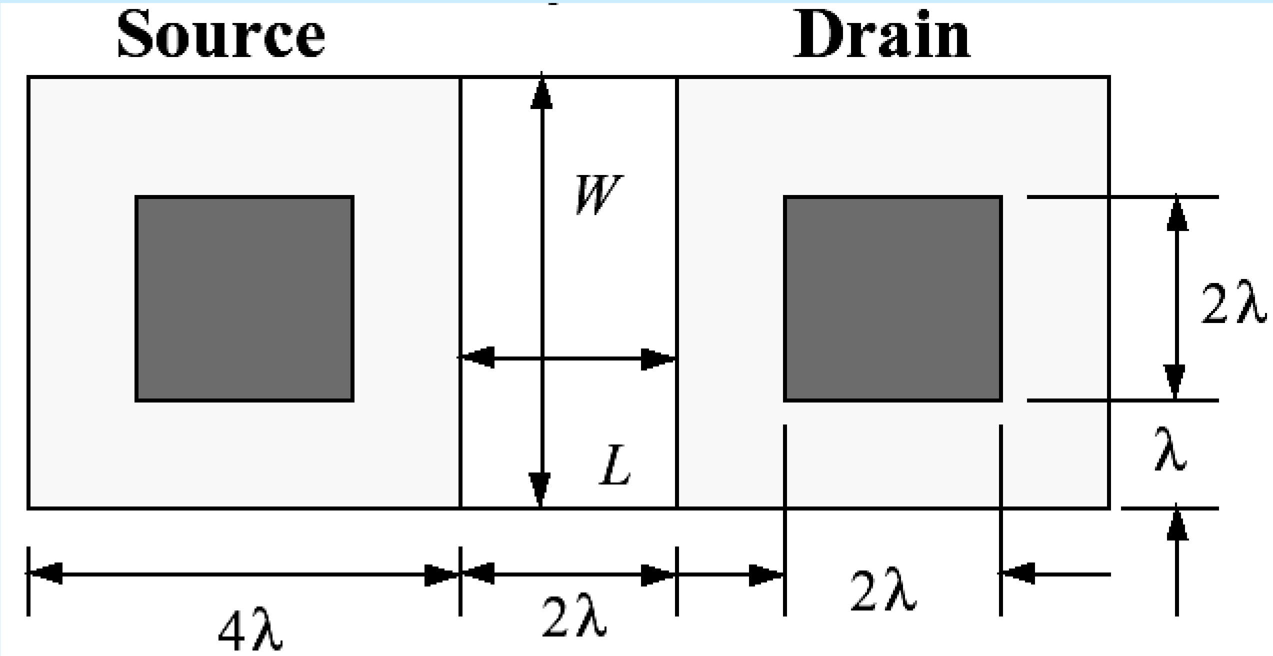
$$C_{SB} = \frac{CJ \bullet AS}{\left(1 + \frac{V_{BS}}{PB}\right)^{MJ}} + \frac{CJSW \bullet PS}{\left(1 + \frac{V_{BS}}{PB}\right)^{MJSW}}$$

a similar equation is used to calculate C_{DB}

C_{GB} = CGBO · L

MOSFET – classic layout

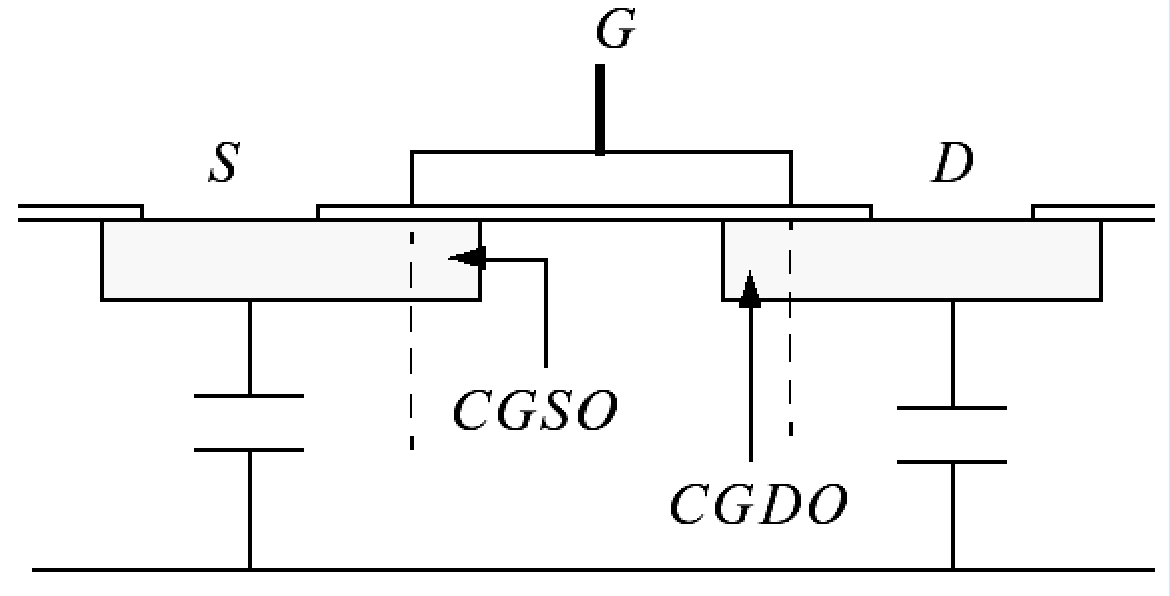
- Area of Source = AS = $4\lambda \cdot W$
- Area of Drain = AD = AS = $4\lambda \cdot W$
- Perimeter of Source = PS = $8\lambda + W$
- Perimeter of Drain = PD = $8\lambda + W$



MOSFET – SPICE attributes

M1 1 2 3 4 NMOS L=2U W=2U

\+ AS=4p AD=4p PS=6U PD=6U



- Overlap capacitances are calculated using W
- Capacitance to body have area and perimeter terms

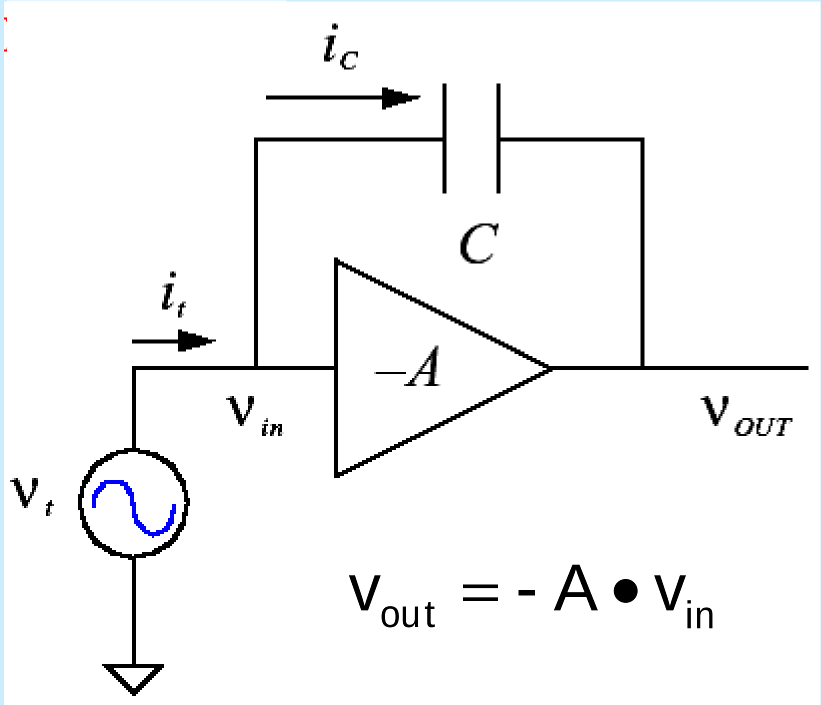
Miller approximation

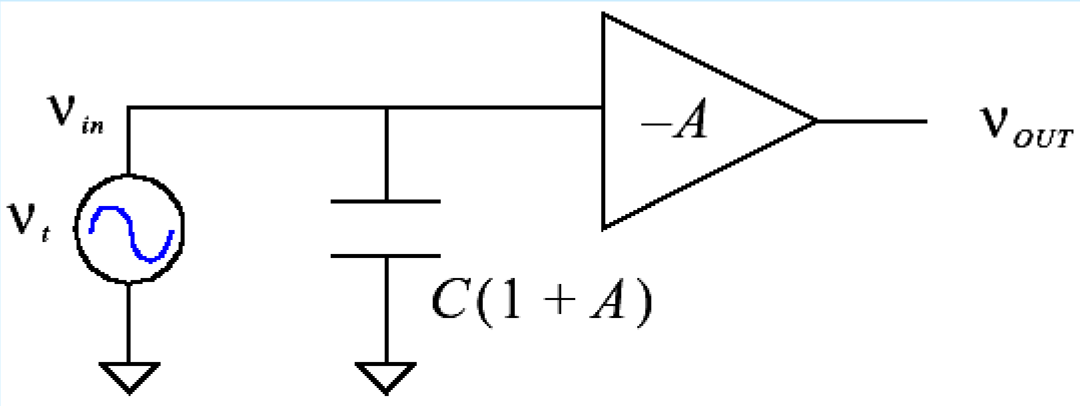
- Capacitance between input and output appears multiplied by the gain at the input

$$i_c = C \bullet \frac{d}{dt}\left(v_{in} - v_{out}\right)$$

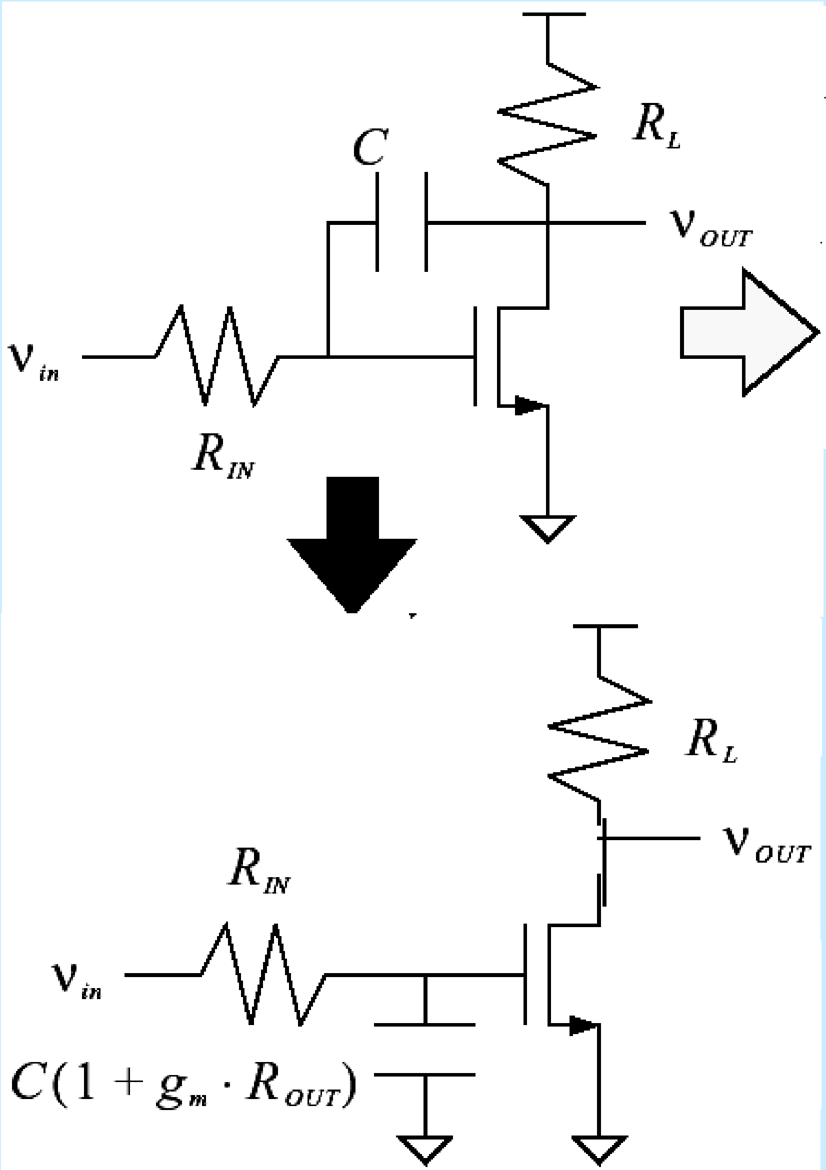
$$i_c = C \bullet \frac{d}{dt}\left(v_{in} + A \bullet v_{in}\right)$$

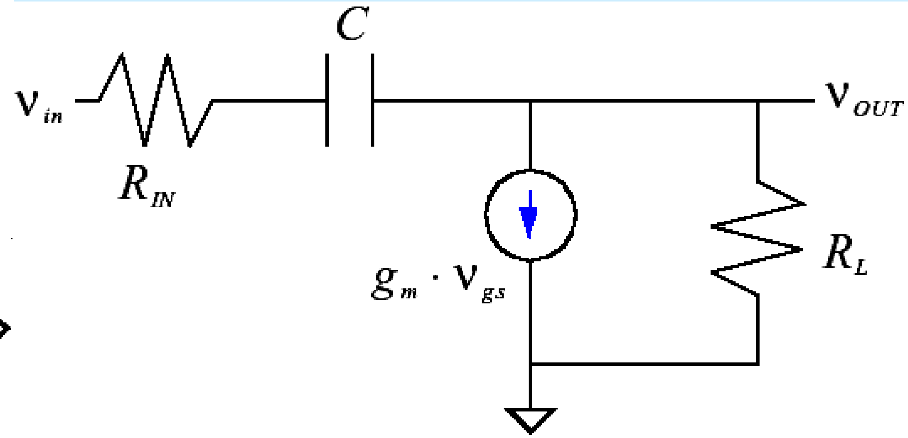
$$i_c = C \bullet \left(1 + A\right) \bullet \frac{dv_{in}}{dt}$$





Miller approximation – Common source



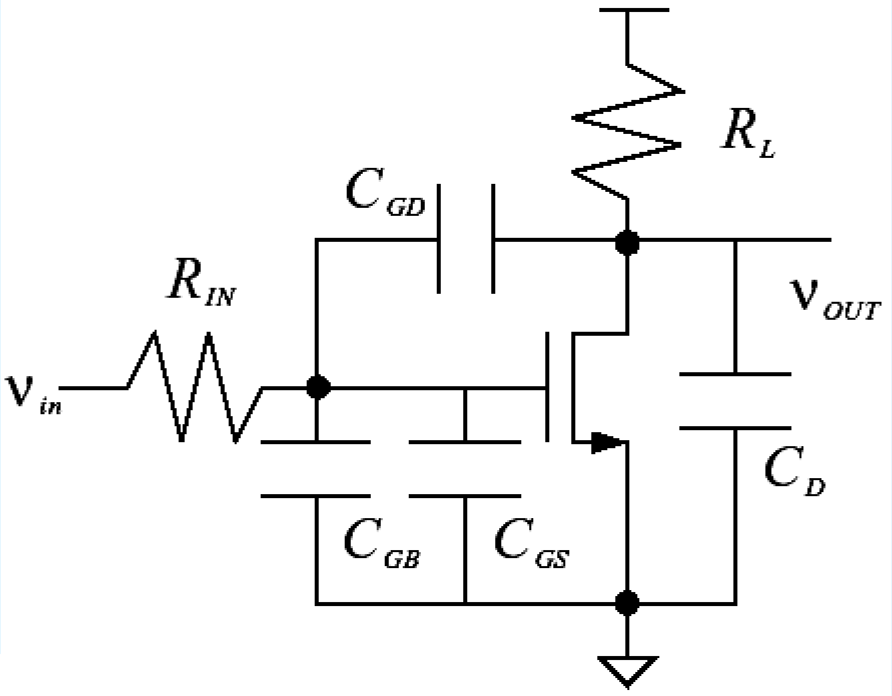


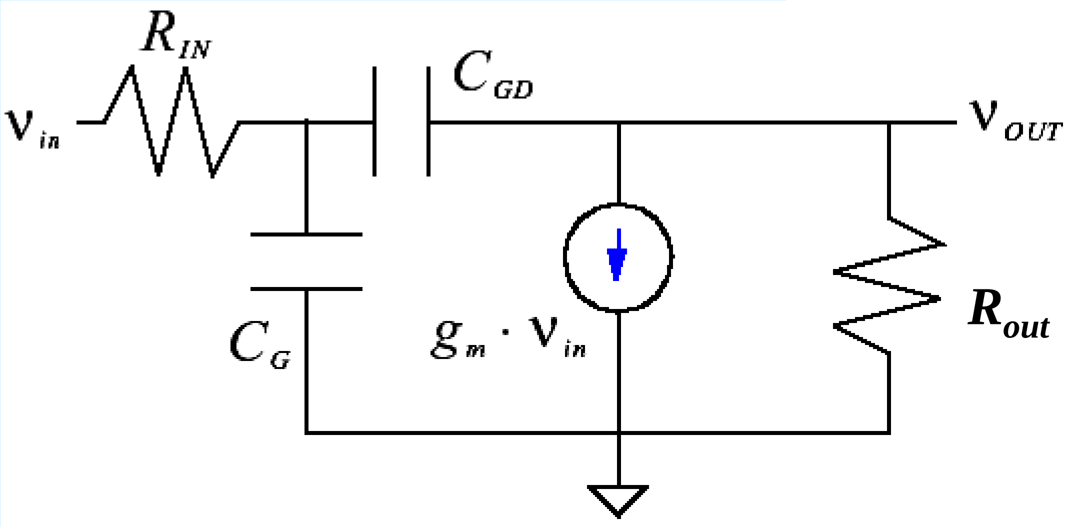
$$\frac{v_{out}}{v_{in}} = \frac{g_m \bullet R_{out}}{1 + j\omega\left[R_{in}C\left(1 + g_m \bullet R_{out}\right) + R_{out}C\right]}$$

$$\omega_p = \frac{1}{R_{in} \bullet \underbrace{C \bullet \left(1 + g_m \bullet R_{out}\right)}_{\text{Miller Capacitor}}}$$

Common Source

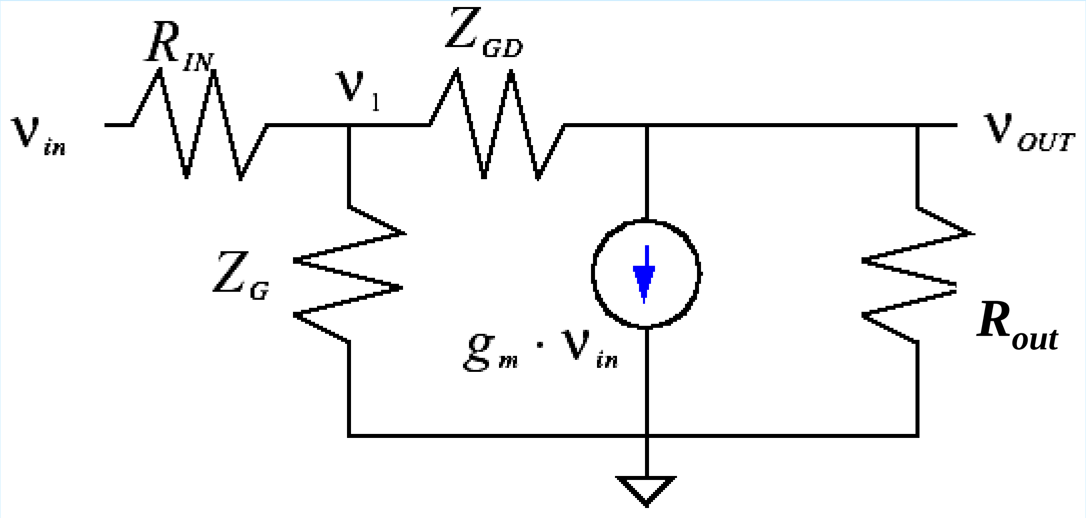
- C_D can be ignored sometimes
- $R_{out} = R_L \mid\mid r_o$
- $C_G = C_{GB} + C_{GS}$





Common source – small signal

- Using impedances



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

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

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

Common source – Poles and Zeros

- From the transfer function:

$$\omega_{p1} = -\frac{1}{R_{in} \bullet \left[C_{GD}\left(1 + g_m \bullet R_{out}\right) + C_G\right] + R_L C_{GD}}$$

$$\omega_{p2} = -\frac{1}{R_{out} C_{GD}} - \frac{1}{\left(R_{out} \,||\, R_{in} \,||\, \frac{1}{gm}\right) C_G}$$

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

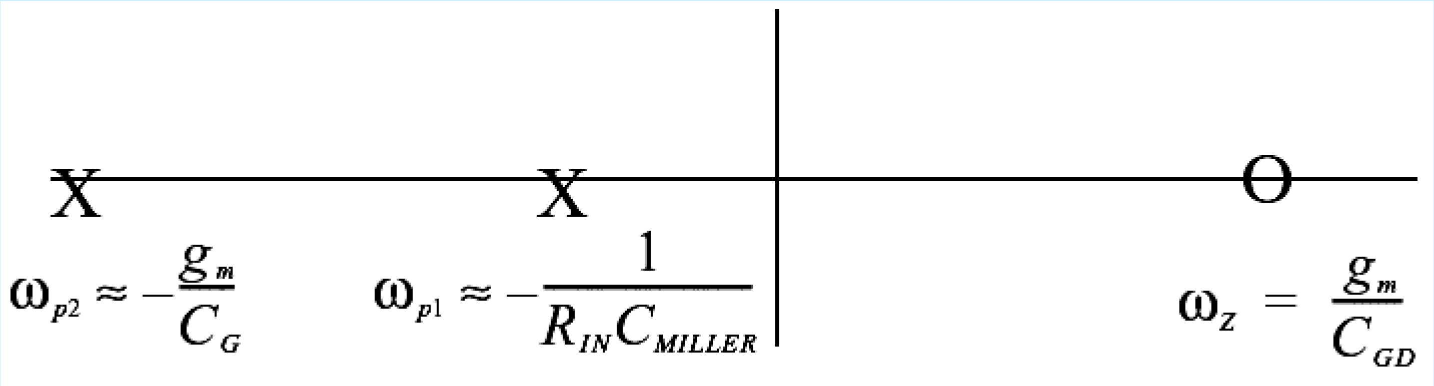
$$H(\omega) = \frac{\left(1 + j\dfrac{\omega}{\omega_z}\right)}{\left(1 + j\dfrac{\omega}{\omega_{p1}}\right) + \left(1 + j\dfrac{\omega}{\omega_{p2}}\right)}$$

Common source – Poles and Zeros

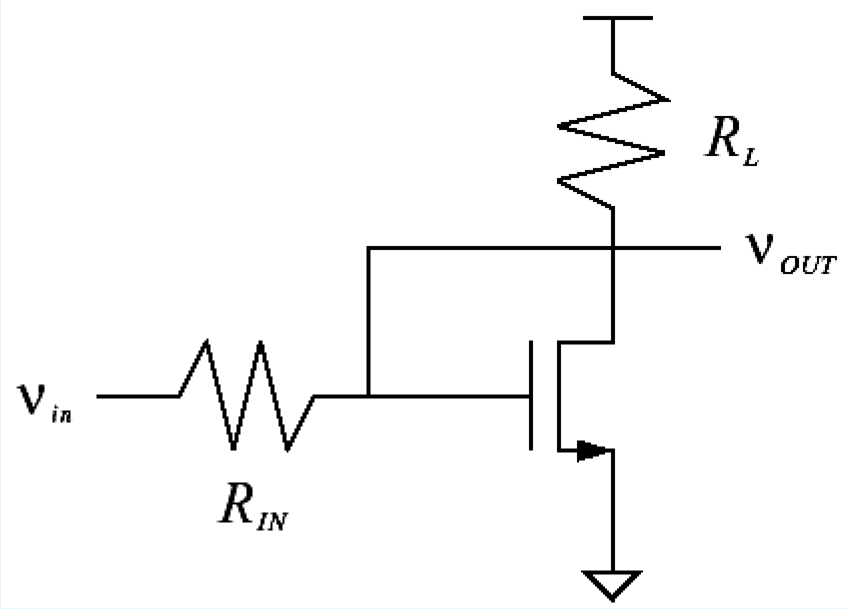
- Converting to s space:

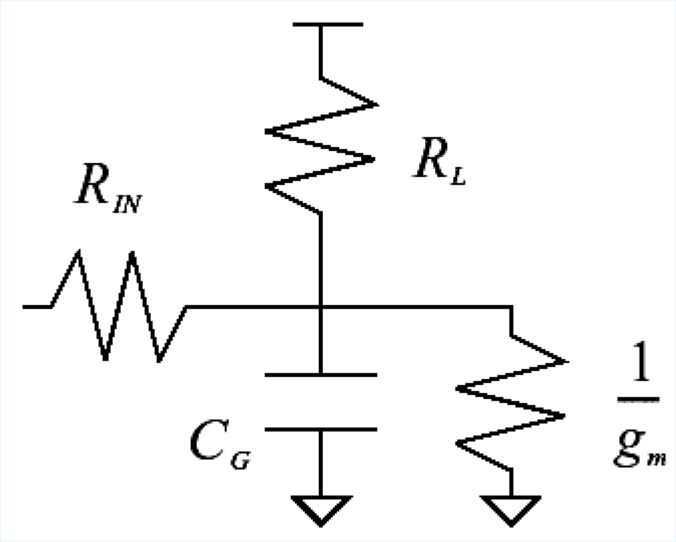
$$s_z = -j\omega_z \qquad s_{p1} = -j\omega_{p1} \qquad s_{p2} = -j\omega_{p2}$$

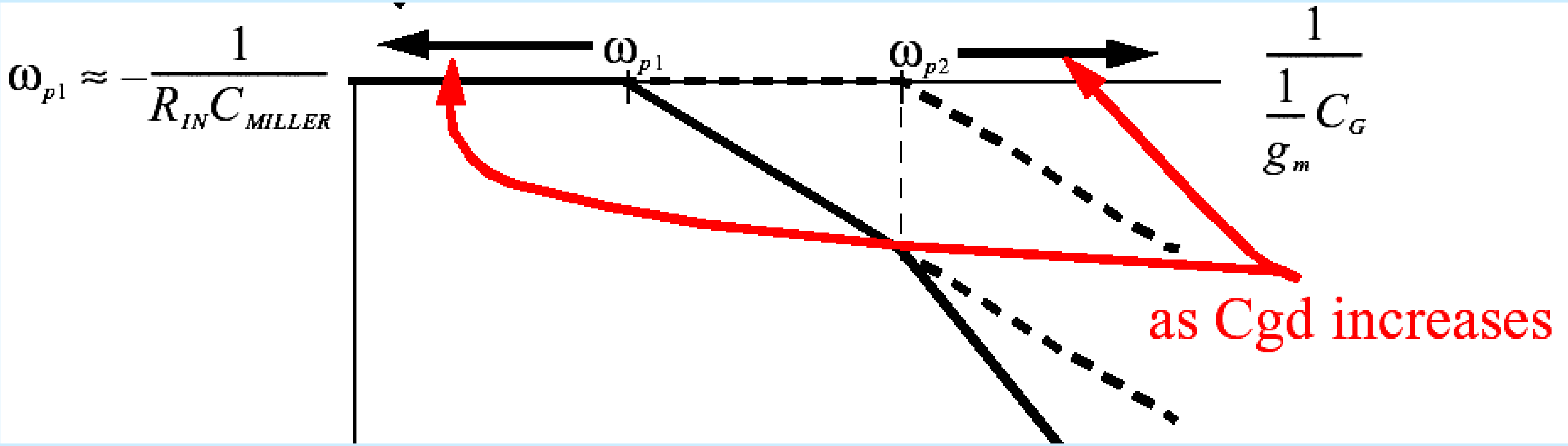
$$H(\omega) = \frac{\left(1 + j\dfrac{\omega}{\omega_z}\right)}{\left(1 + j\dfrac{\omega}{\omega_{p1}}\right) + \left(1 + j\dfrac{\omega}{\omega_{p2}}\right)} \Rightarrow H(s) = \frac{\left(1 - \dfrac{s}{s_z}\right)}{\left(1 - \dfrac{s}{s_{p1}}\right) + \left(1 - \dfrac{s}{s_{p2}}\right)}$$



Diode connected and Pole Splitting





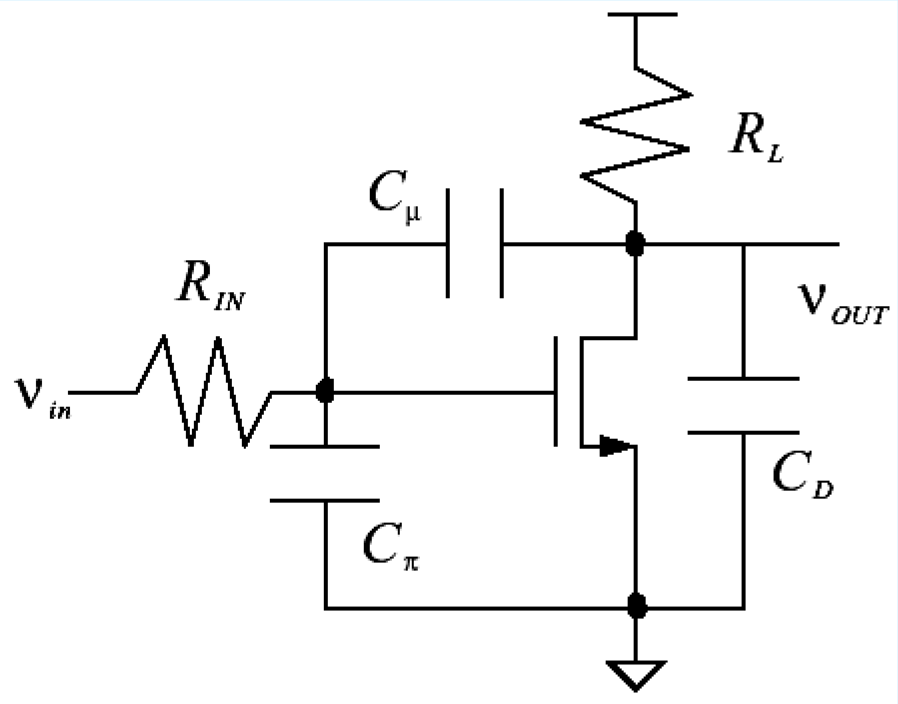


Common source – Capacitance Cases

- Relative magnitude of the capacitors result in different scenarios

- Case1: Miller Cap small

$R_{in}C_{\pi}$, $R_{out}C_D >> R_{in}C_{Miller}$

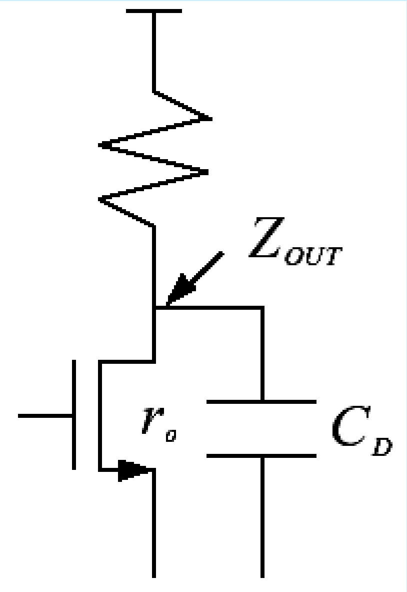


$$\omega_{p1} = \frac{1}{R_{in}C_{\pi}} \qquad \omega_{p2} = \frac{1}{R_{out}C_D} \qquad R_{out} = R_L \,||\, r_o$$

Common source – Small Miller capacitance

- Output Impedance, Z_{out}

$$Z_{out} = R_L \,||\, r_o \,||\, \frac{1}{j\omega C_D} = R_{out} \,||\, \frac{1}{j\omega C_D}$$



- Stage gain, Av

$$A_v = -g_m \bullet Z_{out} = -g_m \bullet \frac{\dfrac{R_{out}}{j\omega C_D}}{R_{out} + \dfrac{1}{j\omega C_D}} = \frac{R_{out}}{1 + j\omega R_{out} C_D}$$

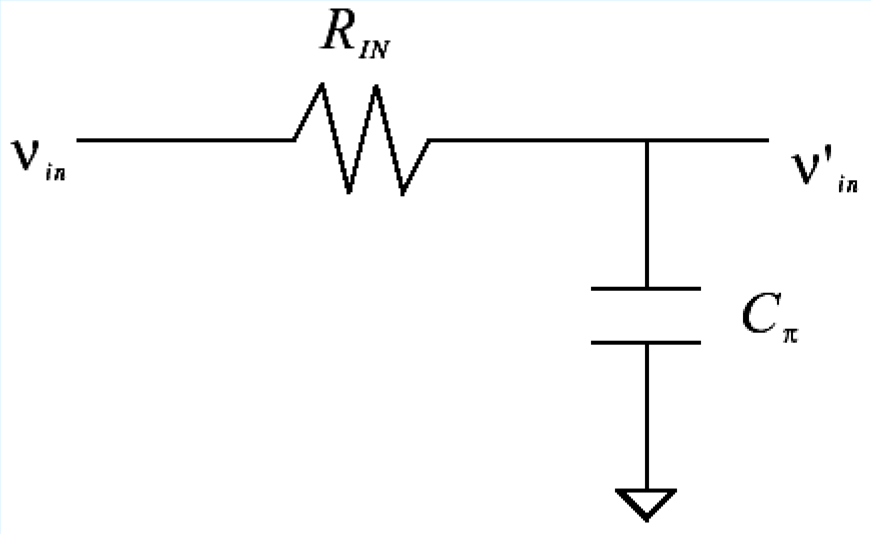
- Output pole

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

Common source – Small Miller capacitance

- Input transfer function

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



- Input pole

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

Common source – Other cases

- Case 2: Large C_D

  $R_{out}C_D \gg R_{in}C_{Miller},\ R_{in}C_\pi$

$$\omega_{p1} = \frac{1}{R_{out}C_D} \qquad \omega_{p2} = \frac{1}{R_{in}\left(C_\pi + C_\mu\right)}$$

- Case 3: Large C_μ

  $R_{in}C_{Miller} \gg R_{out}C_D,\ R_{in}C_\pi$

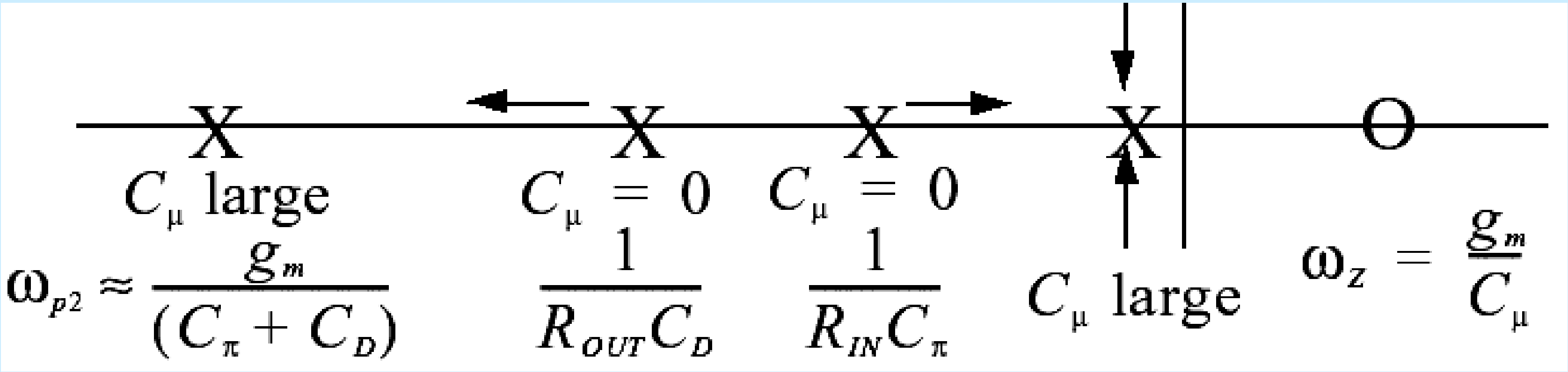
$$\omega_{p1} = \frac{1}{R_{in}\underbrace{\left(1 + g_m R_{out}\right)C_\mu}_{C_{Miller}}} \qquad \omega_{p2} = \frac{1}{\frac{1}{g_m}\left(C_\pi + C_D\right)} = \frac{g_m}{\left(C_\pi + C_D\right)}$$

Poles and Zeros

- Usually the multiplying factor on the Miller capacitor results in poles far apart from each other than in other cases.

- The pole splitting is used to compensate the circuit.

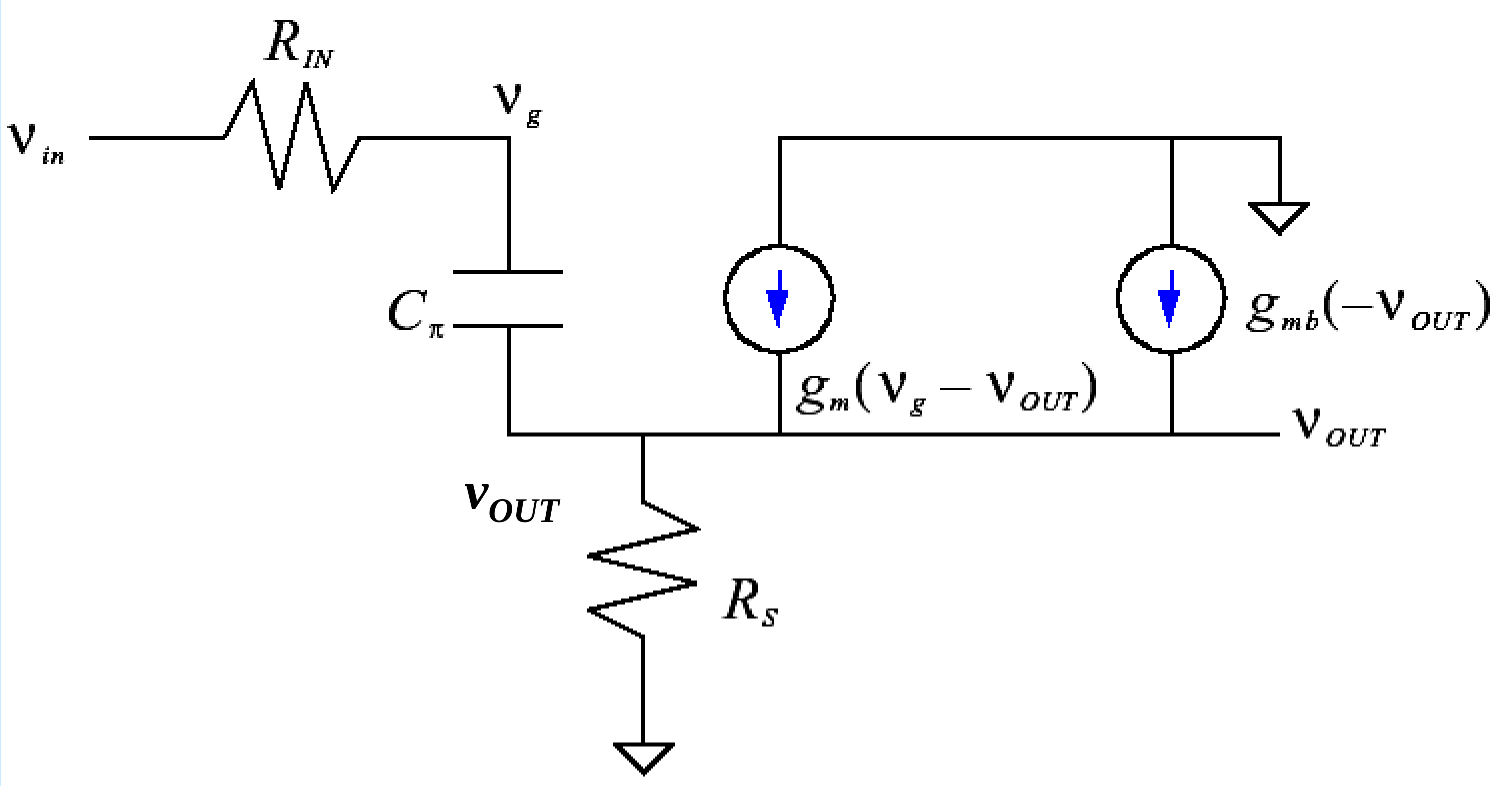
$$\omega_{p1} \approx \frac{1}{R_{in}C_{MILLER}}$$



Common drain (source follower)

- Small circuit analysis

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



Common drain – Small signal analysis

$$\frac{v_{out}}{R_s} = \frac{v_g - v_{out}}{\dfrac{1}{j\omega C_\pi}} + g_m \bullet V_g - (1+\chi) \bullet g_m \bullet v_{out}$$

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

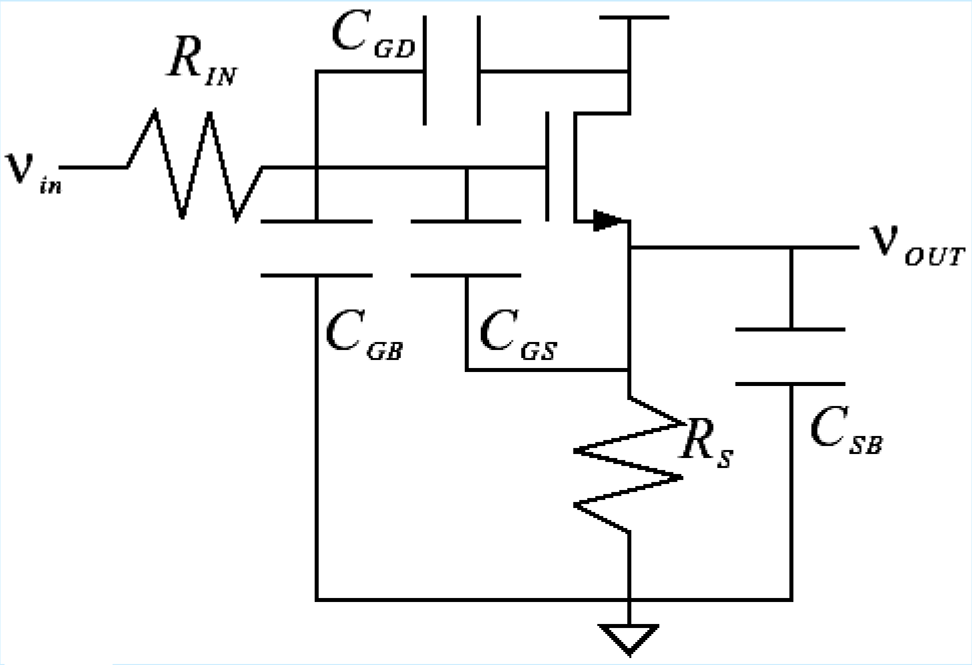
$$\frac{v_{out}}{R_s} = \frac{g_m R_s}{1+(1+\chi) \bullet g_m R_s} \bullet \frac{\left(1 + j\omega \dfrac{C_\pi}{g_m}\right)}{1 + j\omega R_{in} C_\pi \bullet \dfrac{1+\chi \bullet g_m R_s}{1+(1+\chi) \bullet g_m R_s}}$$

$$\omega_z = \frac{g_m}{C_\pi} \qquad \omega_{p1} = \frac{1}{R_{in} C_\pi (1-A)} \qquad A = \frac{g_m R_s}{1+(1+\chi) g_m R_s}$$

Common drain (source follower)

- Effect of C_{SB}

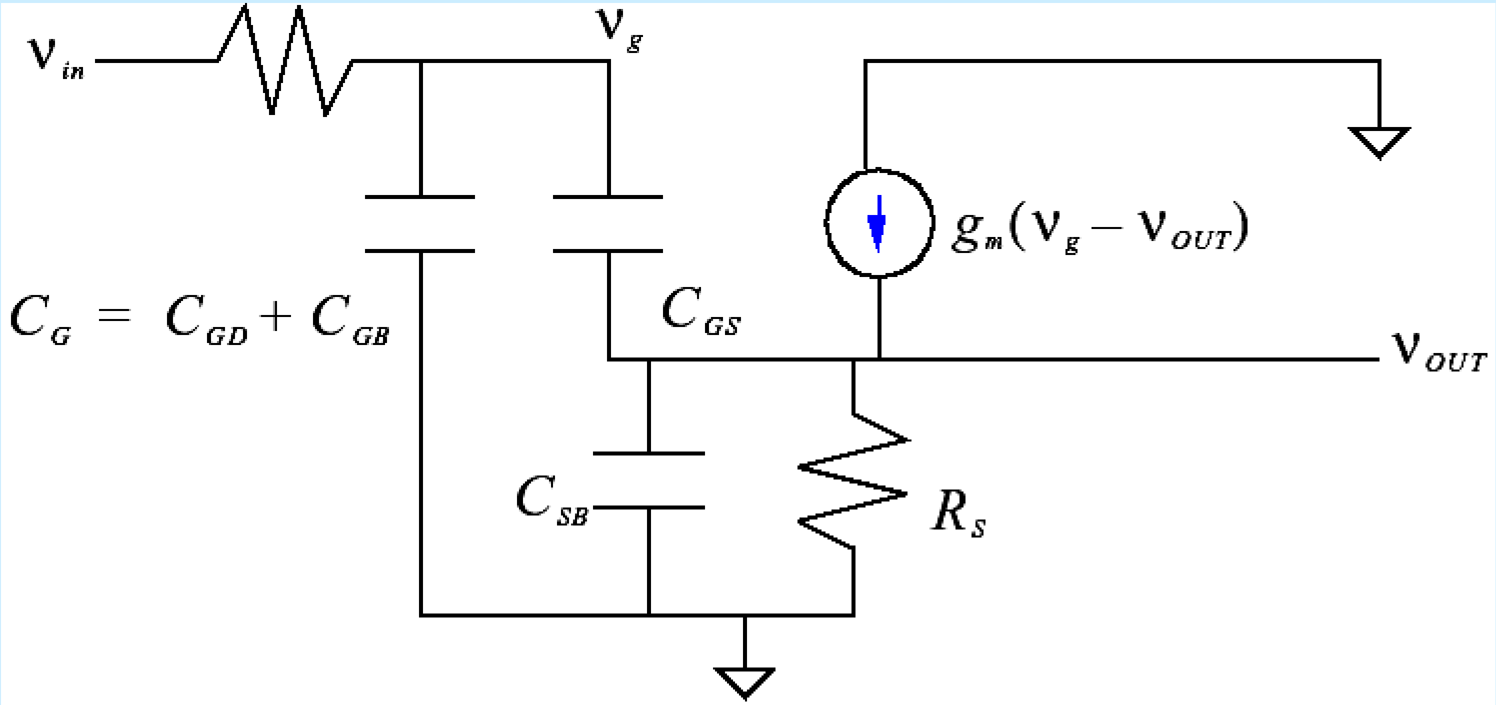
- The Body is Grounded



Common drain – small signal

$$\frac{v_{in} - v_g}{R_{in}} = v_g \bullet j\omega C_G + (v_g - v_{out}) \bullet j\omega C_{GS}$$

$$(v_g - v_{out}) \bullet j\omega C_{GS} - g_m \bullet (v_g - v_{out}) = \frac{v_{out}}{R_s} + v_{out} \bullet j\omega C_{SB}$$



Common drain – Small signal analysis

$$\frac{v_{out}}{v_{in}} = \frac{\dfrac{g_m R_s}{1+g_m R_s} \bullet \left(1 + j\omega \dfrac{C_{GS}}{g_m}\right)}{1 + j\omega\left[R_{in}C_G + \dfrac{R_{in}C_{GS}}{1+g_m R_s} + \dfrac{R_s\left(C_{GS}+C_{SB}\right)}{1+g_m R_s}\right] - \omega^2 R_s R_{in}\left[\dfrac{C_{GS}C_G + C_{SB}\left(C_G + C_{GS}\right)}{1+g_m R_s}\right]}$$

- Having the denominator to be in the format:

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

- The poles are:

$$\omega_{p1} = \frac{1}{R_{in}C_G + \dfrac{R_{in}C_{GS}}{1+g_m R_s} + \dfrac{R_s\left(C_{GS}+C_{SB}\right)}{1+g_m R_s}} = \frac{1}{R_{in}C_G + \dfrac{R_{in}C_{GS}}{1+g_m R_s} + R_O\left(C_{GS}+C_{SB}\right)}$$

$$\omega_{p2} = \frac{R_{in}C_G + \dfrac{R_{in}C_{GS}}{1+g_m R_s} + R_O\left(C_{GS}+C_{SB}\right)}{R_O R_{in}\left[C_{GS}C_G + C_{SB}C_G + C_{SB}C_{GS}\right]}$$

$$R_O = \frac{1}{g_m} \,||\, R_s$$

Common drain - Cases

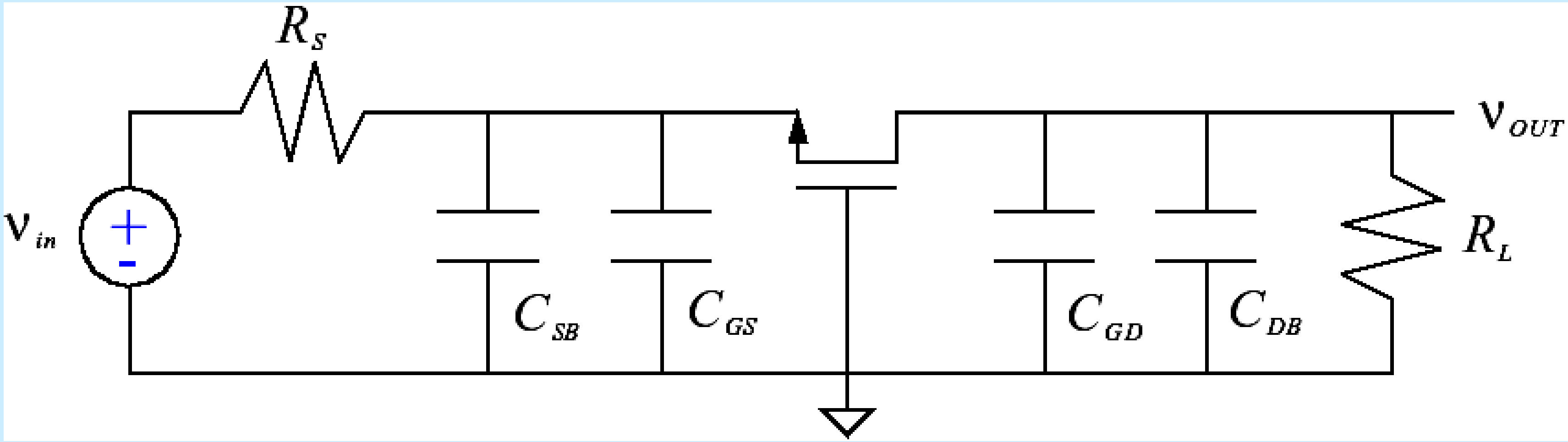
- Case 1: $R_{in}\left(C_G + \dfrac{C_{GS}}{1+g_m R_s}\right) >> R_O\left(C_{GS} + C_{SB}\right)$

$$\omega_{p1} = \frac{1}{R_{in}\left(C_G + \dfrac{C_{GS}}{1+g_m R_s}\right)} \qquad A = \frac{g_m R_s}{1+g_m R_s} \qquad C_{Miller} = C_{GS} \bullet (1 - A)$$

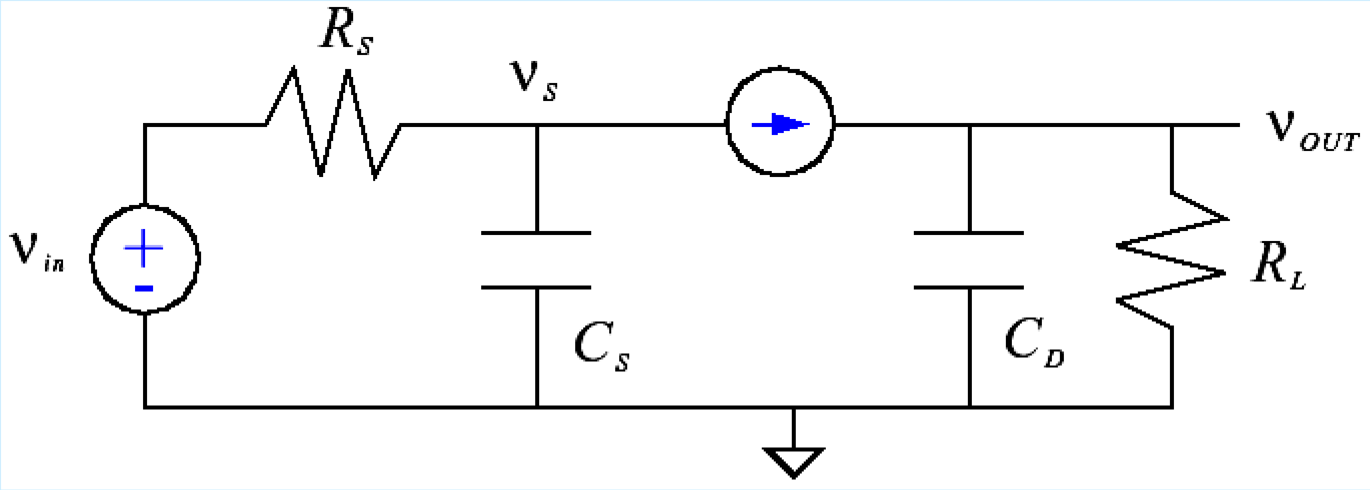
- Case 2: $R_O\left(C_{GS} + C_{SB}\right) >> R_{in}\left(C_G + \dfrac{C_{GS}}{1+g_m R_s}\right)$

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

Common Gate



- Assuming $r_o \to \infty$



Common gate – small signal

- Using KCL @ v_s and @ v_{out}

$$\frac{v_{in} - v_s}{R_s} = v_s \bullet j\omega C_s + g_m v_s$$

$$g_m v_s = v_{out} \bullet j\omega C_D + \frac{v_{out}}{R_L}$$

$$\frac{v_{out}}{v_{in}} = \frac{\dfrac{g_m R_L}{1 + g_m R_s}}{(1 + j\omega R_L C_D) \bullet \left(1 + j\omega \dfrac{R_s C_s}{1 + g_m R_s}\right)}$$

- No Zeros

$$\omega_{p1} = \frac{1}{R_L C_D} \qquad \omega_{p2} = \frac{1}{\dfrac{R_s}{1 + g_m R_s} C_s} = \frac{1}{\left(R_s \,||\, \dfrac{1}{g_m}\right) C_s}$$