ECEN474: (Analog) VLSI Circuit Design Fall 2011
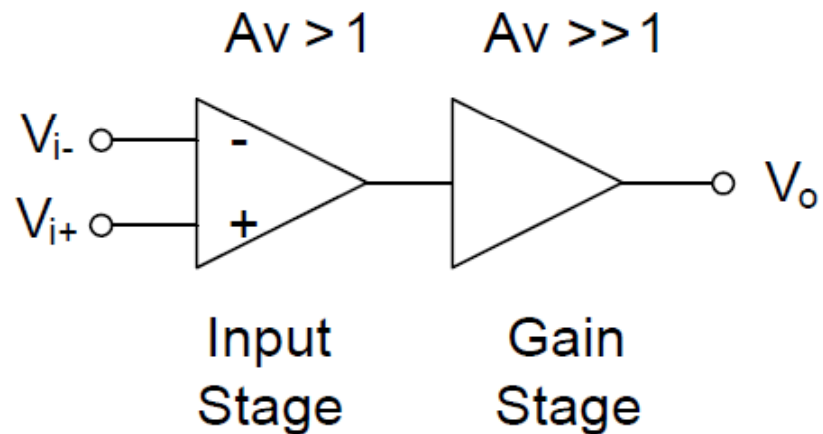
Lecture 17: Two Stage Miller OTA

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Agenda

- Two Stage Miller OTA
- OpAmp Characterization

Multi-Stage Amplifiers

$$A_v > 1 \qquad A_v >> 1$$

V_{i-}

V_{i+}

V_o

Input Stage

Gain Stage

- Single-stage amplifiers typically have to trade-off gain and swing range
- Multi-stage amplifiers allow for higher gain without sacrificing swing range
- The major challenge with multi-stage amplifiers is achieving adequate phase margin to insure stability in a feedback configuration
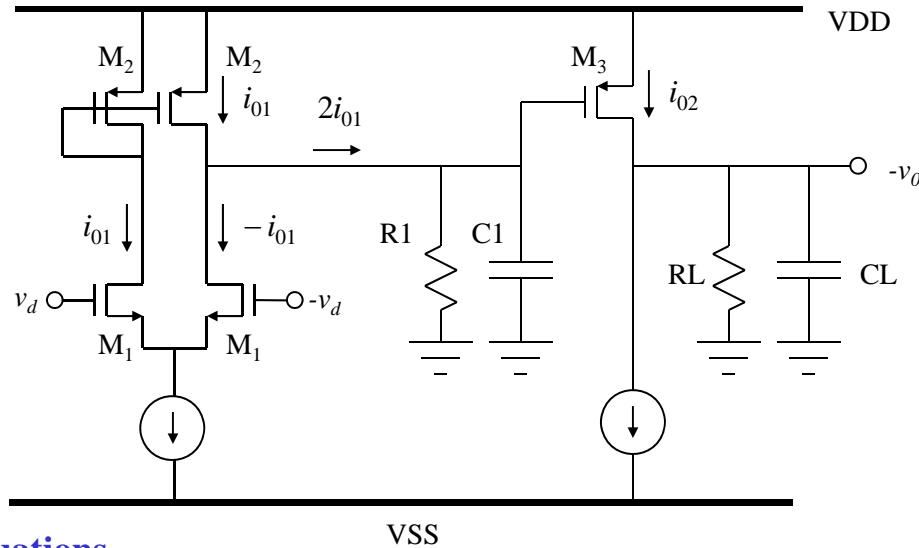
Two Stage Miller OTA
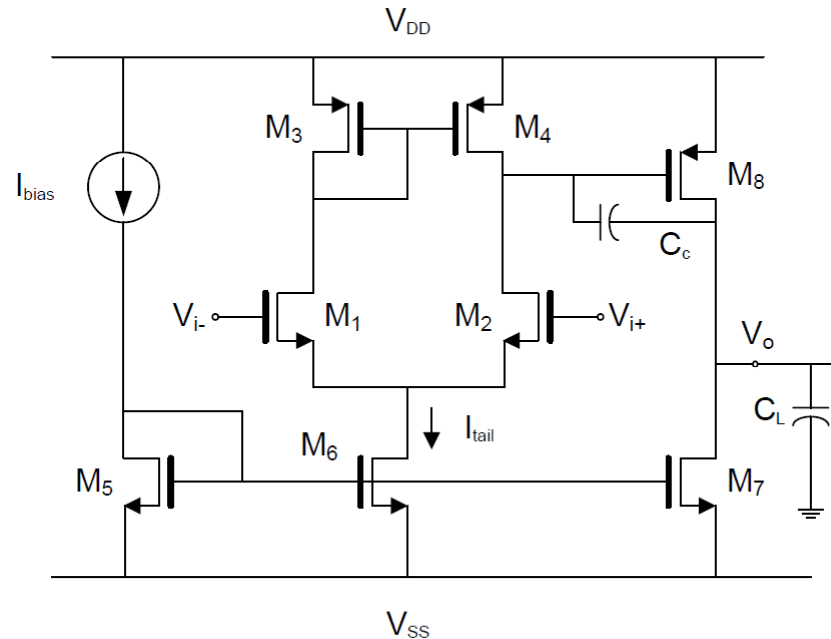
DC Gain $A_{VDC} = A_{v1}A_{v2} = \left(-\dfrac{g_{m2}}{g_{o2} + g_{o4}} \right)\left(-\dfrac{g_{m8}}{g_{o8} + g_{o7}} \right) = \dfrac{g_{m2}g_{m8}}{\left(g_{o2} + g_{o4}\right)\left(g_{o8} + g_{o7}\right)}$
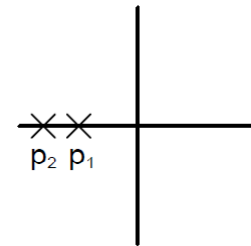
$$A_{VDC} = G_m R_{out}$$

$$R_{out} = \frac{1}{g_{o8} + g_{o7}}$$

$$G_m = -g_{m8}A_{v1} = \frac{g_{m8}g_{m2}}{g_{o2} + g_{o4}}$$

$$A(s) = \frac{A_{VDC}}{\left(1+\dfrac{s}{\omega_{p1}}\right)\left(1+\dfrac{s}{\omega_{p2}}\right)}$$
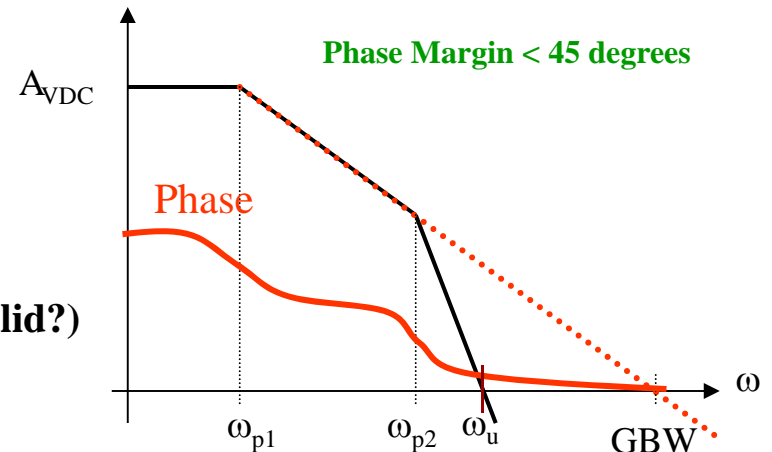
⬇**Main equations**

$$A_{VDC} = -\frac{g_{m1}}{g_1}\frac{g_{m3}}{g_L}$$
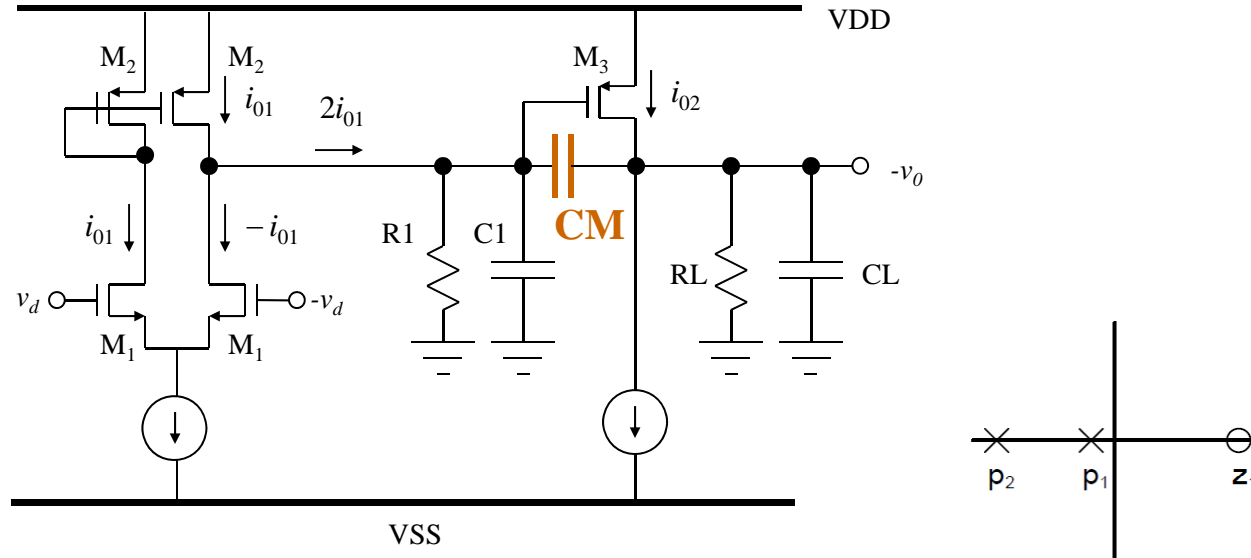
$$\omega_{p1} = -\frac{g_1}{C_1} \text{ (\textbf{LHP})}$$

$$\omega_{p2} = -\frac{g_L}{C_L} \text{ (\textbf{LHP})}$$

$$GBW = (A_{VDC}) * (\min(\omega_{p1}, \omega_{p2})) \text{ \textbf{(if dominant pole system, valid?)}}$$

$$Phase\_m\arg in = 180 - \tan^{-1}\left(\frac{\omega_u}{\omega_{p1}}\right) - \tan^{-1}\left(\frac{\omega_u}{\omega_{p2}}\right)$$

$$A_{VDC} = -\frac{g_{m1}}{g_1}\frac{g_{m3}}{g_L}$$
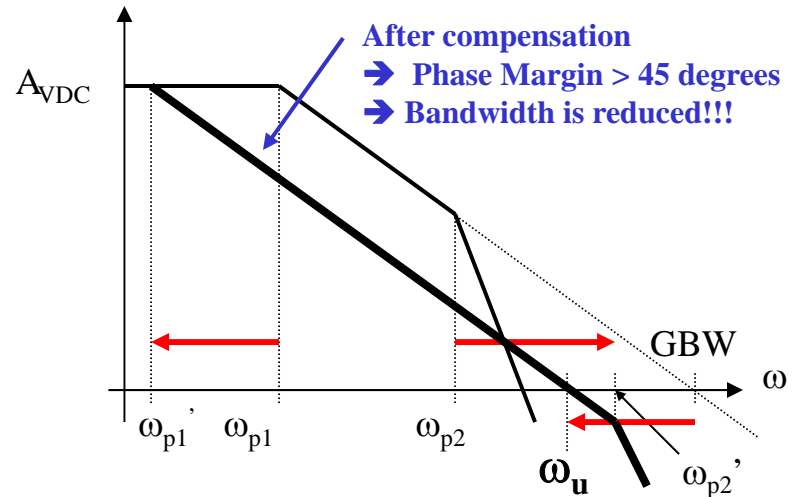
☞**Phase compensation ➜ Pole splitting techniques!!**
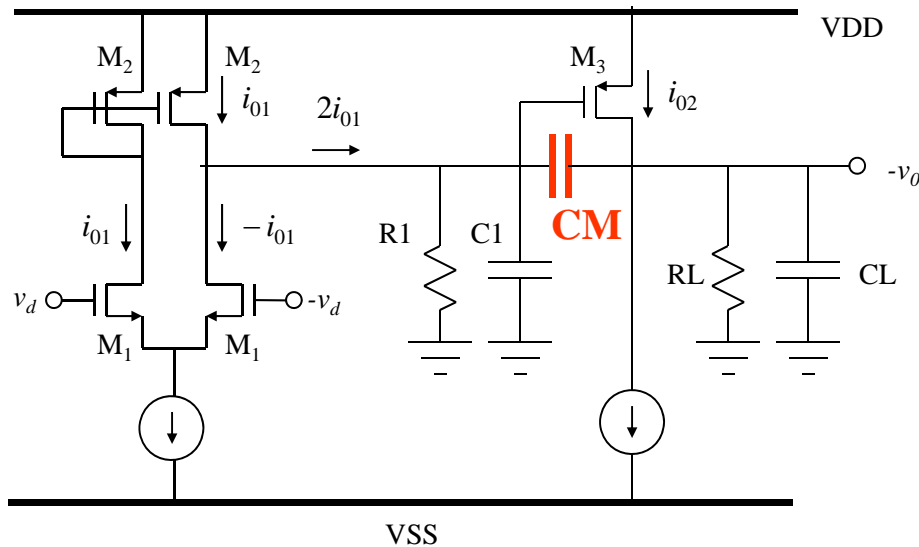
$$\omega_{p1} = -\frac{g_1}{C_1 + \dfrac{g_{m3}}{g_L}C_M} \ \textbf{(LHP)}$$

$$\omega_{p2} = -\frac{g_{m3}}{C_1 + C_L} \ \textbf{(LHP)}$$

$$GBW' = (A_{VDC})*\left|\omega_{p1}\right| \cong \frac{g_{m1}}{C_M}$$

$$Phase\_m\arg in = 180 - \tan^{-1}\left(\frac{GBW'}{\omega_{p1}}\right) - \tan^{-1}\left(\frac{GBW'}{\omega_{p2}}\right)$$

After compensation
➜ **Phase Margin > 45 degrees**
➜ **Bandwidth is reduced!!!**

$$A(s) = \frac{A_{VDC}\left(1 - \dfrac{s}{\omega_z}\right)}{\left(1 + \dfrac{s}{\omega_{p1}}\right)\left(1 + \dfrac{s}{\omega_{p2}}\right)}$$

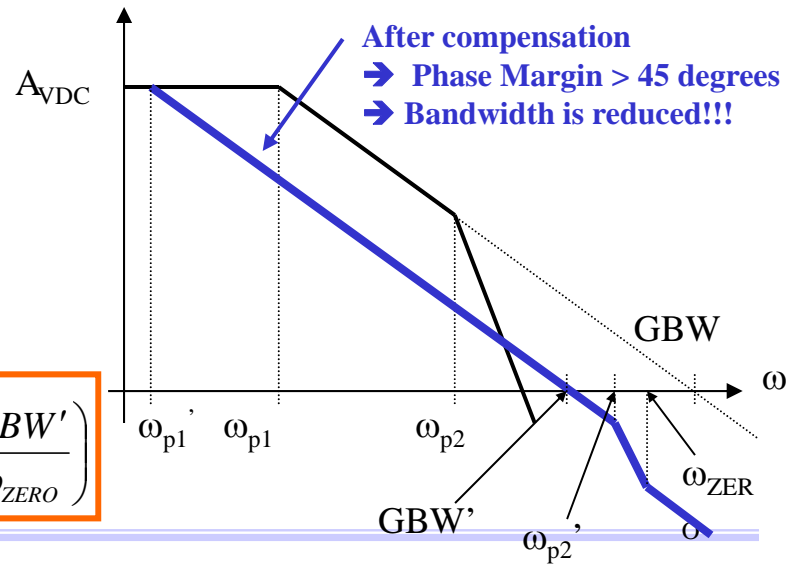☞ **Parasitic (bad) RHP zero!!**

$$\omega_{ZERO} = +\frac{g_{m3}}{C_M} \quad \textbf{(RHP)}$$
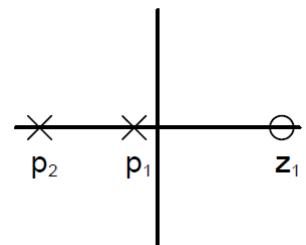
$$A_{VDC} = -\frac{g_{m1}}{g_1}\frac{g_{m3}}{g_L}$$

$$\omega_{p1} = -\frac{g_1}{C_1 + \dfrac{g_{m3}}{g_L}C_M} \quad \textbf{(LHP)}$$

$$\omega_{p2} = -\frac{g_{m3}}{C_1 + C_L} \quad \textbf{(LHP)}$$
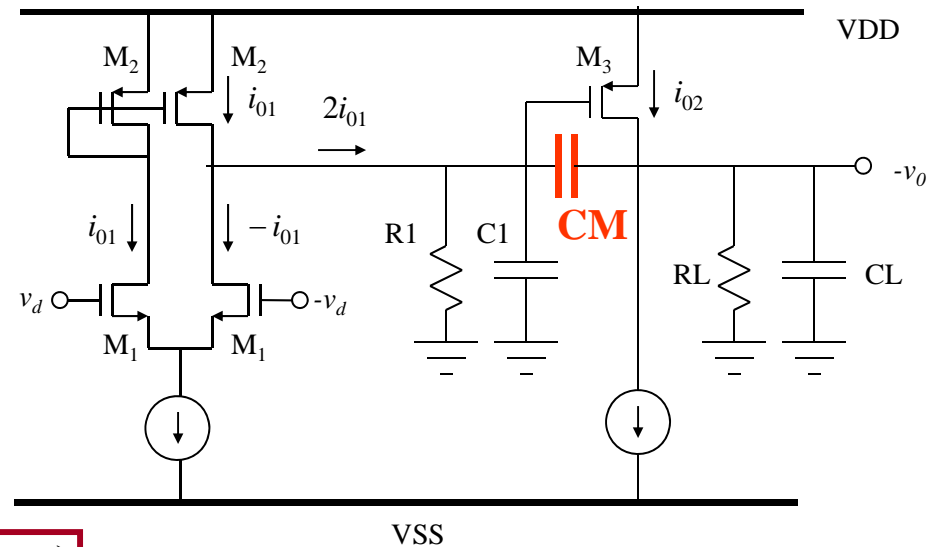
$$GBW' = (A_{VDC})*\left|\omega_{p1}\right| \cong \frac{g_{m1}}{C_M}$$

$$Phase\_m\arg in = 180 - \tan^{-1}\left(\frac{GBW'}{\omega_{p1}}\right) - \tan^{-1}\left(\frac{GBW'}{\omega_{p2}}\right) - \tan^{-1}\left(\frac{GBW'}{\omega_{ZERO}}\right)$$
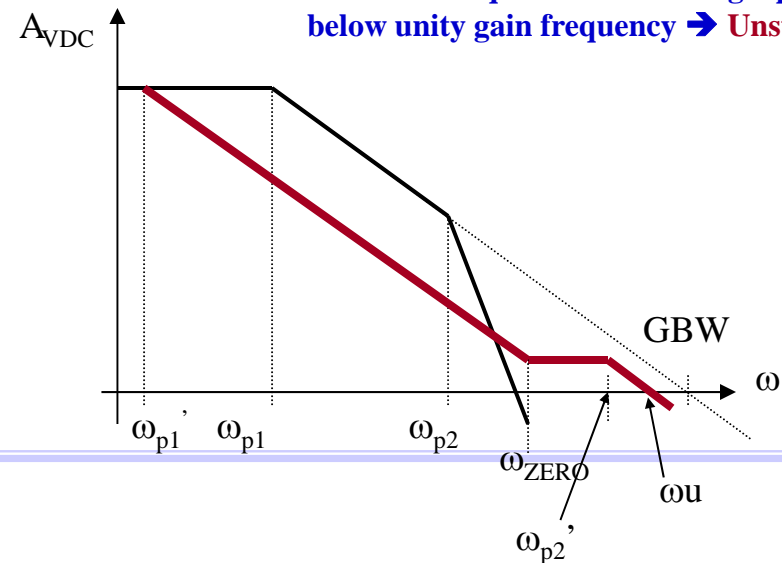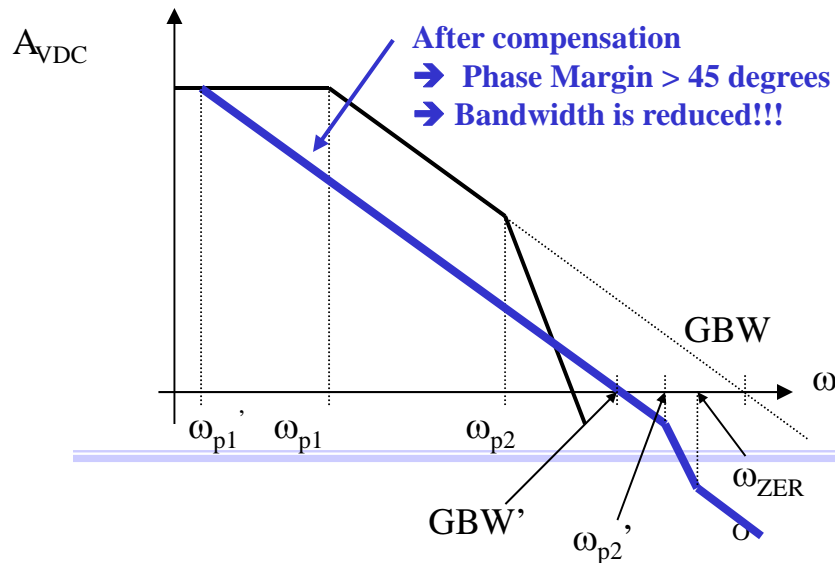
After compensation
➔ **Phase Margin > 45 degrees**
➔ **Bandwidth is reduced!!!**

- 7 -

☞ **Parasitic (bad) RHP zero!!**

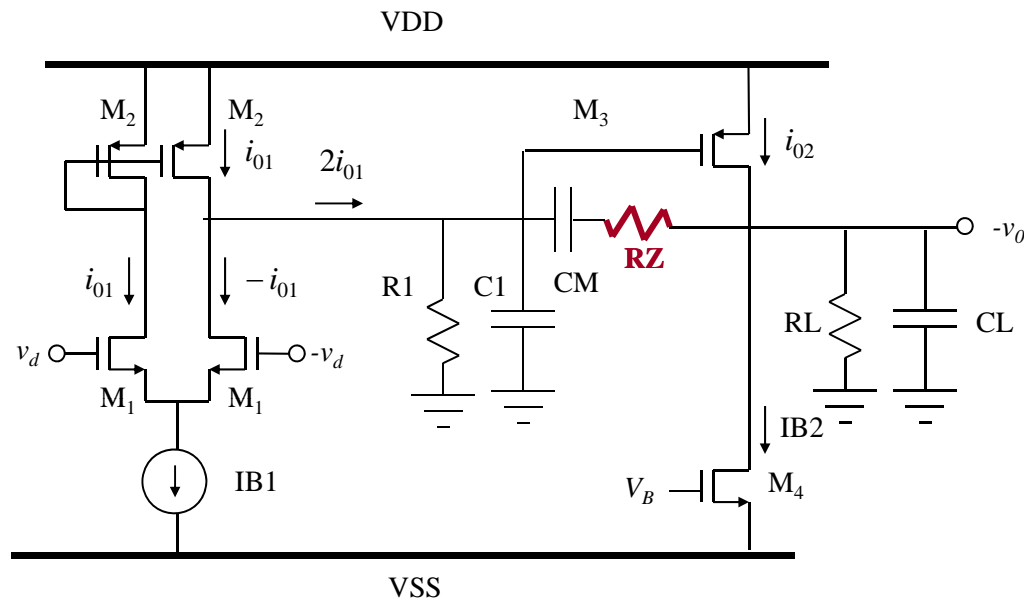☞ **Can be catastrophic if close or below wu!**

$$\omega_{ZERO} = \frac{g_{m3}}{C_M}$$

$$\text{Phase\_margin} = 180 - \tan^{-1}\left(\frac{\omega_u}{\omega_{p1}'}\right) - \tan^{-1}\left(\frac{\omega_u}{\omega_{p2}'}\right) - \boxed{\tan^{-1}\left(\frac{\omega_u}{\omega_{ZERO}}\right)}$$

After compensation
→ **Phase Margin << 45 degrees**
→ **Phase is equivalent to having 3 poles below unity gain frequency → Unstable!**

After compensation
→ **Phase Margin > 45 degrees**
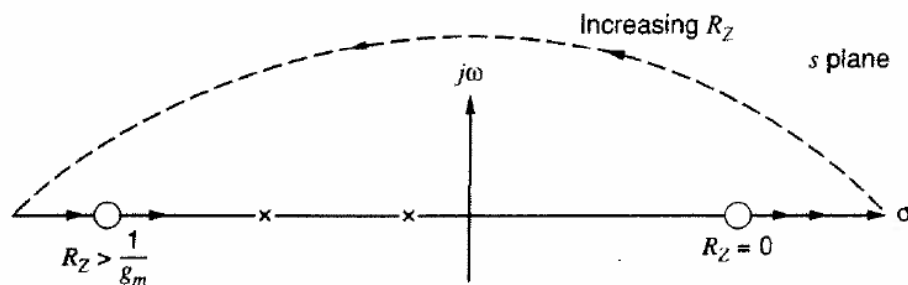→ **Bandwidth is reduced!!!**

Adding a series resistance

VDD

$$A(s) = \frac{A_{VDC}\left(1 - \dfrac{s}{\omega_z}\right)}{\left(1 + \dfrac{s}{\omega_{p1}}\right)\left(1 + \dfrac{s}{\omega_{p2}}\right)\left(1 + \dfrac{s}{\omega_{p3}}\right)}$$

$\omega_{p3} \approx -\dfrac{1}{R_Z C_1}$ (Generally high frequency & can be ignored)

$$\boxed{\omega_z = \frac{1}{\left(\dfrac{1}{g_{m3}} - R_Z\right)C_M}}$$

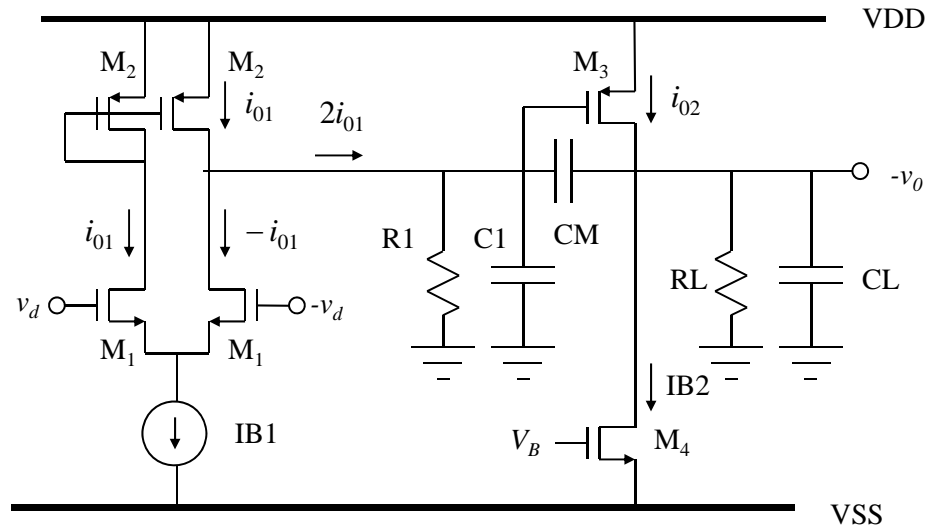**Can design R_Z to improve phase margin**

Non - zero R_Z will push RHP to a higher frequency (initially)

$R_Z = \dfrac{1}{g_{m3}}$ **pushes the RHP zero to infinity**

$R_Z > \dfrac{1}{g_{m3}}$ **pushes zero from RHP to LFP**

$R_Z = \dfrac{C_L + C_M + C_1}{g_{m3} C_M}$ **can cancel ω_{p2}**

◆**Spectral noise density at low frequencies (capacitors are neglected)**

$$i_{eq\_out}{}^2 = \frac{8kT}{3}\left[(2g_{m1}+2g_{m2})\left(\frac{g_{m3}}{g_1}\right)^2 + g_{m3} + g_{m4}\right]$$

Output referred current noise density

$$v_{eq\_in}{}^2 = \frac{i_{eq\_out}{}^2}{\left(\dfrac{g_{m1}g_{m3}}{g_1}\right)^2} = \frac{8kT}{3g_{m1}}\left[2 + 2\frac{g_{m2}}{g_{m1}} + \frac{g_{m3}+g_{m4}}{g_{m1}\left(\dfrac{g_{m3}}{g_1}\right)^2}\right]$$

Input referred voltage noise density

OPAMP Characterization

Main parameters to be measured:

- **DC gain (10^4-10^6) V/V)**
- **Frequency Limitations**
  - **Bandwith (Few Hertz~1kHz)**
  - **Gain-Bandwidth product (1~100 Mhz)**
- **Output resistance**
- **Input Impedance**
- **Signal Swing**
  - **Common-mode input range**
  - **Output swing**
- **Stability**
- **DC Offset**
- **Slew-rate**
- **CMRR**
- **PSRR**

For this section, see:
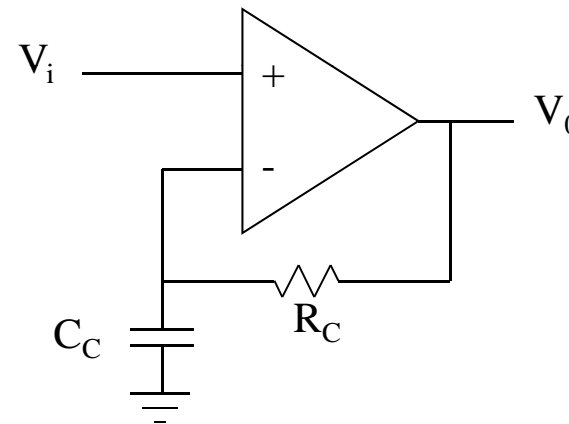**CMOS Analog design, Allen & Holberg 2nd edition, HPR, 2002.**

OPAMP Characterization

DC gain $(10^4\text{-}10^6)$ V/V) :

How to measure/characterize it?

•**Very difficult to measure in open-loop due to DC offsets.**

•**Stabilize for DC**

$V_0 \neq 0$
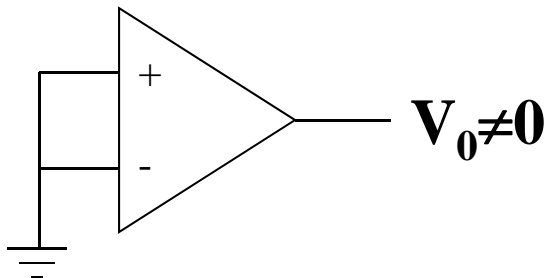
•**For DC, the OPAMP operates in closed loop!!**

•**For frequencies higher than $1/R_C C_C$, the OPAMP operates in open-loop with a grounded load given by R_C.**
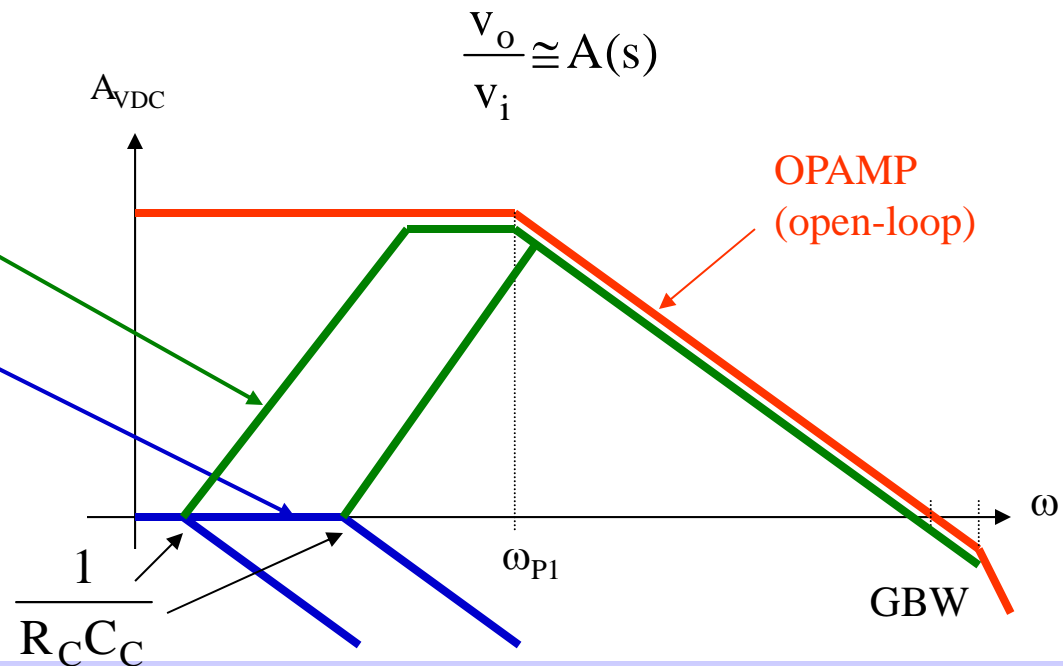
OPAMP: DC Characterization

V_i ──── + A(s) ──── V_0 ─

C_C R_C
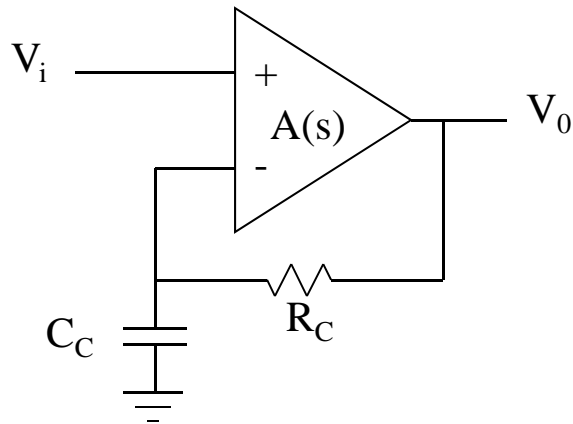
How to measure/characterize it?

•At DC

$$\frac{v_o}{v_i} = \frac{A(s)}{1+A(s)} \cong 1$$

•If A(s)B(s) <<1 then the measured gain is dominated by the OPAMP transfer function!

$$\frac{v_o}{v_i} = \frac{A(s)}{1+A(s)B(s)}$$
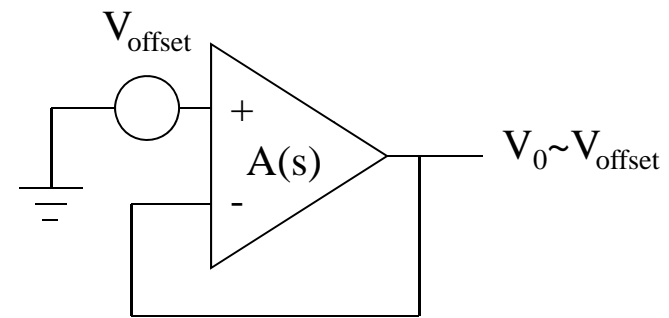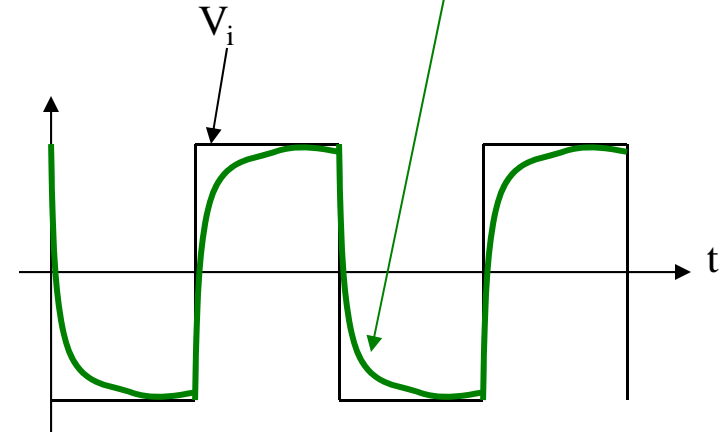
$$B(s) = \frac{\dfrac{1}{sC_C}}{R_C + \dfrac{1}{sC_C}} = \frac{1}{1+sR_CC_C}$$
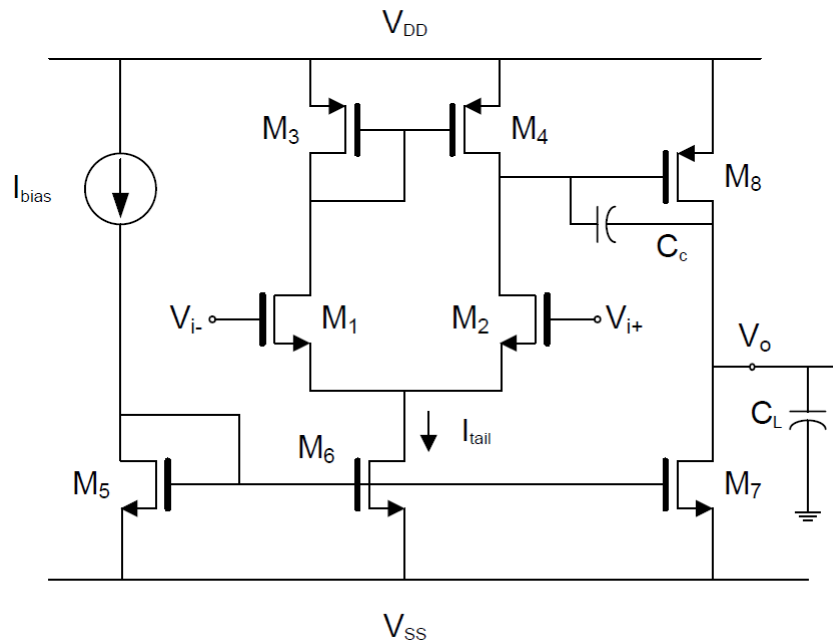
$$\boxed{\omega_{P1} > \left[A_{DC}\right]\left[\frac{1}{R_CC_C}\right]}$$

$$\frac{v_o}{v_i} \cong A(s)$$
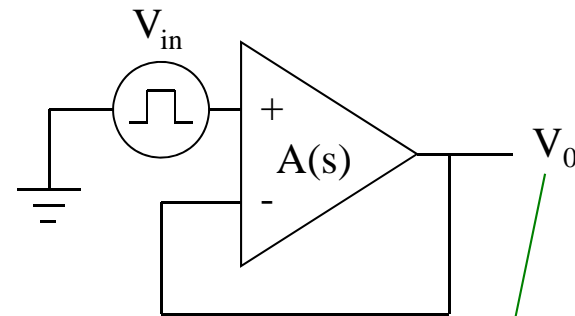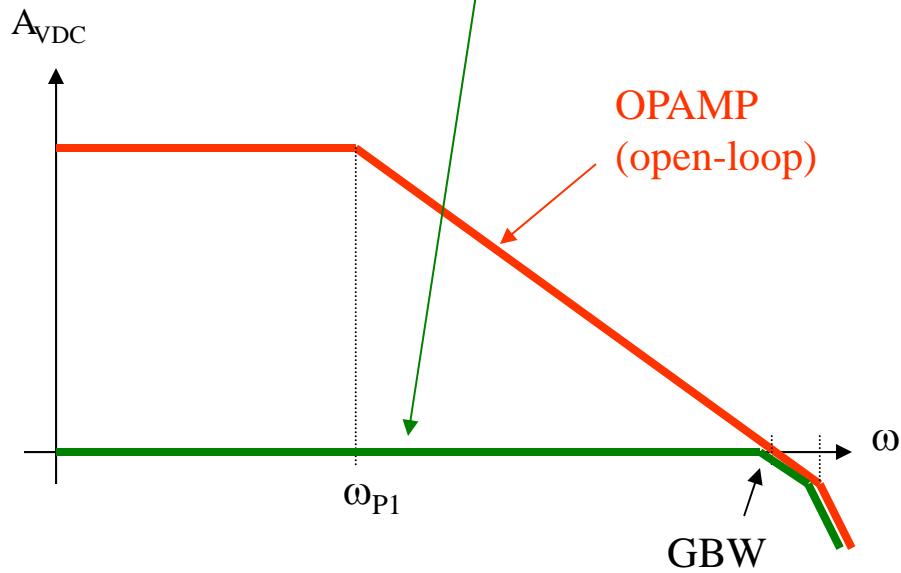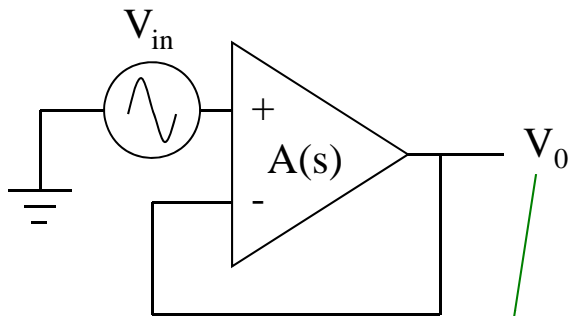
A_{VDC}

OPAMP (open-loop)

ω_{P1}

$\dfrac{1}{R_CC_C}$
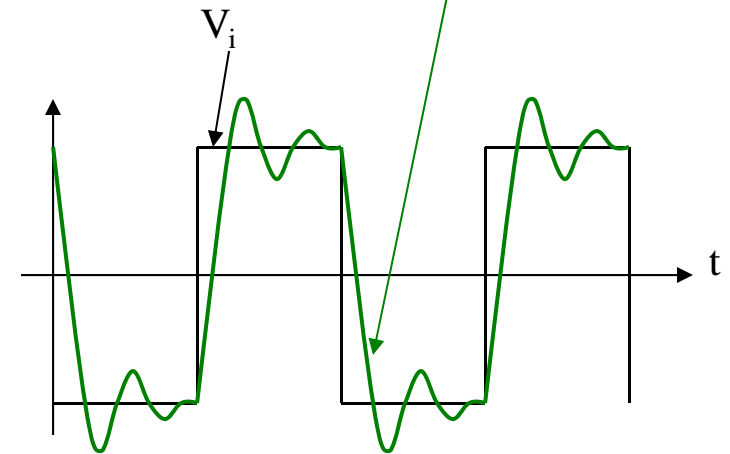
ω

GBW

OPAMP Characterization

DC Offset

$V_0 \sim V_{offset}$

OPAMP Characterization: GBW and stability

V_{in}

$+$

$A(s)$

$-$

V_0

A_{VDC}

OPAMP
(open-loop)

ω

ω_{P1}

GBW

V_{in}

$+$

$A(s)$

$-$

V_0

V_i

t

Enough phase margin

OPAMP Characterization: GBW and stability

A_{VDC}

OPAMP
(open-loop)
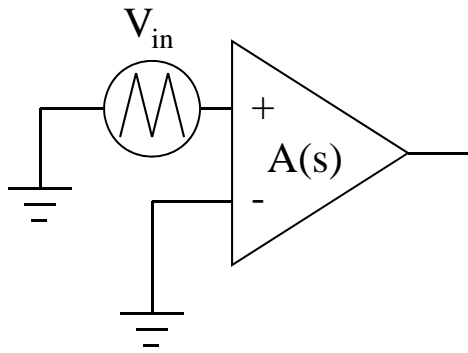
ω_{P1}

ω

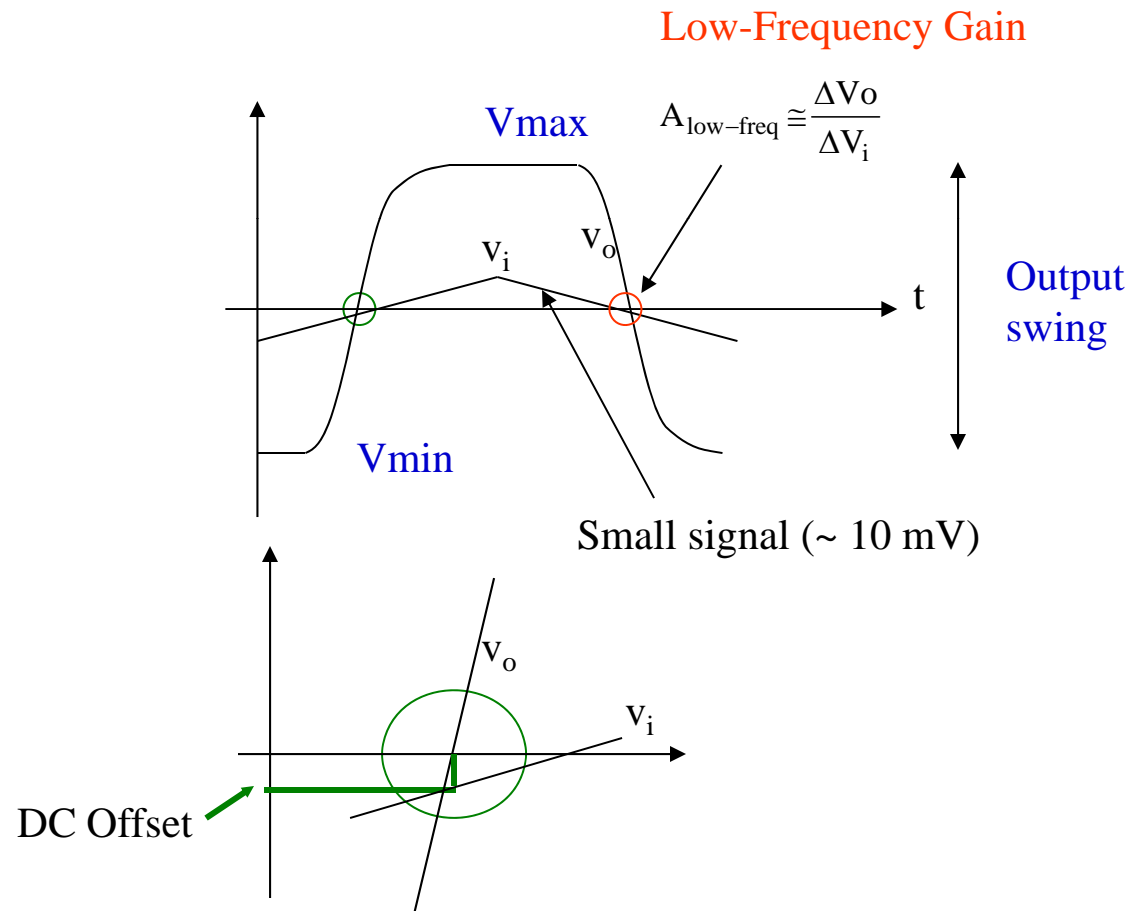V_i

t
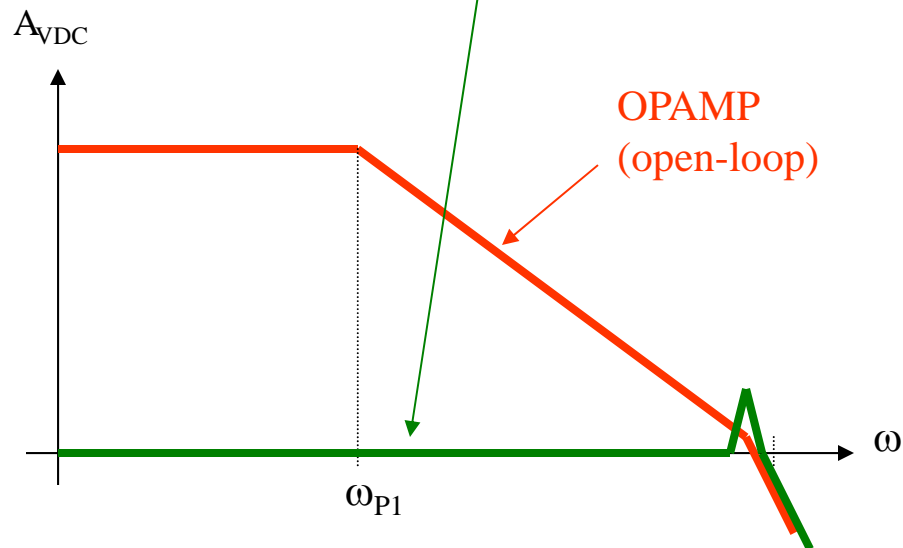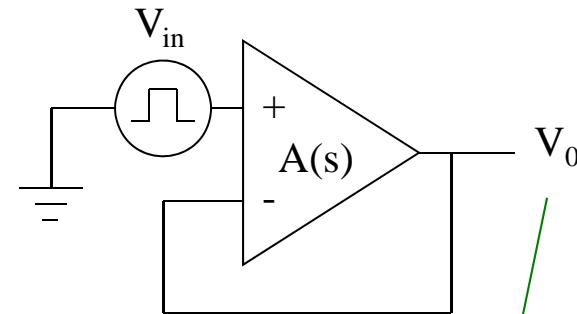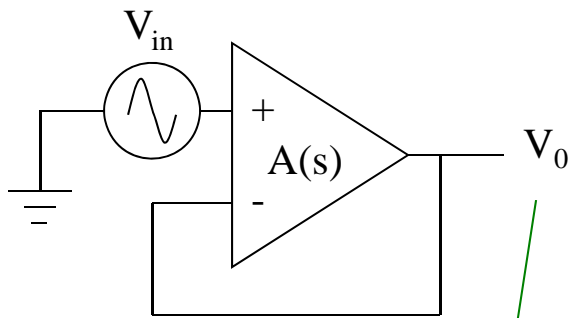
Not enough phase margin

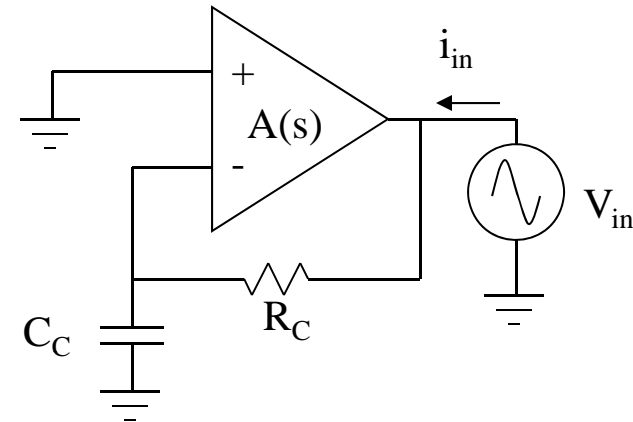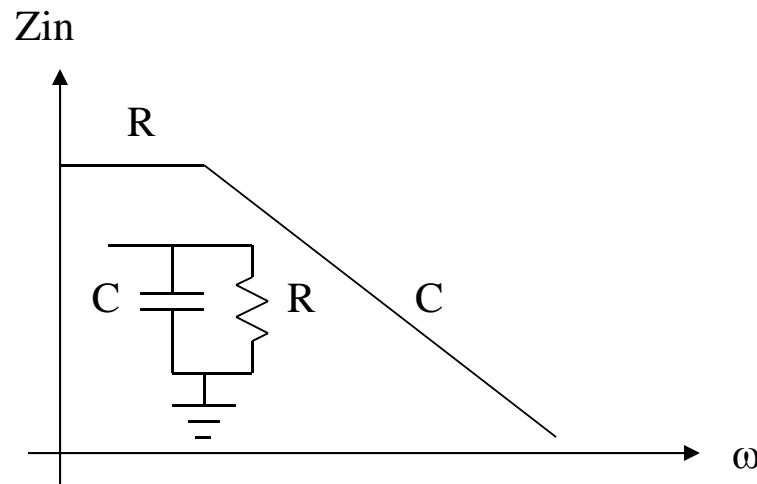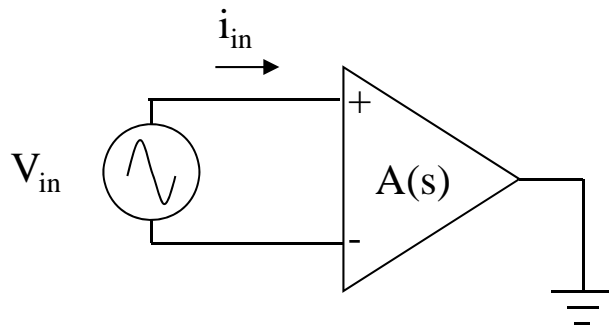# OPAMP Characterization: Slew-Rate (max speed)
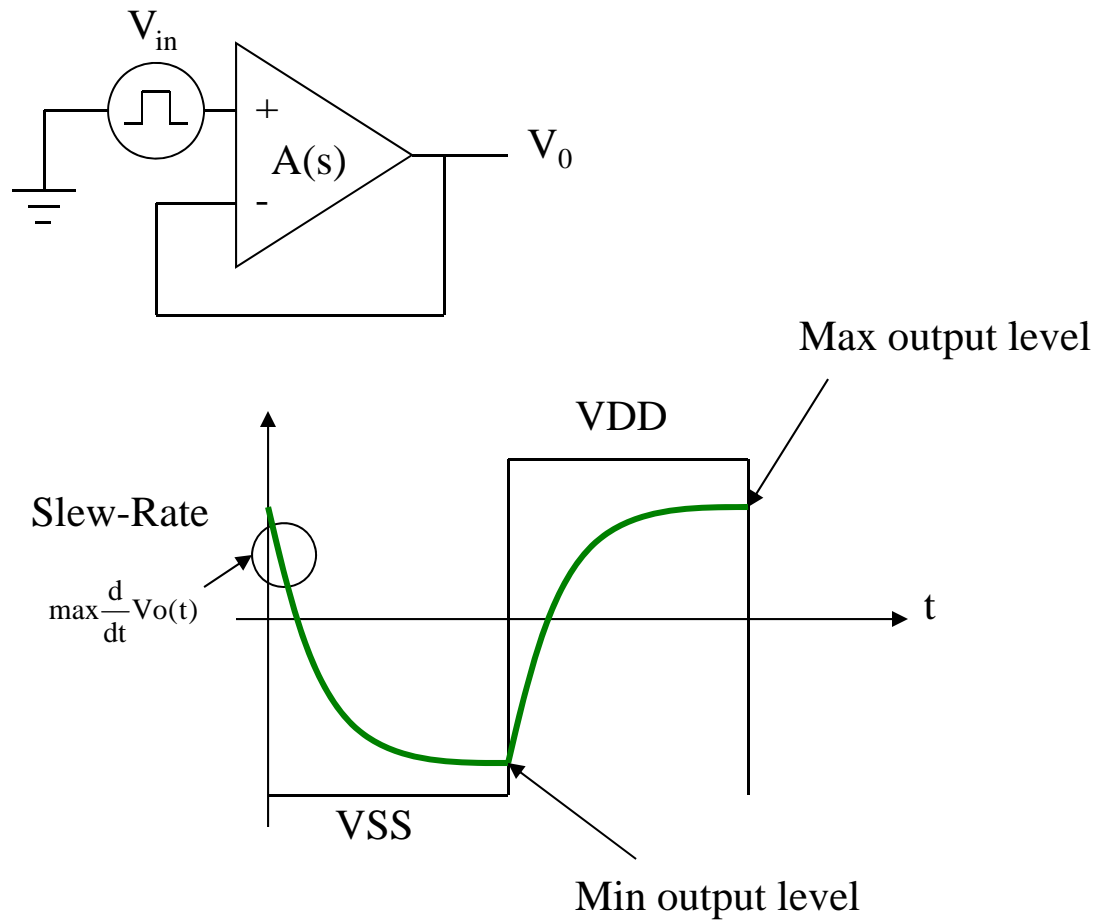
OPAMP Characterization: Output Swing

V_{in}

A(s)

+

-

Use a slow triangular input signal such that the raising and falling edges are not determined by slew rate limitations

Low-Frequency Gain

$$A_{low-freq} \cong \frac{\Delta Vo}{\Delta V_i}$$

Vmax

v_i

v_o

t

Output swing

Vmin

Small signal (~ 10 mV)

v_o

v_i

DC Offset

OPAMP Characterization: Input and Output impedance

R_C and C_C as large as possible!!

At Low frequencies:
$Z_{measured} \neq Z_o$ (Why????)

At medium frequencies:
$Z_{measured} = Z_o \| R_C$

Be sure that the OPAMP (all internal transistors) is properly biased during characterization!!

Next Time

- OpAmp Feedback & Stability
- Common-Mode Feedback Techniques