

# ECEN474: (Analog) VLSI Circuit Design

## Fall 2010

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### Lecture 18: Two Stage Miller OTA



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# Announcements

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- HW4 Due Now
- HW5 assigned today and due Friday 10/29 (5:00PM)
- Exam 2 Wednesday Nov 3 9:10-10:10AM
  - Material through Lecture 17
  - Will post some reference exams this weekend

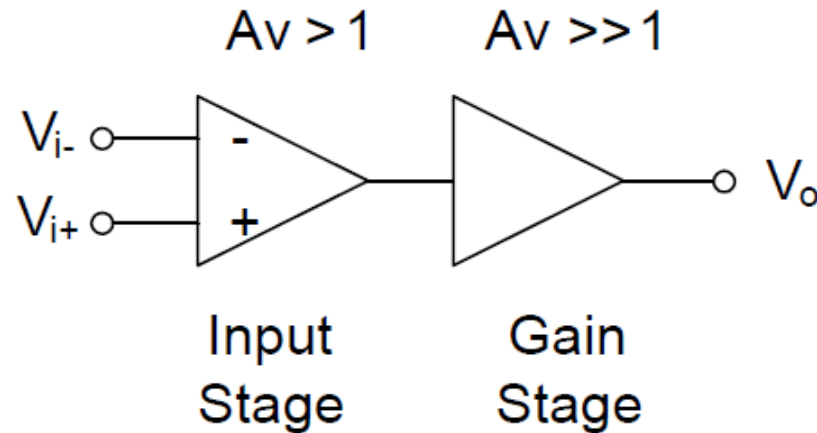
# Agenda

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- Two Stage Miller OTA
- OpAmp Characterization

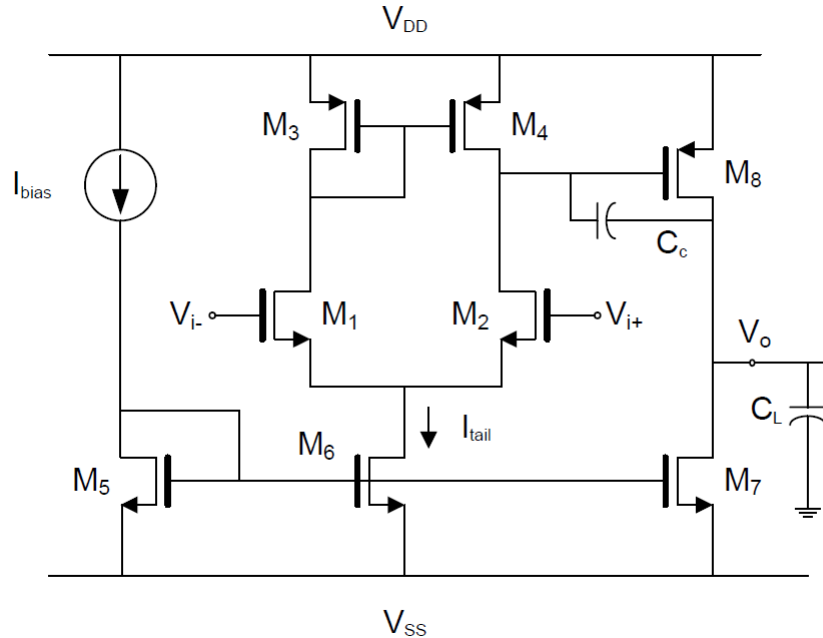
# Multi-Stage Amplifiers

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- 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

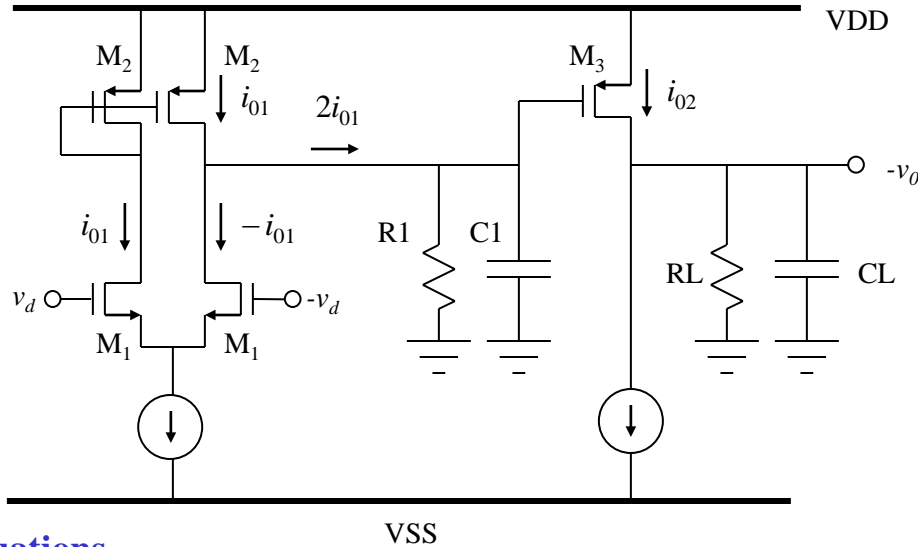


$$\text{DC Gain } A_{VDC} = A_{v1}A_{v2} = \left( -\frac{g_{m2}}{g_{o2} + g_{o4}} \right) \left( -\frac{g_{m8}}{g_{o8} + g_{o7}} \right) = \frac{g_{m2}g_{m8}}{(g_{o2} + g_{o4})(g_{o8} + g_{o7})}$$

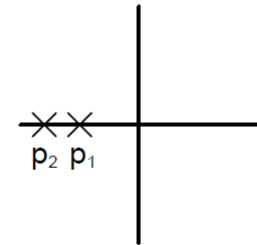
$$A_{VDC} = G_m R_{out}$$

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

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



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



↓ Main equations

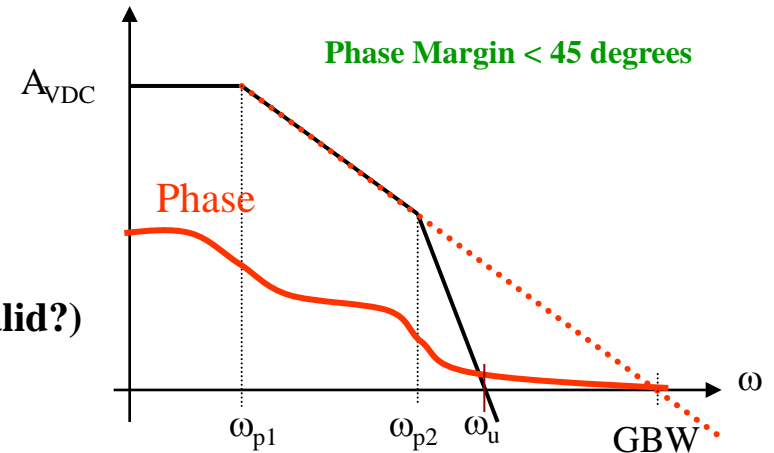
$$A_{VDC} = -\frac{g_{m1} g_{m3}}{g_1 g_L}$$

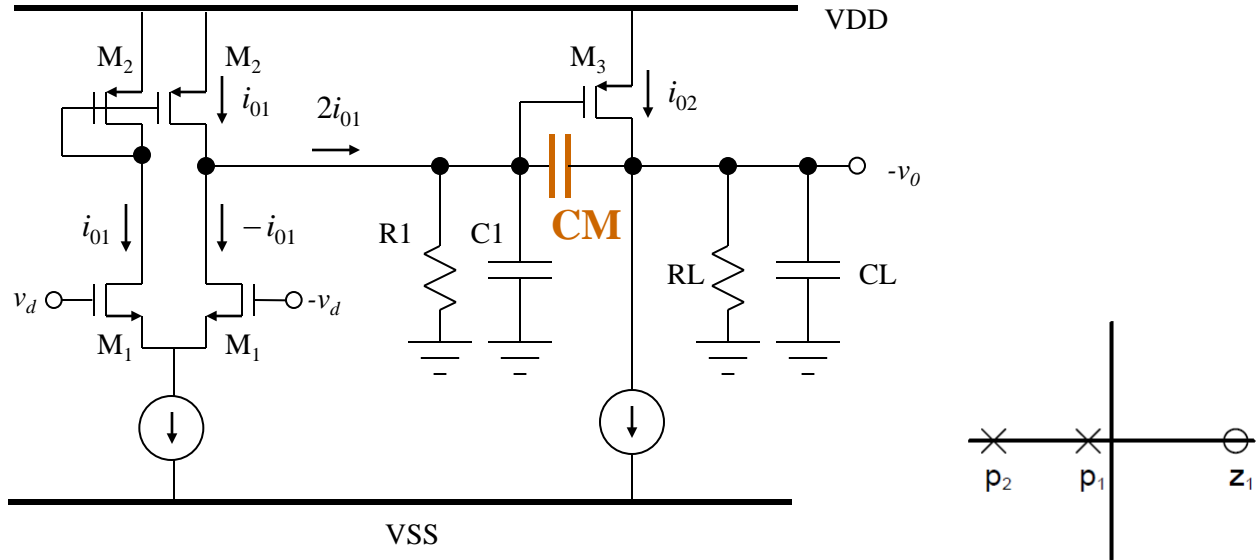
$$\omega_{p1} = -\frac{g_1}{C_1} \text{ (LHP)}$$

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

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

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





$$A_{VDC} = -\frac{g_{m1}}{g_1} \frac{g_{m3}}{g_L}$$

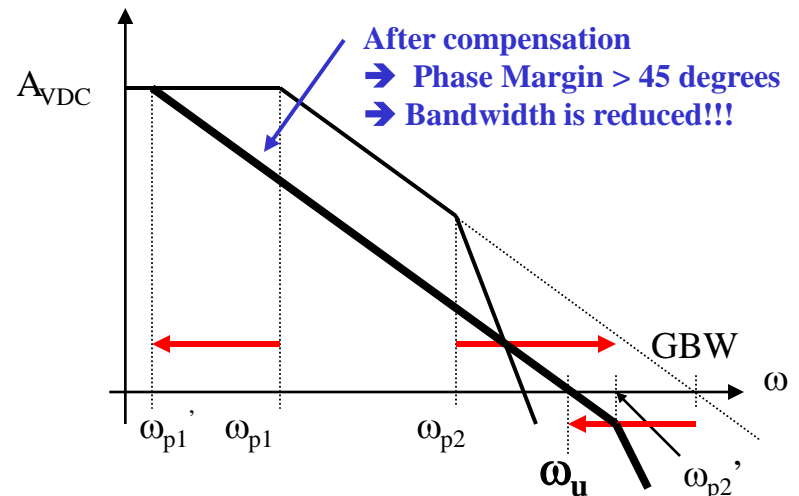
**Phase compensation → Pole splitting techniques!!**

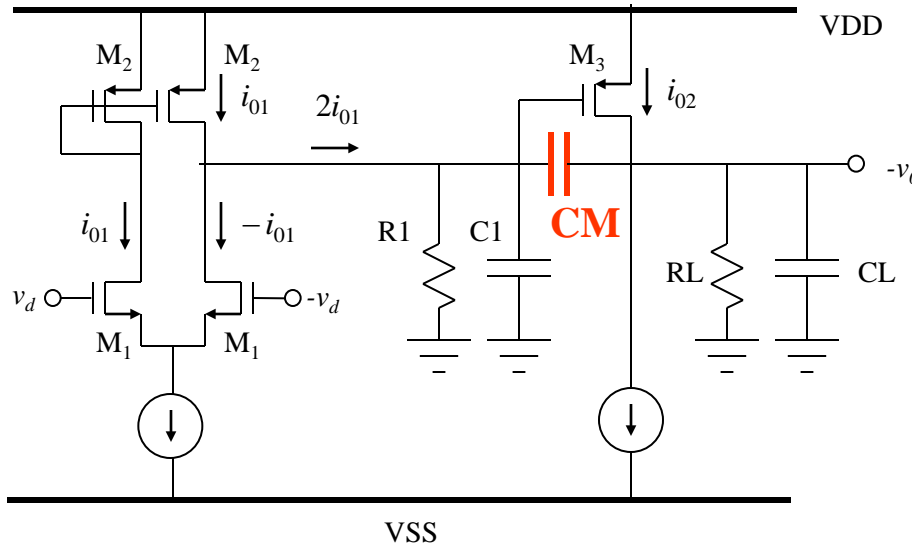
$$\omega_{p1} = -\frac{g_1}{C_1 + \frac{g_{m3}}{g_L} C_M} \quad (\text{LHP})$$

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

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

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





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

☞ **Parasitic (bad) RHP zero!!**

$$\omega_{ZERO} = + \frac{g_{m3}}{C_M} \text{ (RHP)}$$

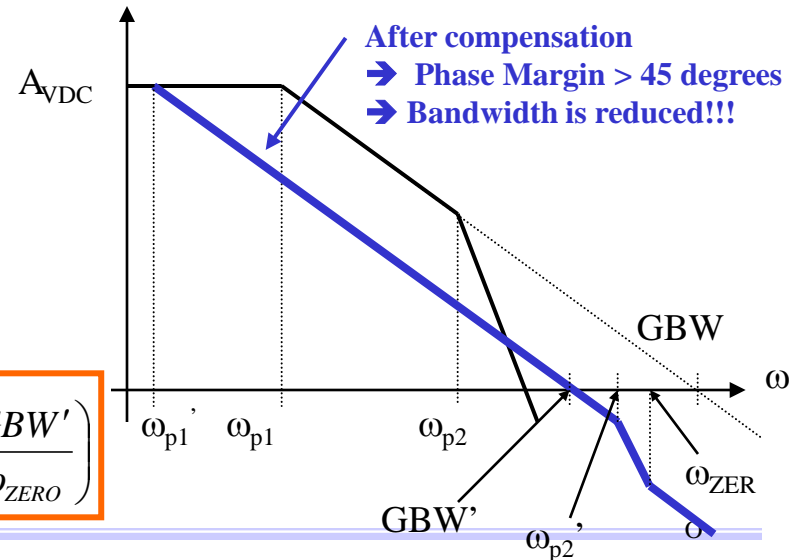
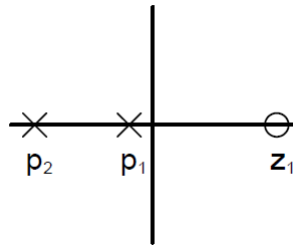
$$A_{VDC} = - \frac{g_{m1}}{g_L} \frac{g_{m3}}{g_L}$$

$$\omega_{p1} = - \frac{g_{m1}}{C_1 + \frac{g_{m3}}{g_L} C_M} \text{ (LHP)}$$

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

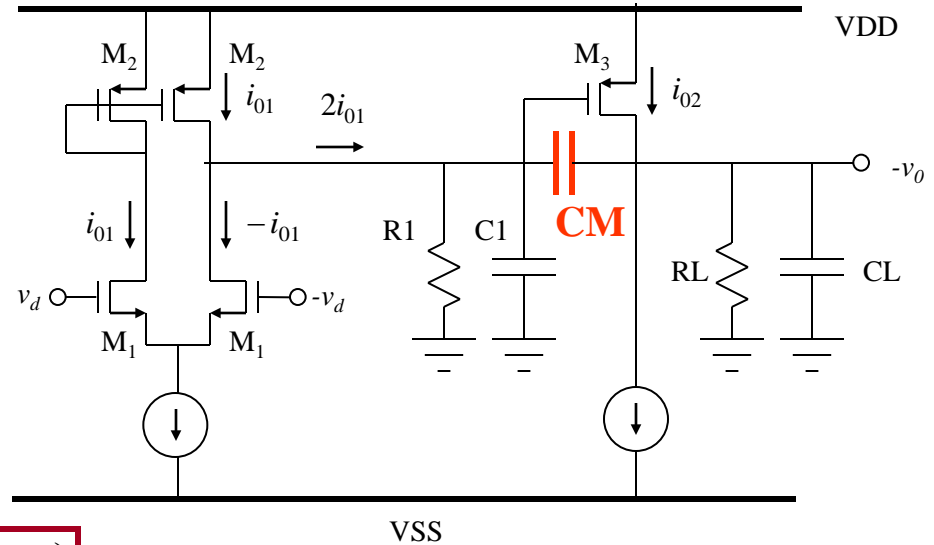
$$GBW' = (A_{VDC}) * |\omega_{p1}| \cong \frac{g_{m1}}{C_M}$$

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



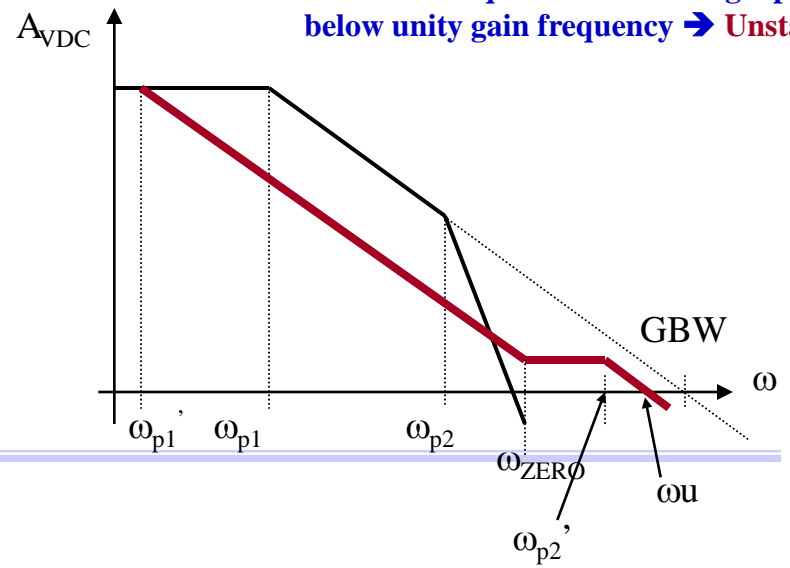
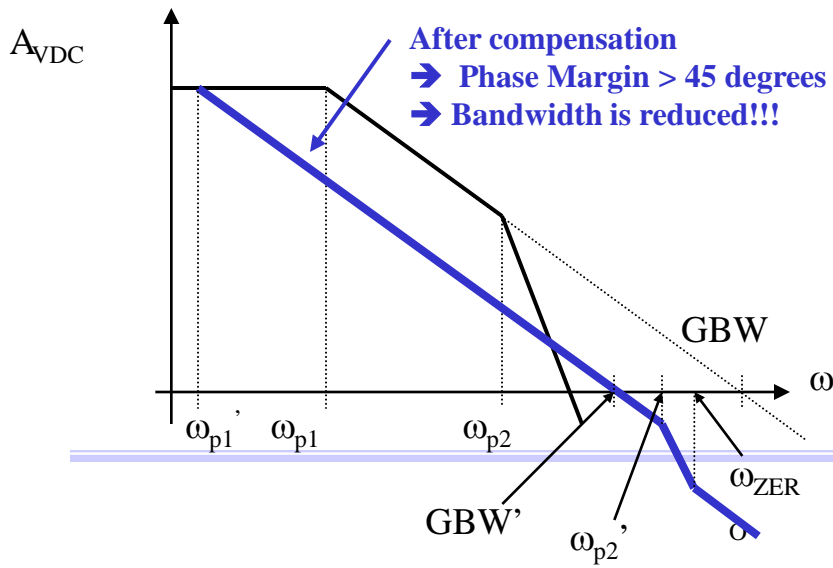
- ☞ **Parasitic (bad) RHP zero!!**
- ☞ **Can be catastrophic if close or below  $\omega_u$ !**

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

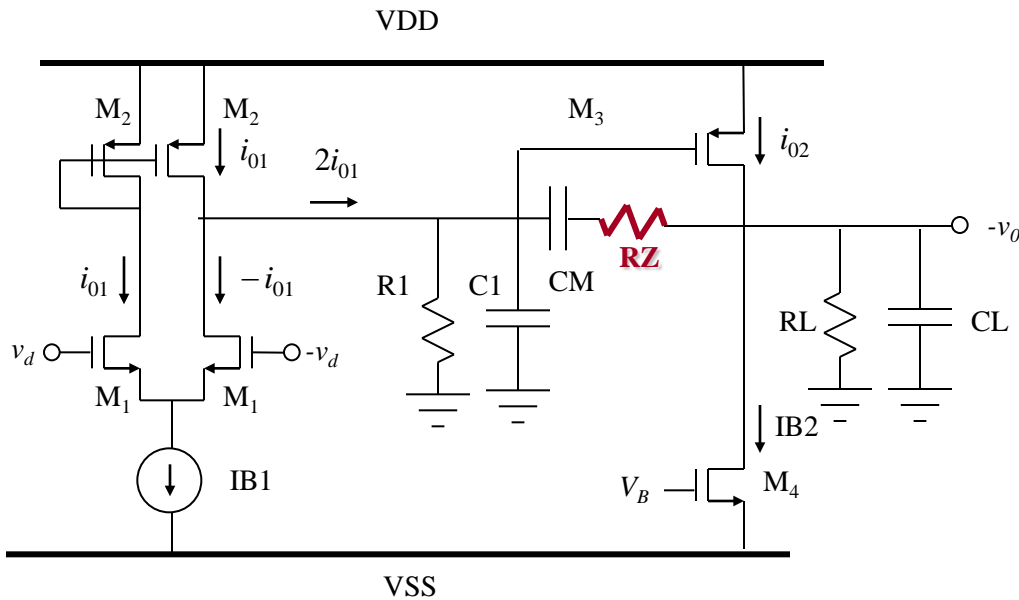


$$\text{Phase\_margin} = 180 - \tan^{-1}\left(\frac{\omega_u}{\omega_{p1}'}\right) - \tan^{-1}\left(\frac{\omega_u}{\omega_{p2}'}\right) - \tan^{-1}\left(\frac{\omega_u}{\omega_{ZERO}}\right)$$

- After compensation
- ➔ Phase Margin  $\ll 45$  degrees
  - ➔ Phase is equivalent to having 3 poles below unity gain frequency ➔ **Unstable!**



# Adding a series resistance



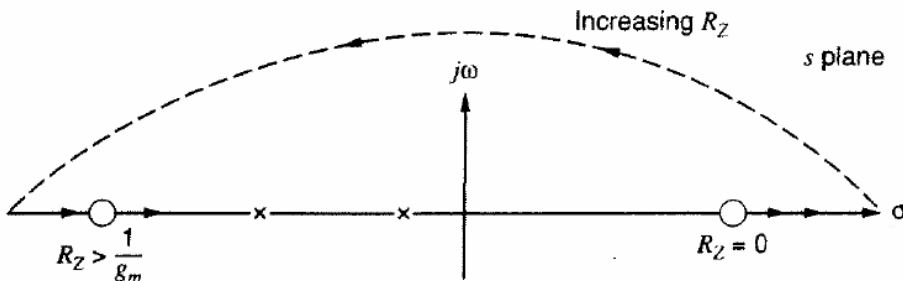
$$A(s) = \frac{A_{VDC} \left(1 - \frac{s}{\omega_z}\right)}{\left(1 + \frac{s}{\omega_{p1}}\right) \left(1 + \frac{s}{\omega_{p2}}\right) \left(1 + \frac{s}{\omega_{p3}}\right)}$$

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

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

**Can design  $R_Z$  to improve phase margin**

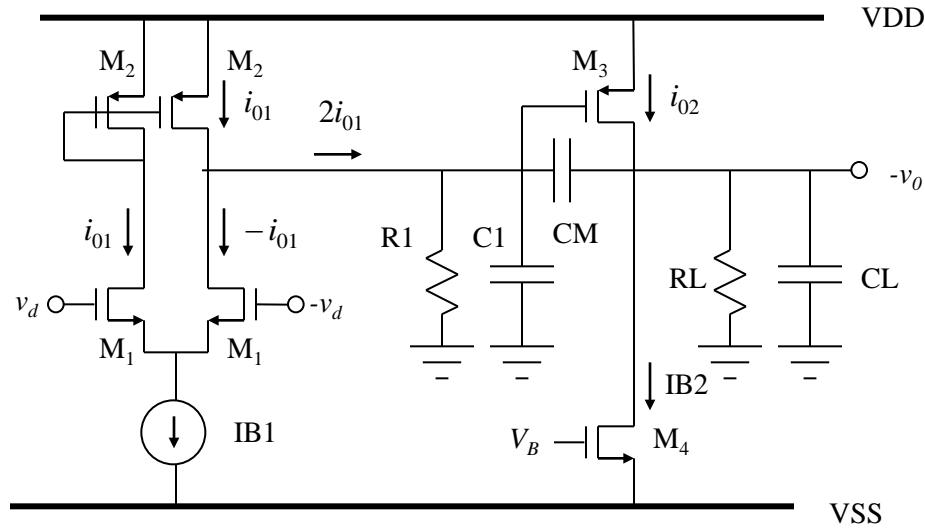
**Non - zero  $R_Z$  will push RHP to a higher frequency (initially)**



$$R_Z = \frac{1}{g_{m3}} \quad \text{pushes the RHP zero to infinity}$$

$$R_Z > \frac{1}{g_{m3}} \quad \text{pushes zero from RHP to LFP}$$

$$R_Z = \frac{C_L + C_M + C_1}{g_{m3} C_M} \quad \text{can cancel } \omega_{p2}$$



↓ 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

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

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

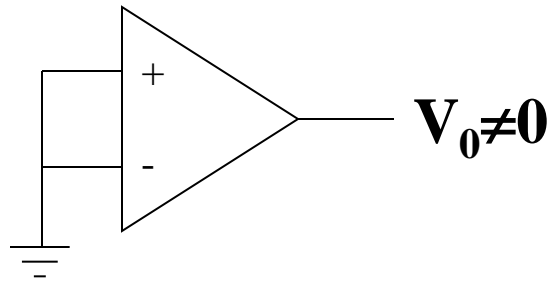
For this section, see:

**CMOS Analog design, Allen & Holberg  
2nd edition, HPR, 2002.**

# OPAMP Characterization

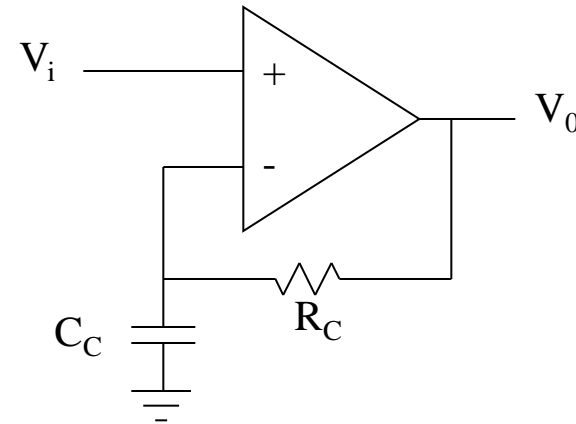
**DC gain ( $10^4$ - $10^6$ ) V/V) :**

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



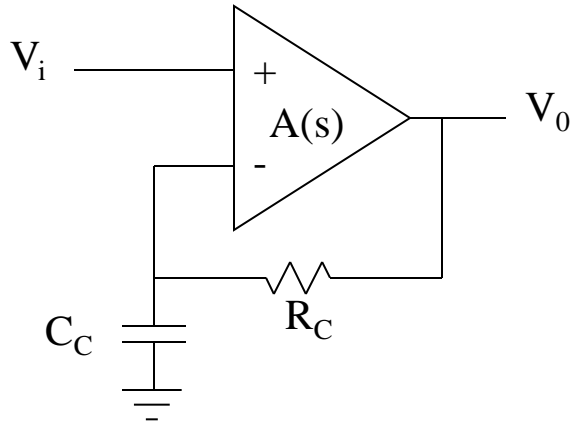
**How to measure/characterize it?**

- Stabilize for DC



- 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



How to measure/characterize it?

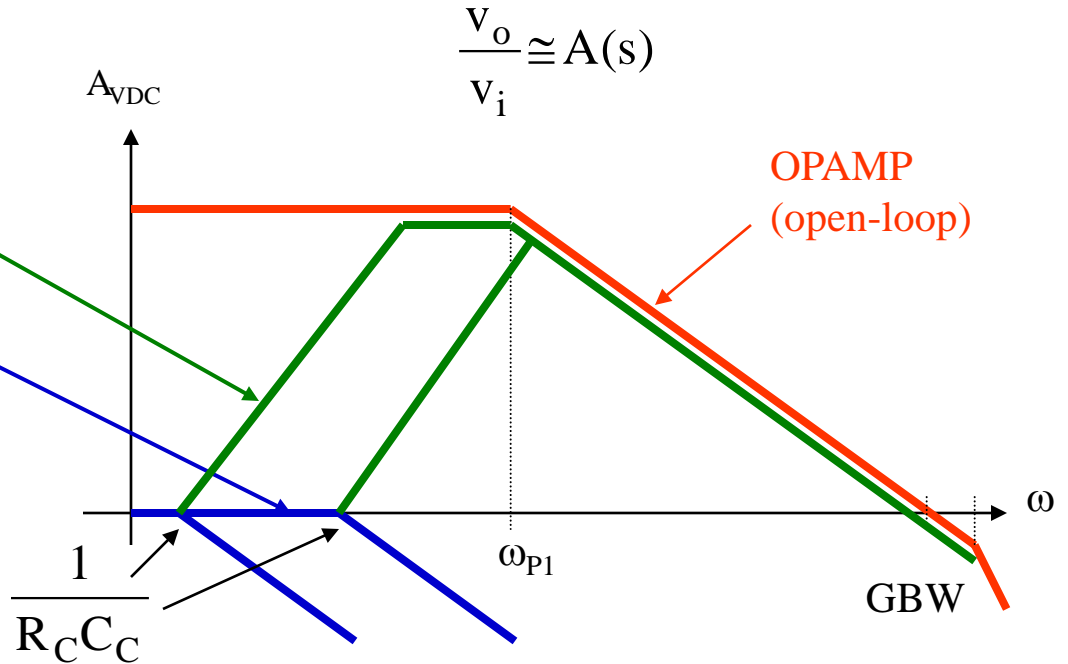
•At DC  $\frac{v_o}{v_i} = \frac{A(s)}{1+A(s)} \cong 1$

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

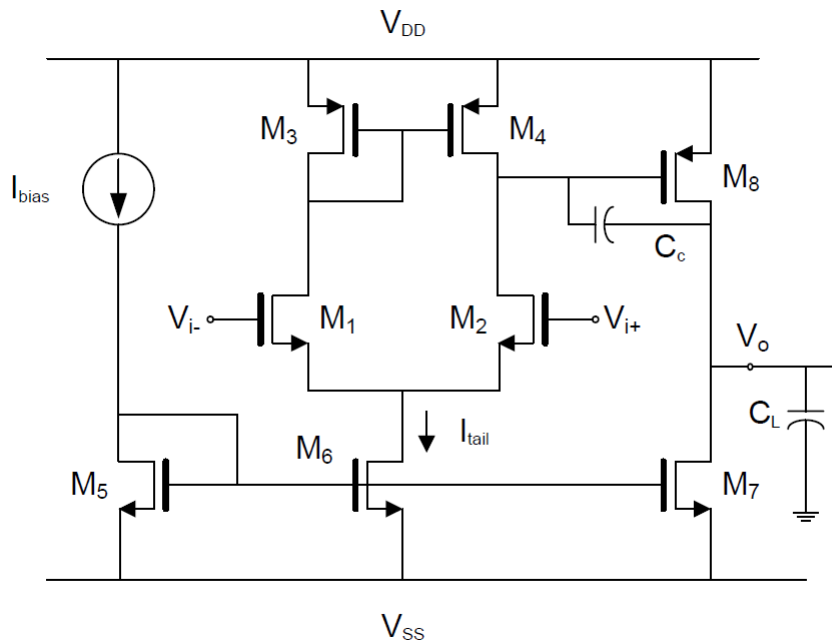
$$\frac{v_o}{v_i} = \frac{A(s)}{1+A(s)B(s)}$$

$$B(s) = \frac{1}{R_C + \frac{1}{sC_C}} = \frac{1}{1+sR_C C_C}$$

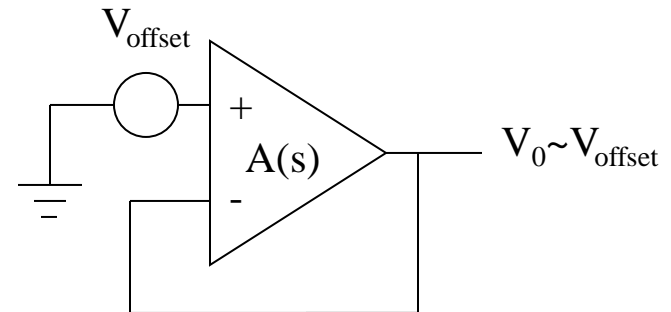
$$\omega_{PI} > [A_{DC}] \left[ \frac{1}{R_C C_C} \right]$$



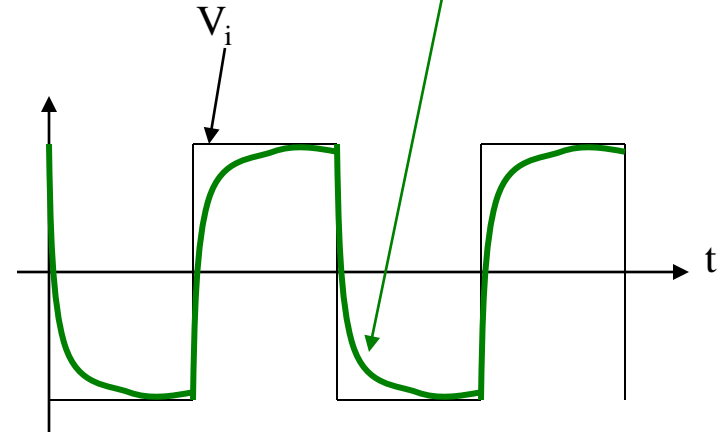
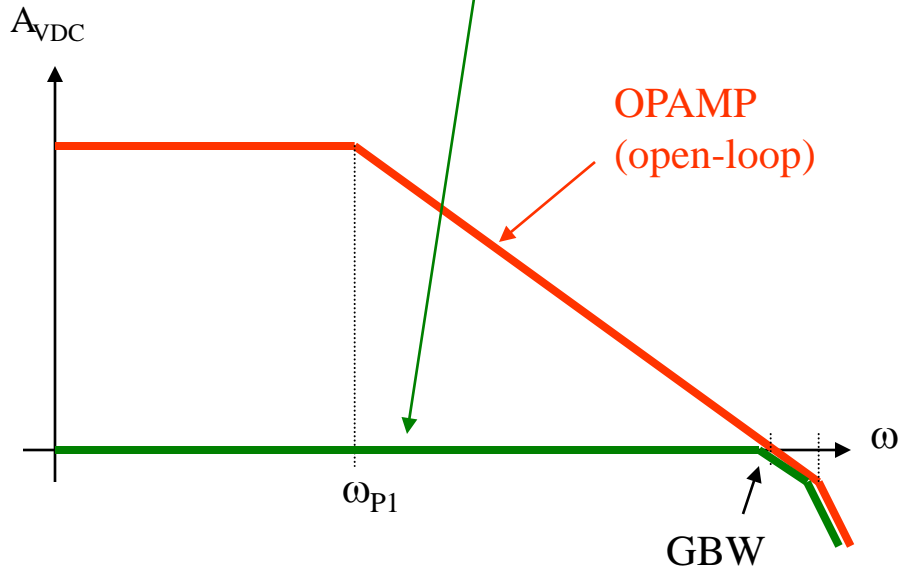
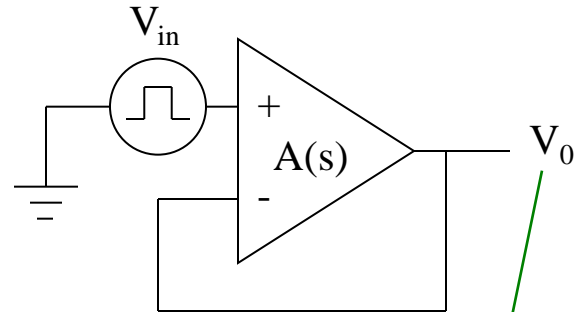
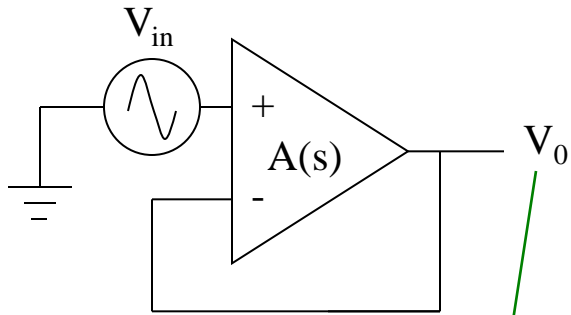
# OPAMP Characterization



## DC Offset

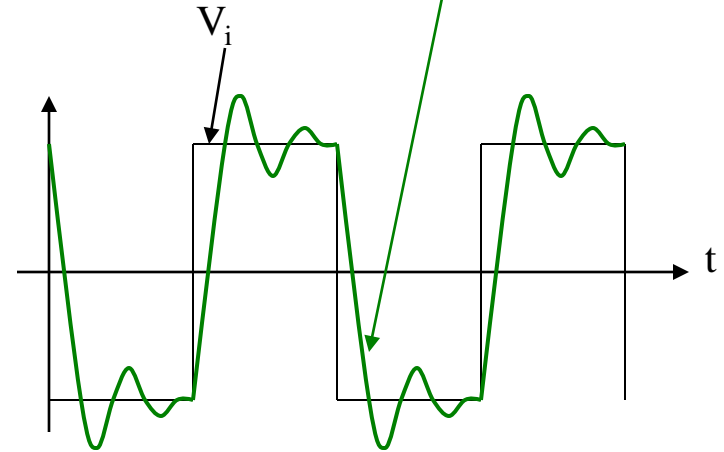
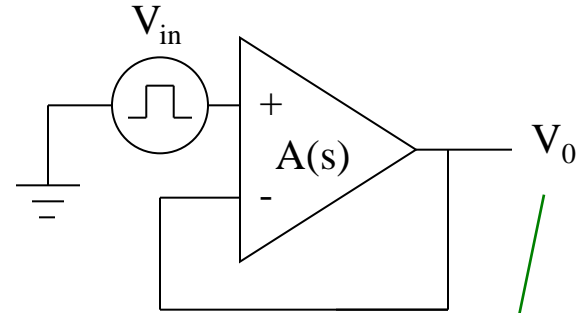
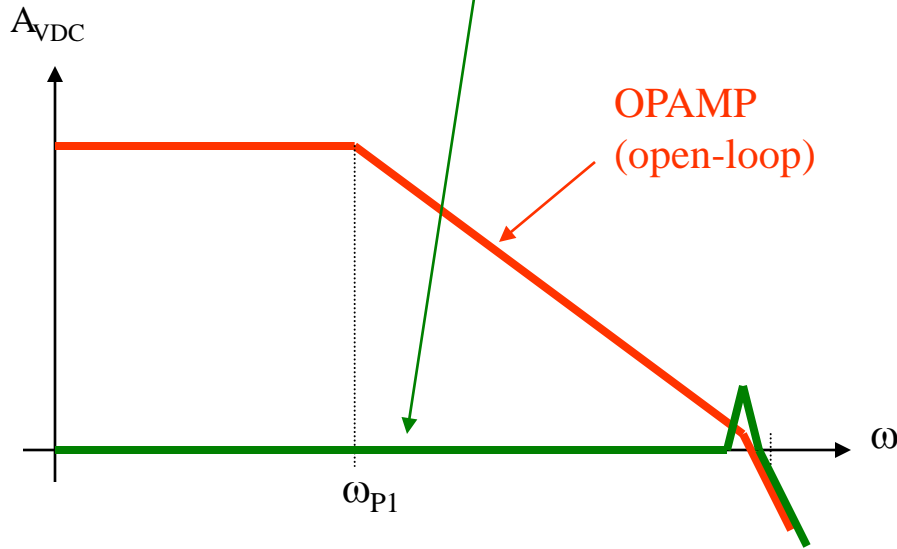
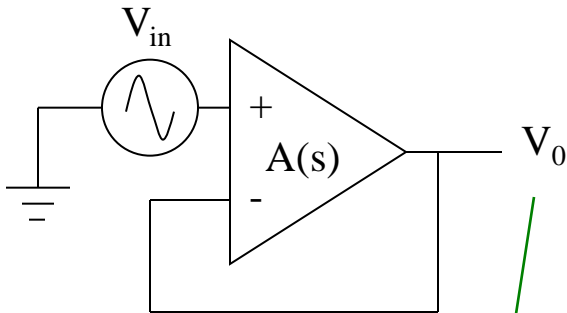


# OPAMP Characterization: GBW and stability



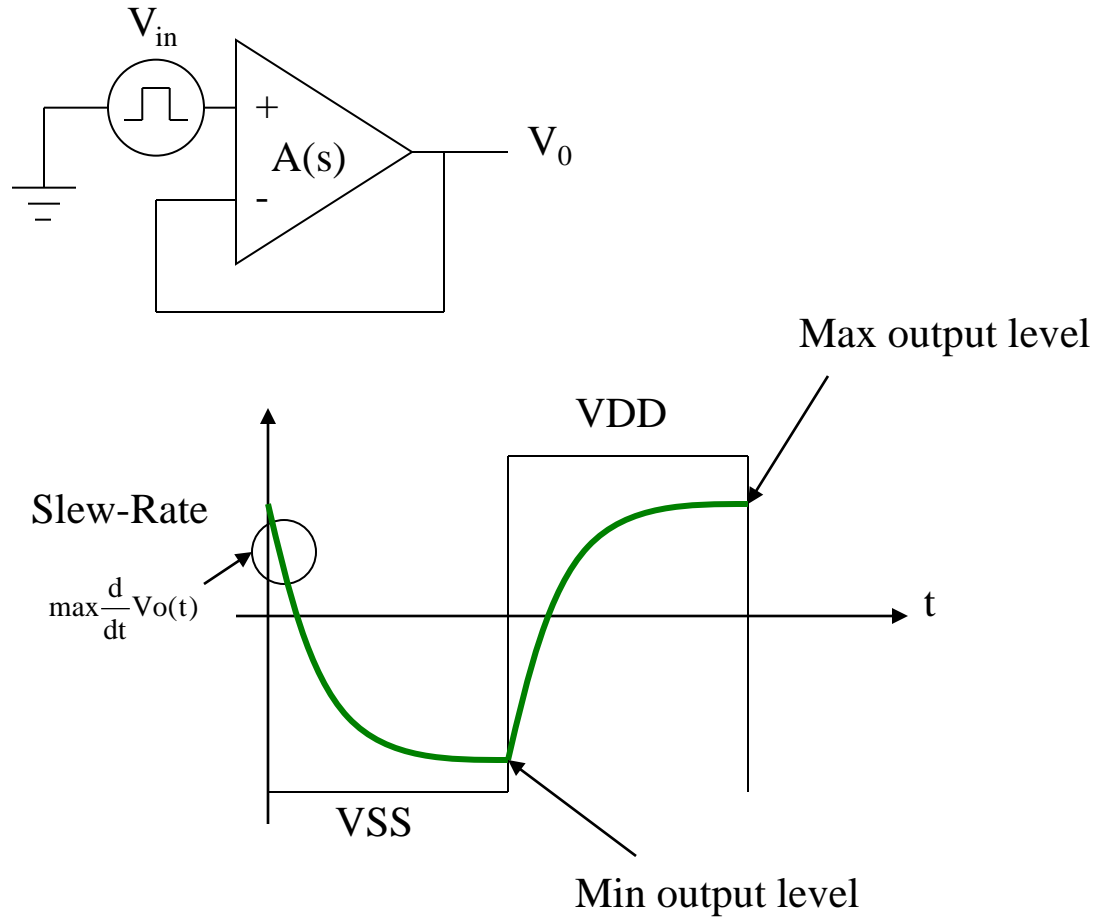
Enough phase margin

# OPAMP Characterization: GBW and stability

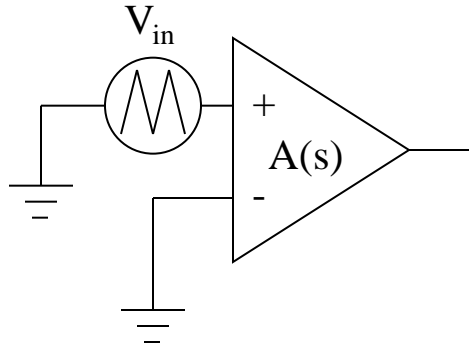


**Not enough phase margin**

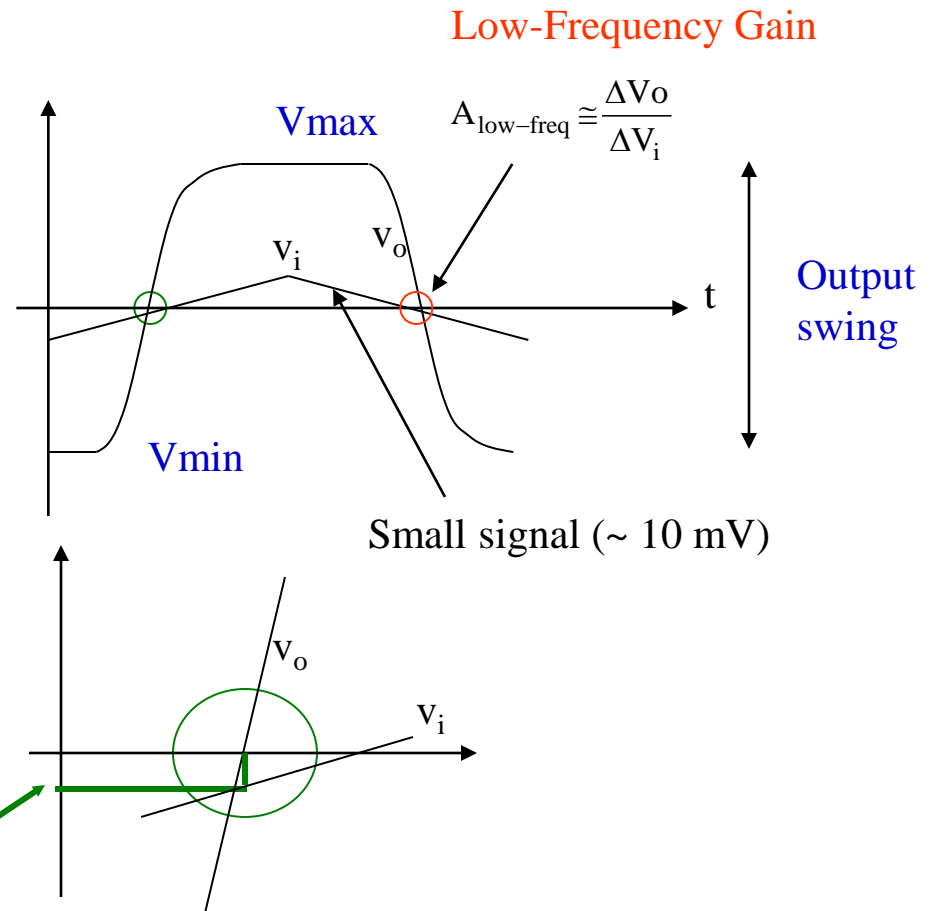
# OPAMP Characterization: Slew-Rate (max speed)



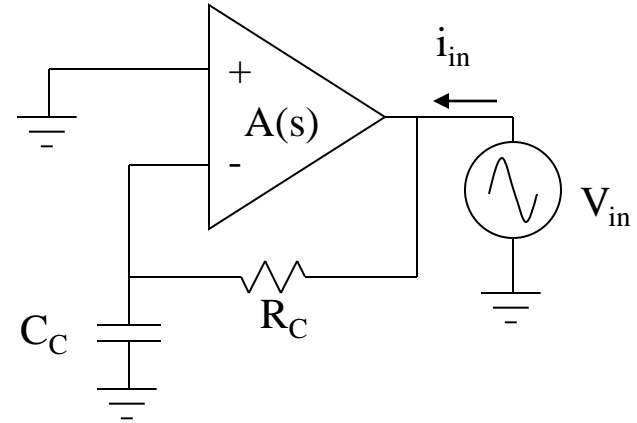
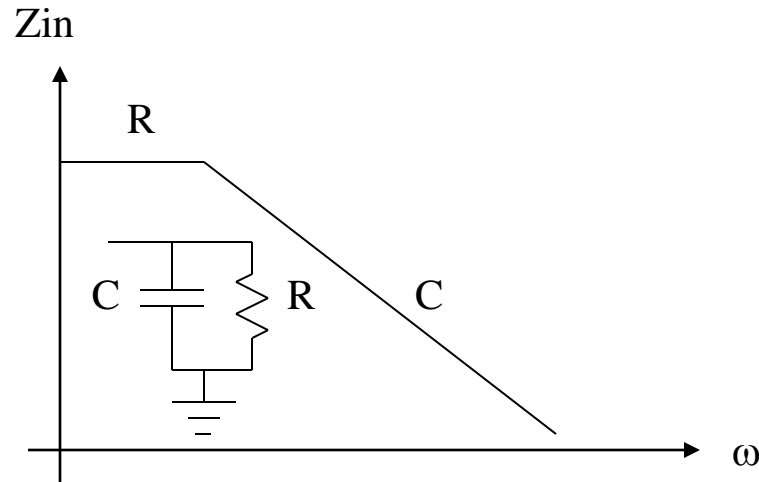
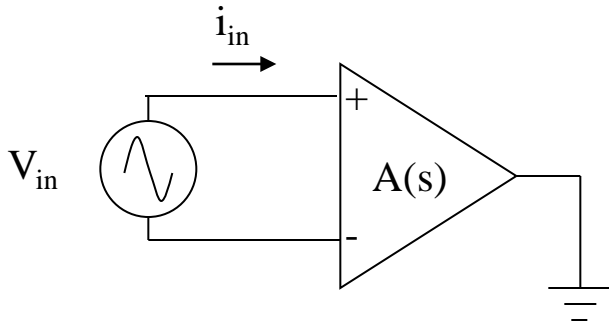
# OPAMP Characterization: Output Swing



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



# OPAMP Characterization: Input and Output impedance



$R_C$  and  $C_C$  as large as possible!!

At Low frequencies:

$$Z_{\text{measured}} \neq Z_o \text{ (Why????)}$$

At medium frequencies:

$$Z_{\text{measured}} = Z_o \parallel R_C$$

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

# Next Time

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- OpAmp Feedback & Stability
- Common-Mode Feedback Techniques