

# EE 435

## Lecture 17

Compensation of Feedback Amplifiers  
Two-Stage Op Amp Design Strategies

# Executive summary of Lecture 16

Thanks to Emile

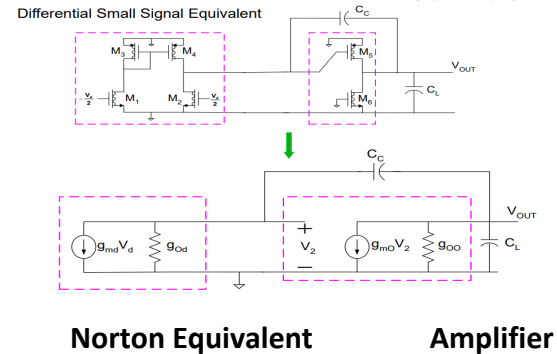
- Review of Compensation criteria: Obtained from  $0.5 < Q < 0.75$  →
- Internal Node Compensation General Case
- Miller Capacitor and Miller Compensation
- General Analysis of 2 stage amplifiers
- Miller Compensation Vs external Compensation

$$4\beta A_{OTOT} > k > 2\beta A_{OTOT}$$

$$A_{V0} = \left( \frac{g_{mF1}}{g_{oF1} + g_{oP1}} \right) \left( \frac{g_{mF2}}{g_{oF2} + g_{oP2}} \right) \quad |p_2| = \frac{(g_{oF2} + g_{oP2})}{C_L}$$

$$|p_1| = \frac{(g_{oF1} + g_{oP1})}{C_C} \quad BW = |p_1|$$

$$GB = \frac{g_{mF1} g_{mF2}}{(g_{oF2} + g_{oP2}) C_C}$$



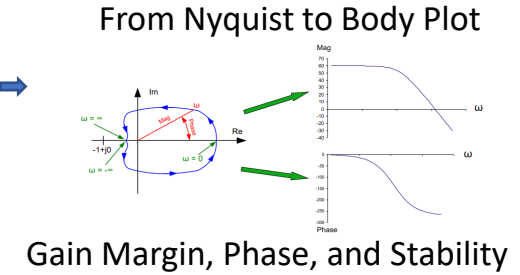
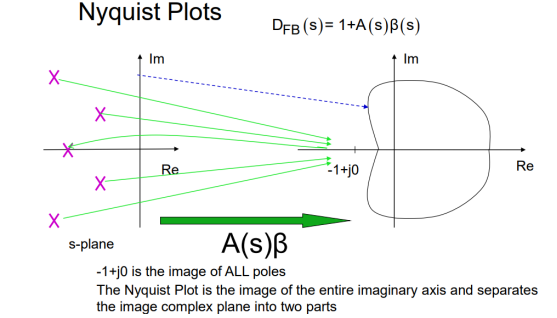
$$A(s) = \frac{g_{md}(g_{m0} - sC_C)}{s^2 C_C C_L + s g_{m0} C_C + g_{o0} g_{od}}$$

$$A(s) \cong \frac{g_{md} g_{m0}}{s^2 C_C C_L + s C_C g_{o0} + g_{o0} g_{od}}$$

$$A_{FFB}(s) \cong \frac{g_{md}(g_{m0} - sC_C)}{s^2 C_C C_L + s C_C (g_{m0} - \beta g_{md}) + \beta g_{m0} g_{m0}}$$

$$A_{FB}(s) \cong \frac{g_{md} g_{md}}{s^2 C_C C_L + s C_C g_{o0} + \beta g_{m0} g_{md}}$$

$$C_C = \frac{C_L \beta}{Q^2} \frac{g_{m0} g_{md}}{(g_{m0} - \beta g_{md})^2}$$



Pole Approximation

$$D(s) = (s-p_1)(s-p_2) = s^2 - s(p_1+p_2) + p_1 p_2 \approx s^2 - p_2 s + p_1 p_2$$

thus

$$p_2 = -a_1 \quad \text{and} \quad p_1 = -a_0/a_1$$

determines  $p_2$

# Compensation

Compensation is the manipulation of the poles and/or zeros of the open-loop amplifier so that when feedback is applied, the closed-loop circuit will perform acceptably

Acceptable performance is often application dependent and somewhat interpretation dependent

Acceptable performance should include effects of process and temperature variations

Although some think of compensation as a method of maintaining stability with feedback, acceptable performance generally dictates much more stringent performance than simply stability

Compensation criteria are often an indirect indicator of some type of desired (but unstated) performance

Varying approaches and criteria are used for compensation often resulting in similar but not identical performance

Over compensation often comes at a considerable expense (increased power, decreased frequency response, increased area, ...)

# Nyquist Plots

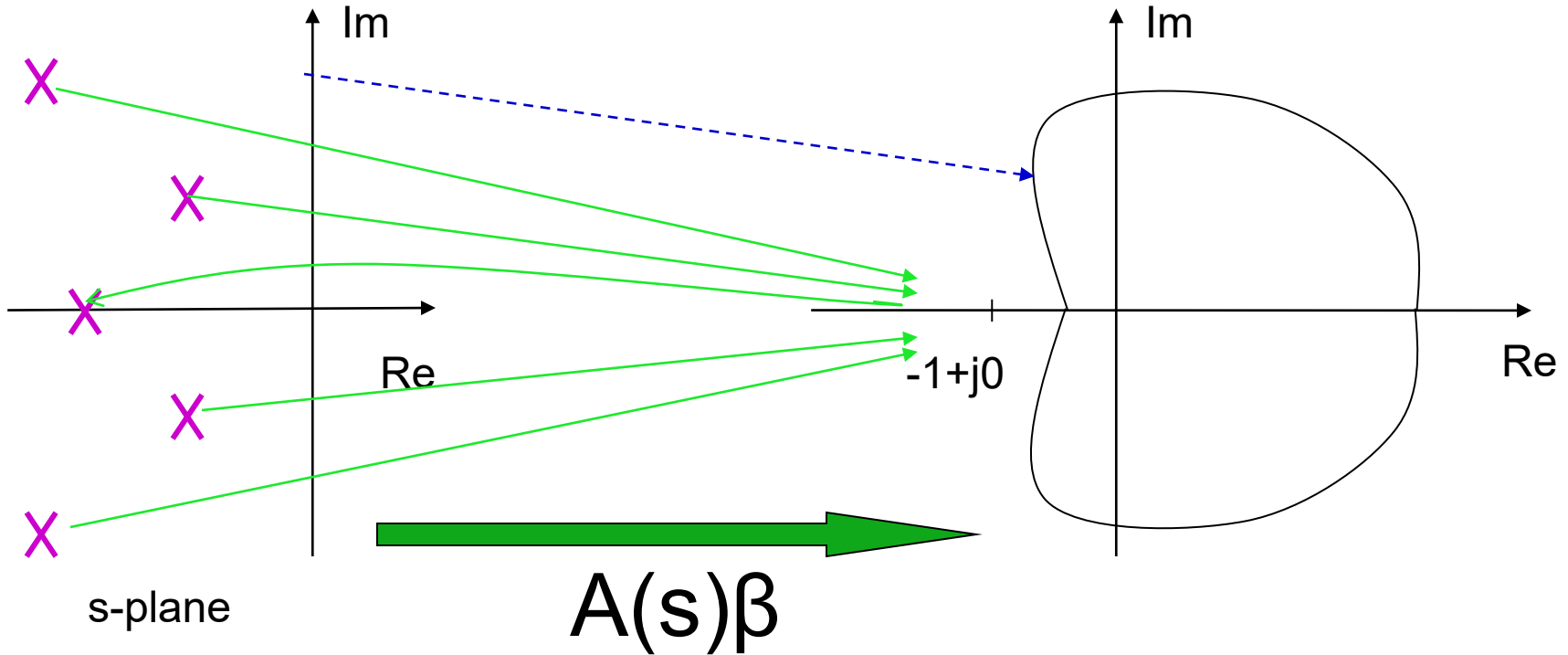
The Nyquist Plot is a plot of the Loop Gain ( $A\beta$ ) versus  $j\omega$  in the complex plane for  $-\infty < \omega < \infty$

**Theorem:** A system is stable iff the Nyquist Plot does not encircle the point  $-1+j0$ .

Note: If there are multiple crossings of the real axis by the Nyquist Plot, the term encirclement requires a formal definition that will not be presented here

# Nyquist Plots

$$D_{FB}(s) = 1 + A(s)\beta(s)$$



-1+j0 is the image of ALL poles

The Nyquist Plot is the image of the entire imaginary axis and separates the image complex plane into two parts

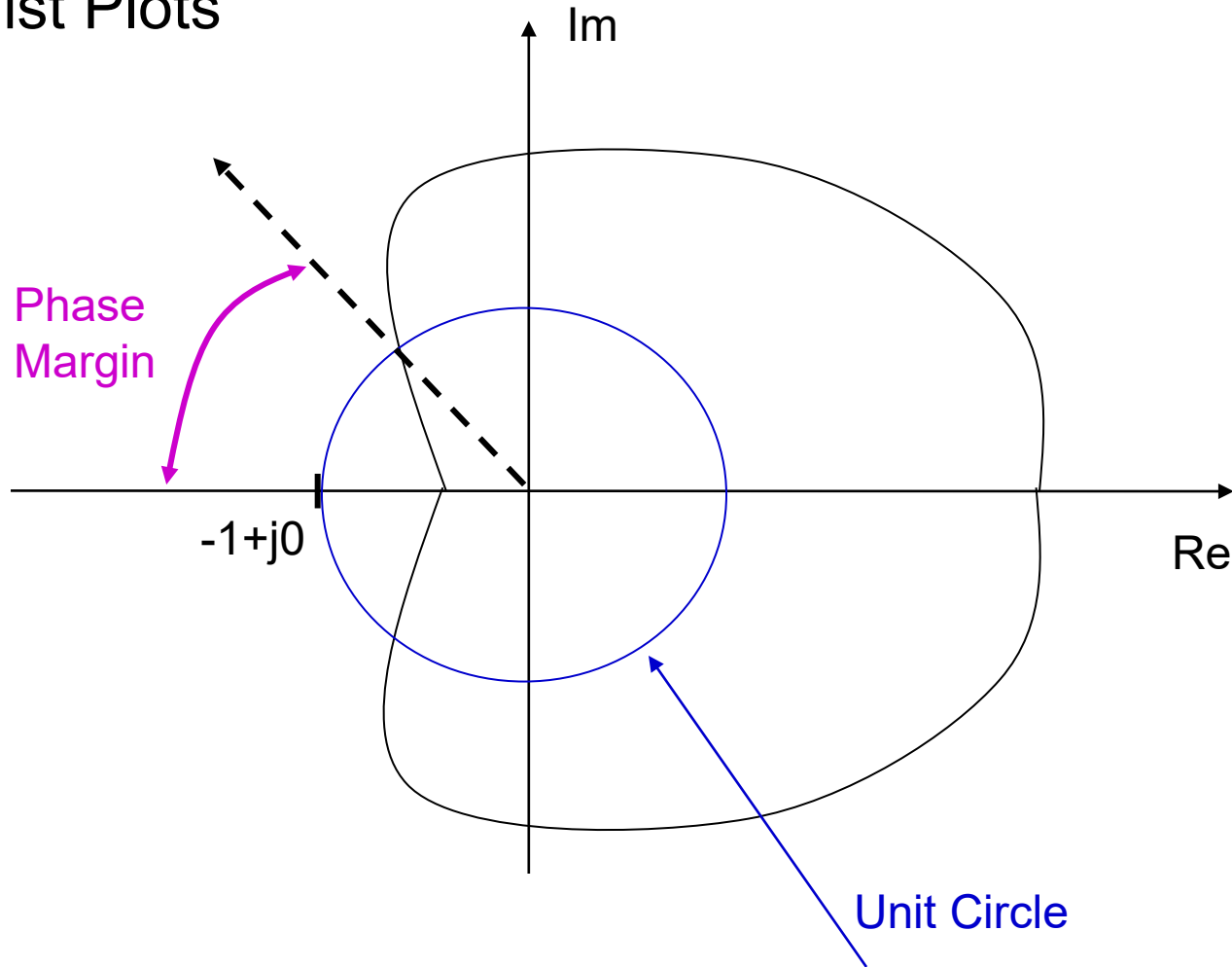
Everything outside of the Nyquist Plot is the image of the LHP

Nyquist plot can be generated with pencil and paper



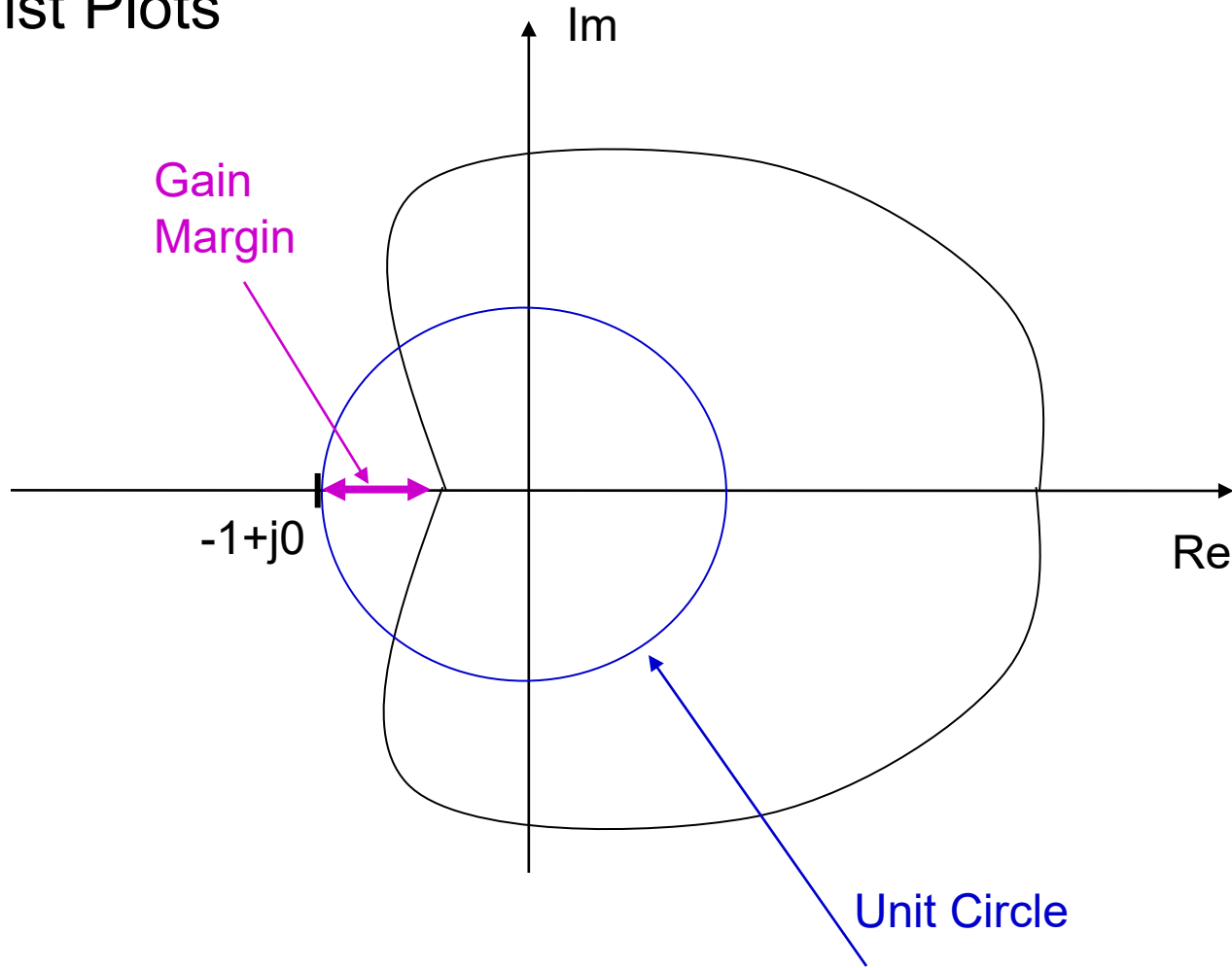
Important in the '30s - '60's

# Nyquist Plots



Phase margin is  $180^\circ - \text{angle of } A\beta \text{ when the magnitude of } A\beta = 1$

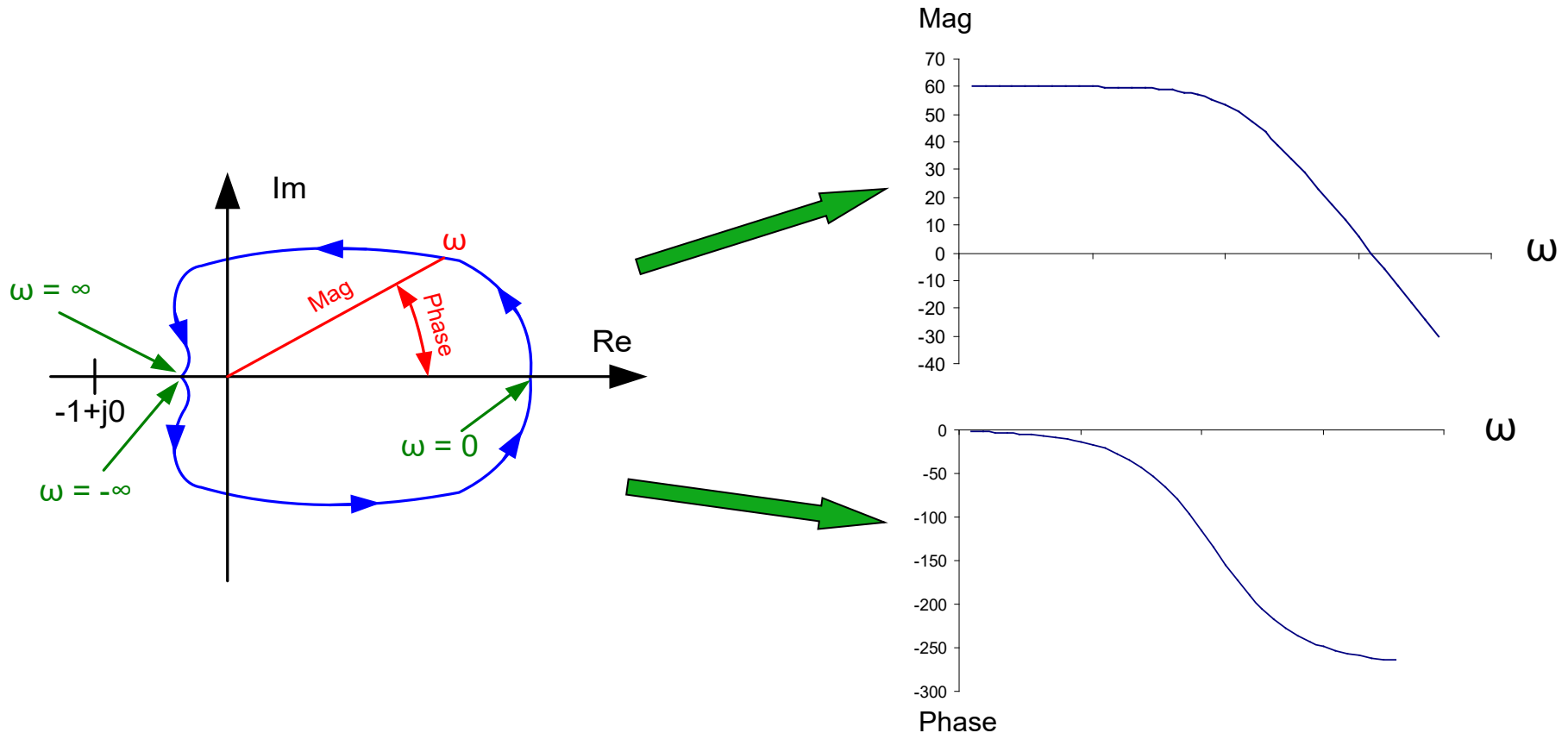
# Nyquist Plots



Gain margin is  $1 - \text{magnitude of } A\beta$  when the angle of  $A\beta = 180^\circ$

# Nyquist and Gain-Phase Plots

Nyquist and Gain-Phase Plots convey identical information but gain-phase plots often easier to work with



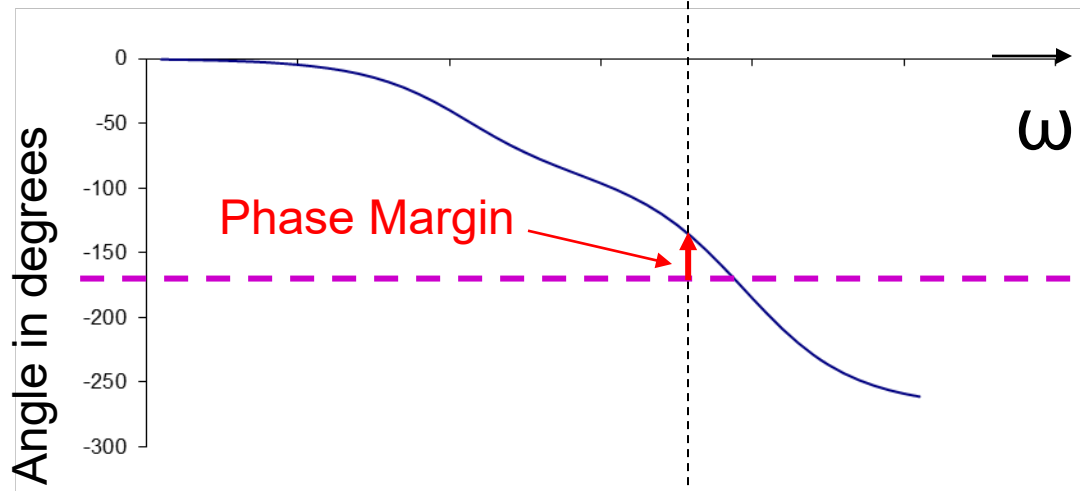
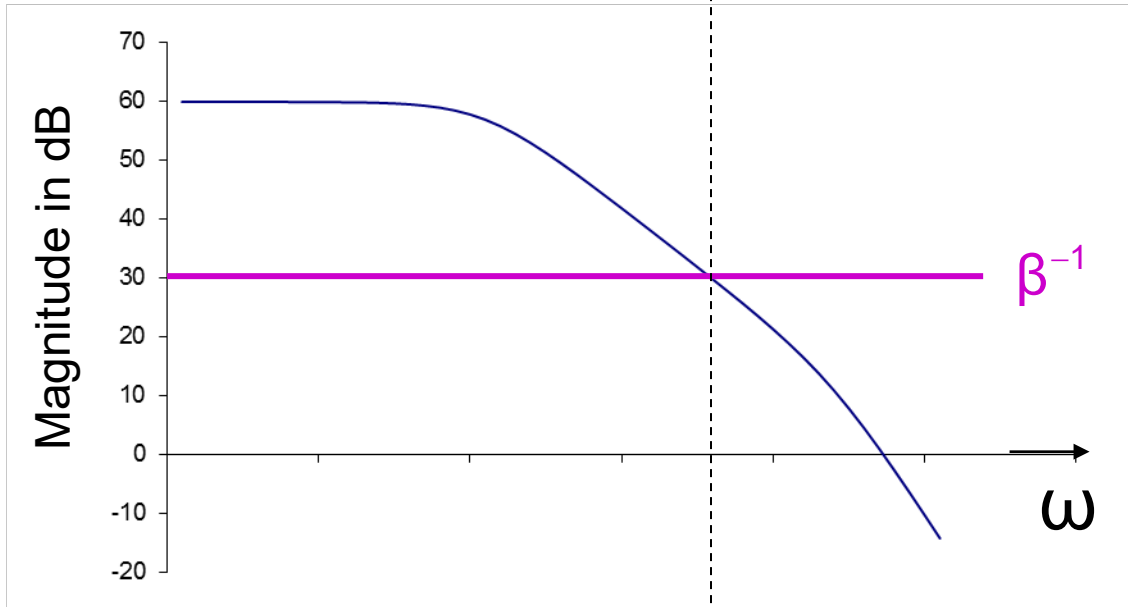
Note: The two plots do not correspond to the same system in this slide



# Gain and Phase Margin Examples

$$A(s) = \frac{1000}{(s+1)\left(\frac{s}{200} + 1\right)}$$

$$\beta = .031$$



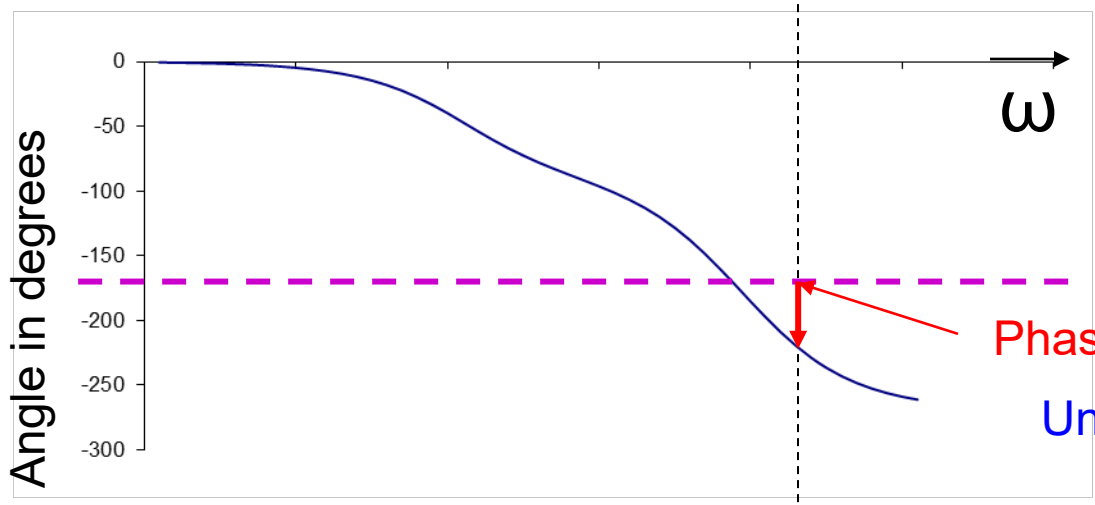
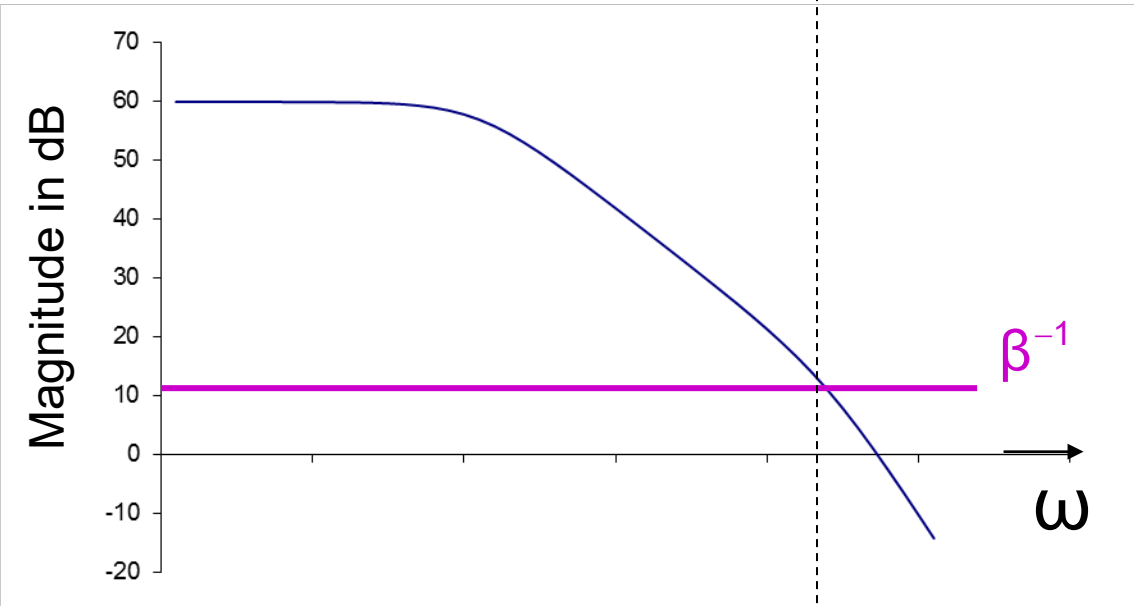
Stable !

But is it a good compensation ?

# Gain and Phase Margin Examples

$$A(s) = \frac{1000}{(s+1)\left(\frac{s}{200} + 1\right)}$$

$\beta = .31$



# Gain and Phase Margin Criteria

Now that we know how to get gain-margin and phase-margins, what gain-margin or phase-margin should be targeted?

What considerations should go into making this determination?

Remember gain and phase margin criteria were primarily developed for determining whether a feedback amplifier is stable or unstable

Most authors simply give a number for the desired phase margin or gain margin

**There is no natural relationship between gain margin, phase margin and amplifier characteristics such as ringing and overshoot !**



# Relationship between pole Q and phase margin

In general, the relationship between the phase margin and the pole Q is dependent upon the order of the transfer function and on the location of the zeros as well as the poles

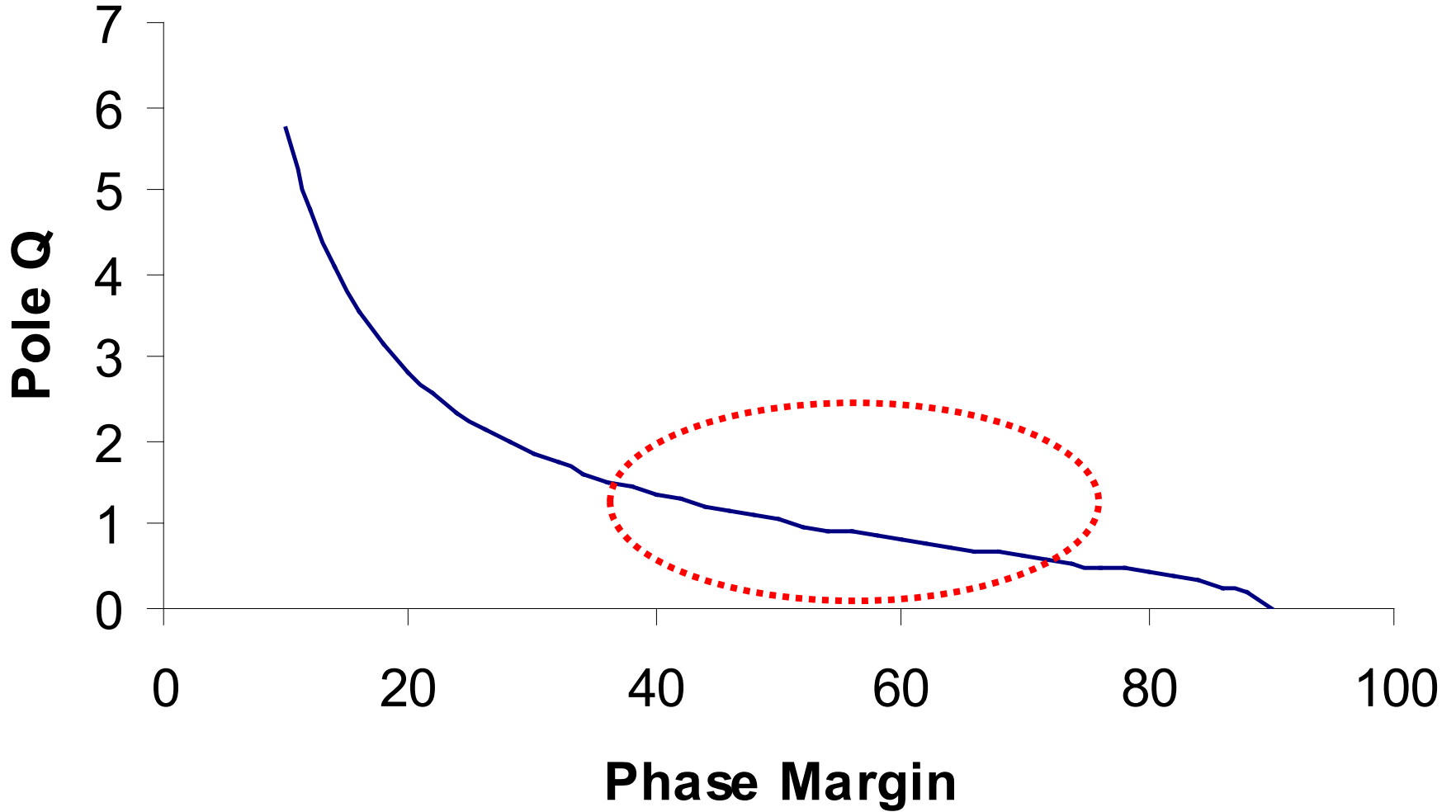
In the special case that the open loop amplifier is second-order low-pass, a closed form analytical relationship between pole Q and phase margin exists and this is independent of  $A_0$  and  $\beta$ .

$$Q = \frac{\sqrt{\cos(\varphi_M)}}{\sin(\varphi_M)} \quad \varphi_M = \cos^{-1} \left( \sqrt{1 + \frac{1}{4Q^4}} - \frac{1}{2Q^2} \right)$$

The region of interest is invariable only for  $0.5 < Q < 0.7$   
larger Q introduces unacceptable ringing and settling  
smaller Q slows the amplifier down too much

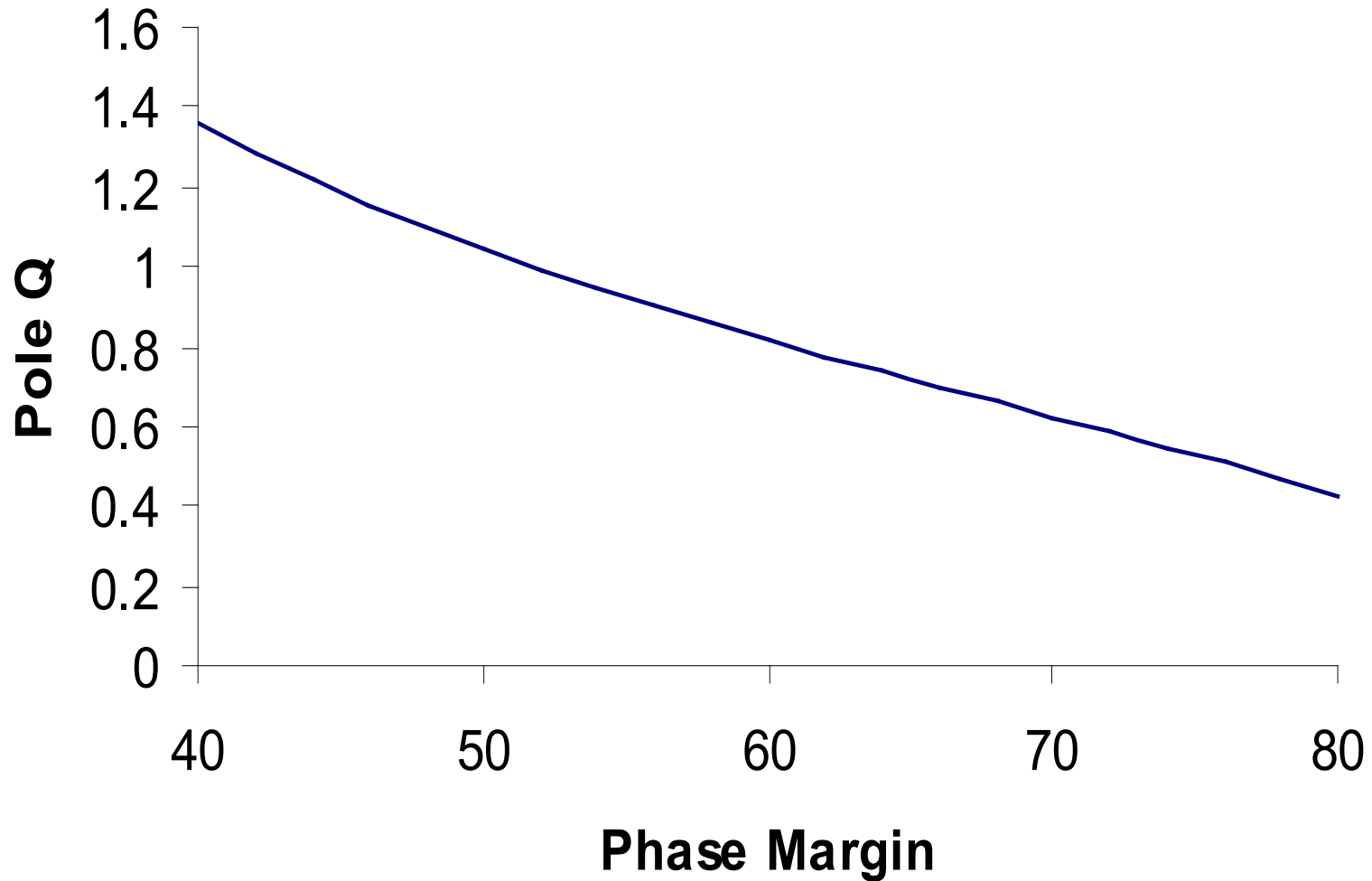
# Phase Margin vs Q

Second-order low-pass Amplifier



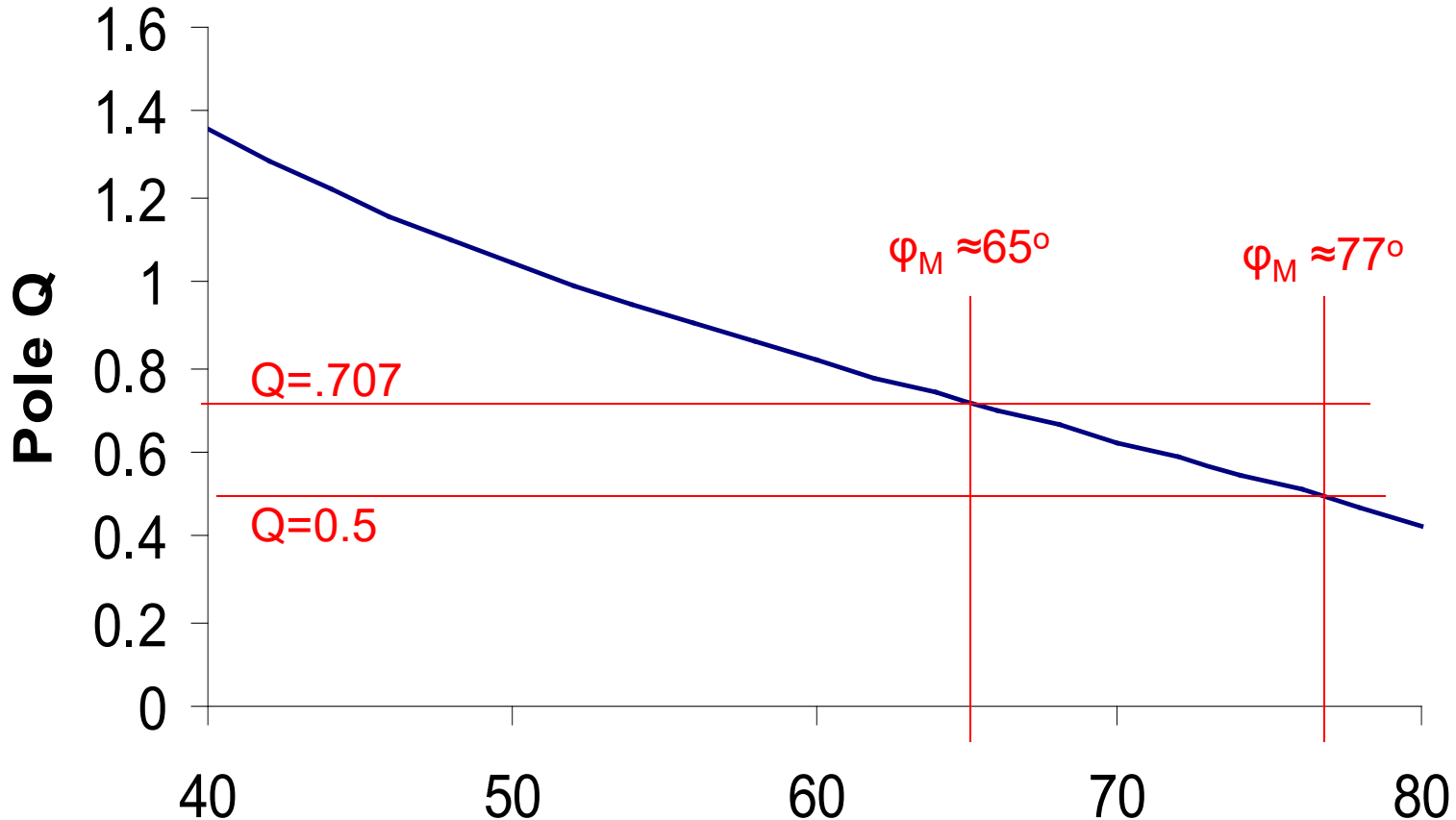
# Phase Margin vs Q

Second-order low-pass Amplifier



# Phase Margin vs Q

Second-order low-pass Amplifier



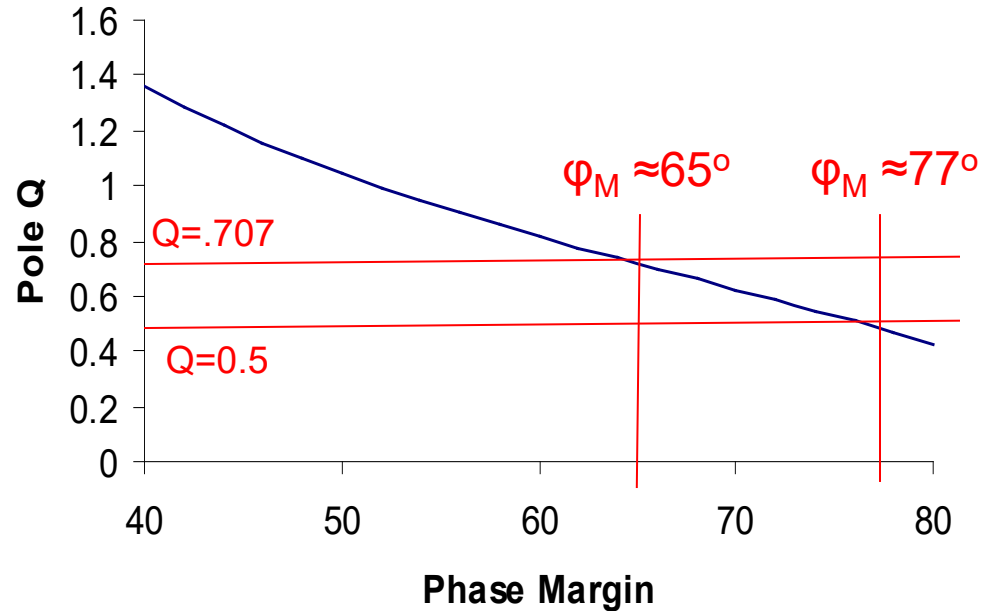
$.707 < Q < 0.5$



$65^\circ < \varphi_M < 75^\circ$

# Phase-Margin Compensation Criteria

## Phase Margin vs Q



$$.707 < Q < 0.5$$

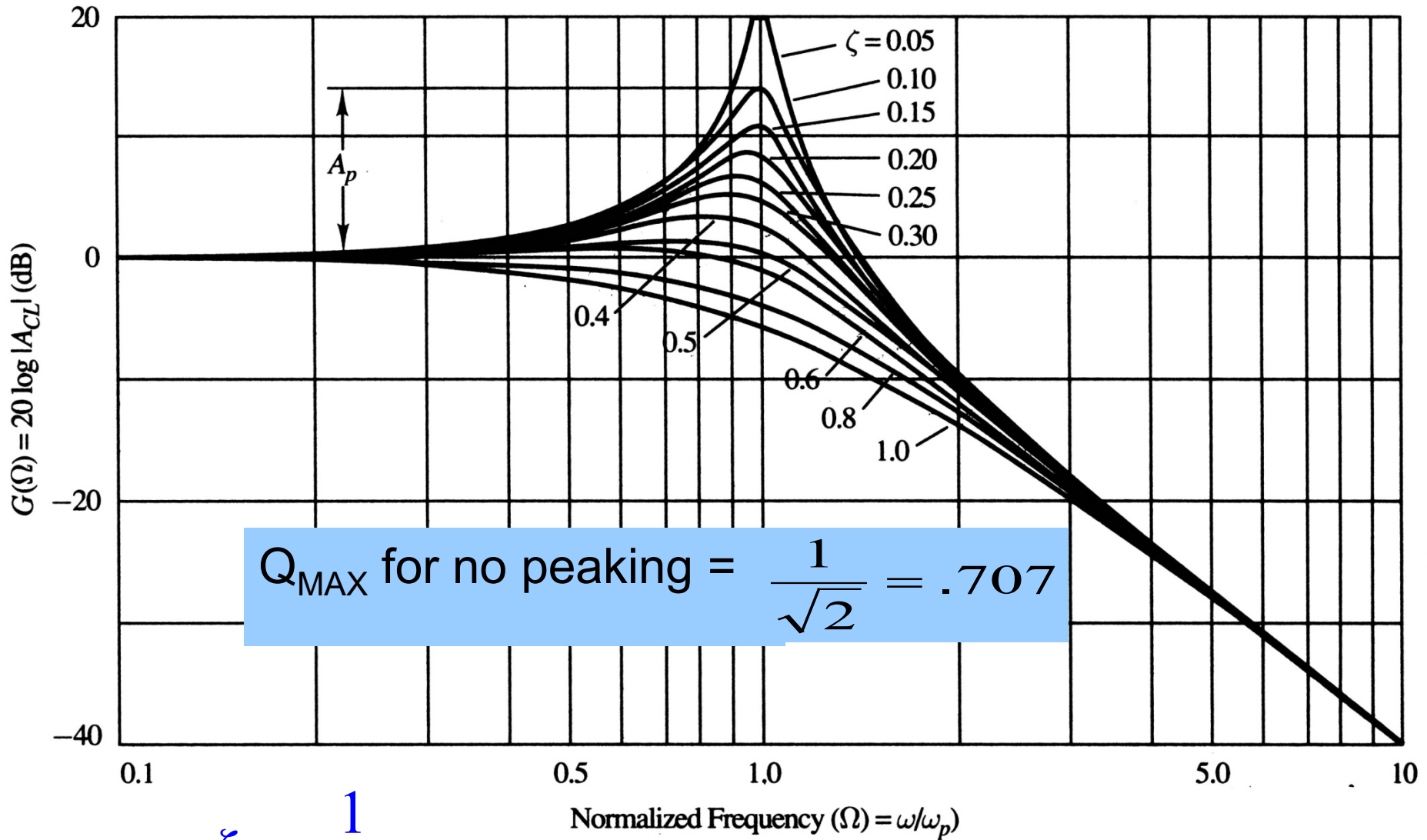


$$65^\circ < \phi_M < 75^\circ$$

- This relationship holds only for 2<sup>nd</sup>-order low-pass open loop amplifiers
- Considerable evidence of use of these phase margin criteria when not 2<sup>nd</sup>-order low-pass but not clear what relevance this may have for FB performance

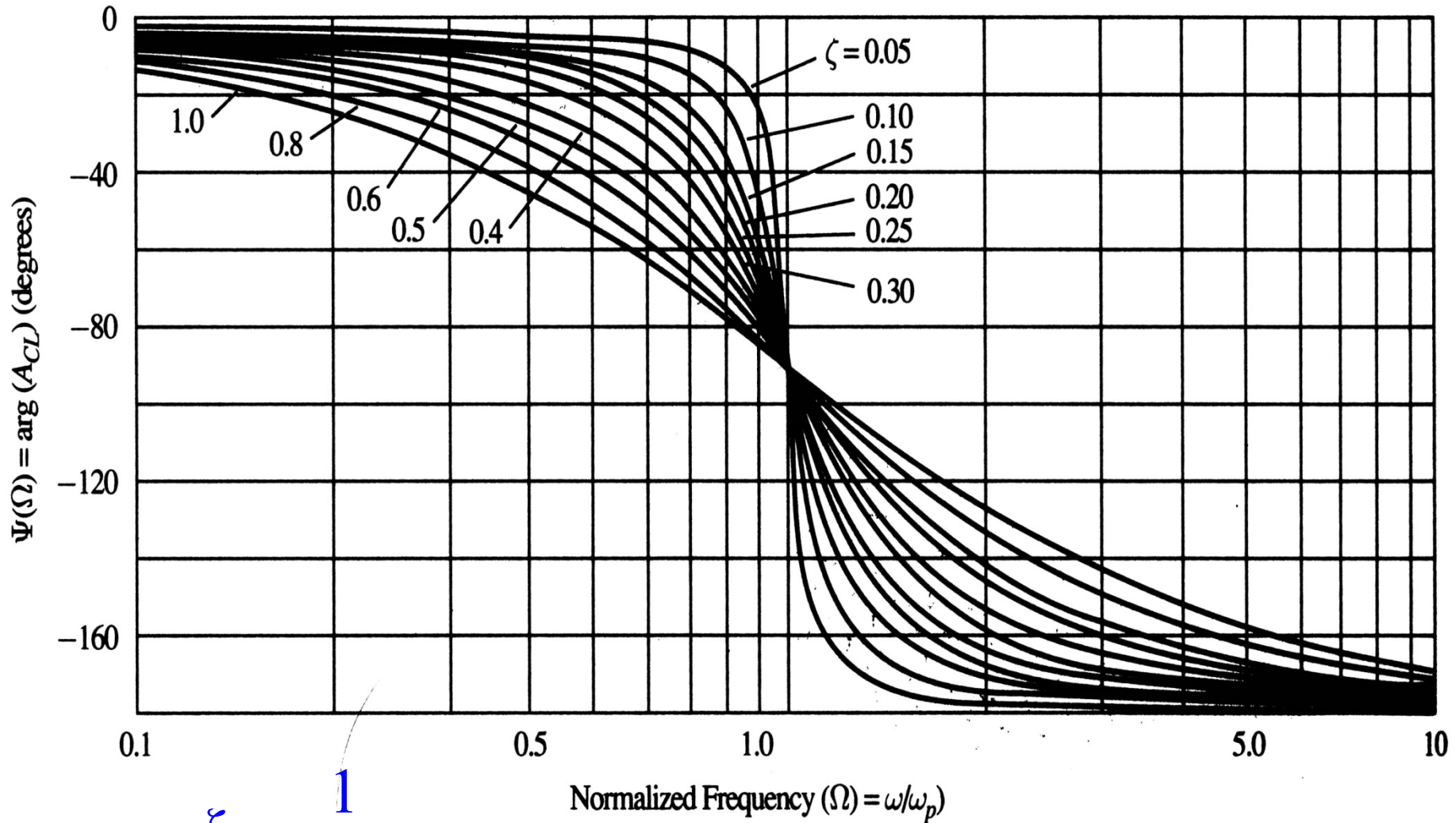


# Magnitude Response of 2<sup>nd</sup>-order Lowpass Function



From Laker-Sansen Text

# Phase Response of 2<sup>nd</sup>-order Lowpass Function

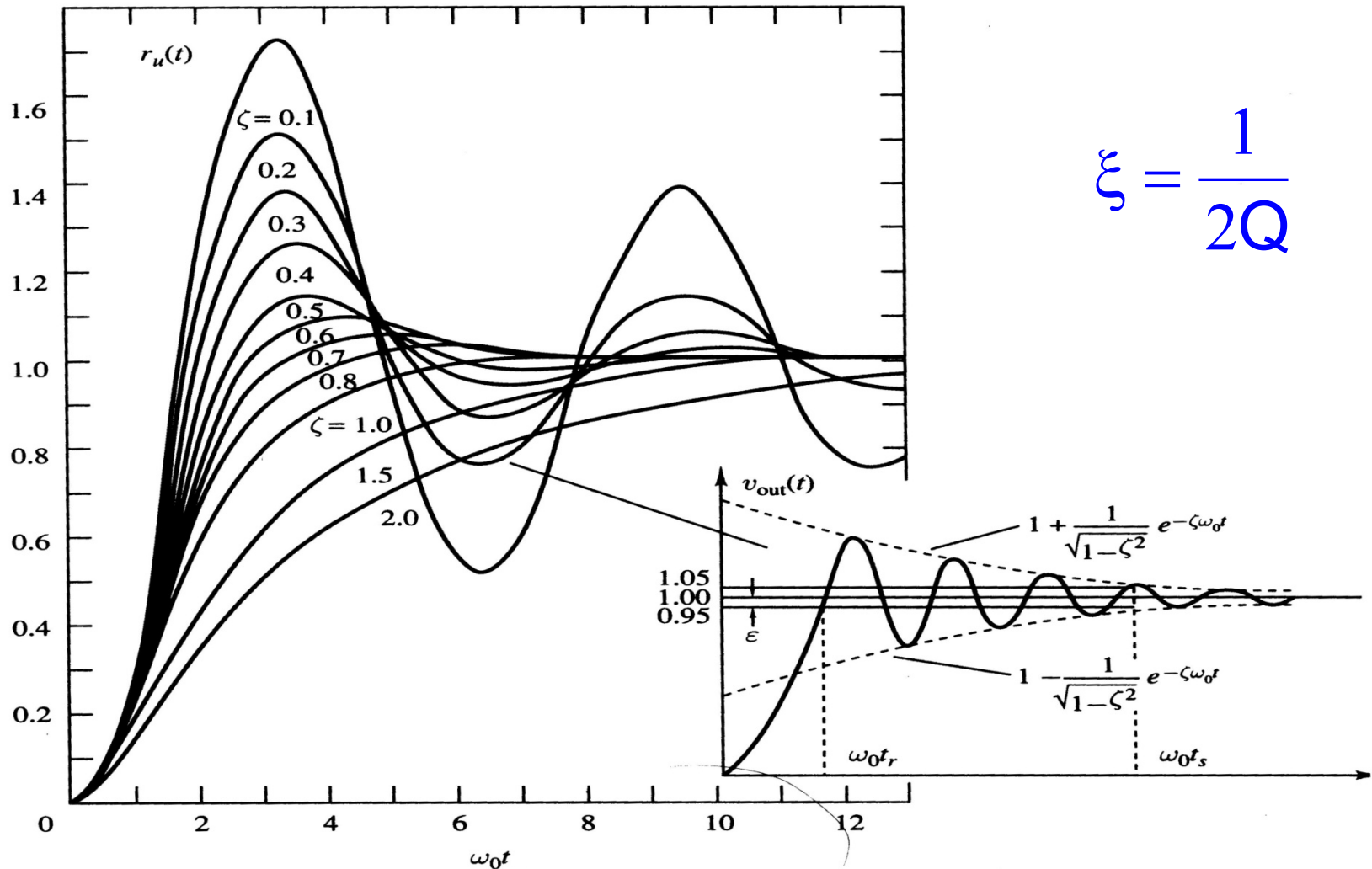


$$\zeta = \frac{1}{2Q}$$

(b)

From Laker-Sansen Text

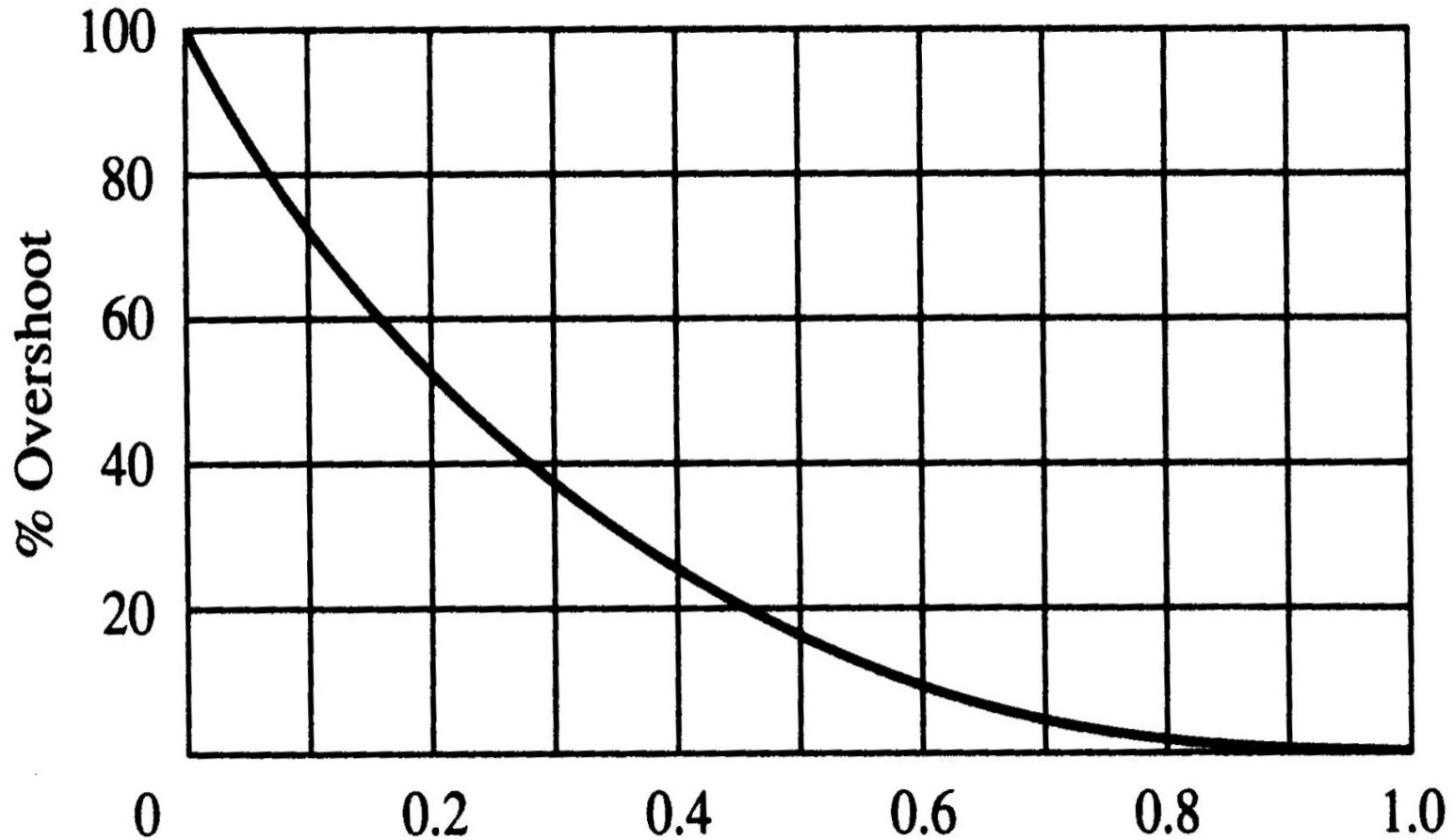
# Step Response of 2<sup>nd</sup>-order Lowpass Function



$$\zeta = \frac{1}{2Q}$$

$Q_{MAX}$  for no overshoot = 1/2

# Step Response of 2<sup>nd</sup>-order Lowpass Function



$$\zeta = \frac{1}{2Q}$$

$\zeta$

From Laker-Sansen Text

# Compensation Summary

- Gain and phase margin performance often strongly dependent upon architecture
- Relationship between overshoot and ringing and phase margin were developed only for 2<sup>nd</sup>-order lowpass gain characteristics and differ dramatically for higher-order structures
- Absolute gain and phase margin criteria are not robust to changes in architecture or order
- It is often difficult to correctly “break the loop” to determine the loop gain  $A\beta$  with the correct loading on the loop (will discuss this more later)

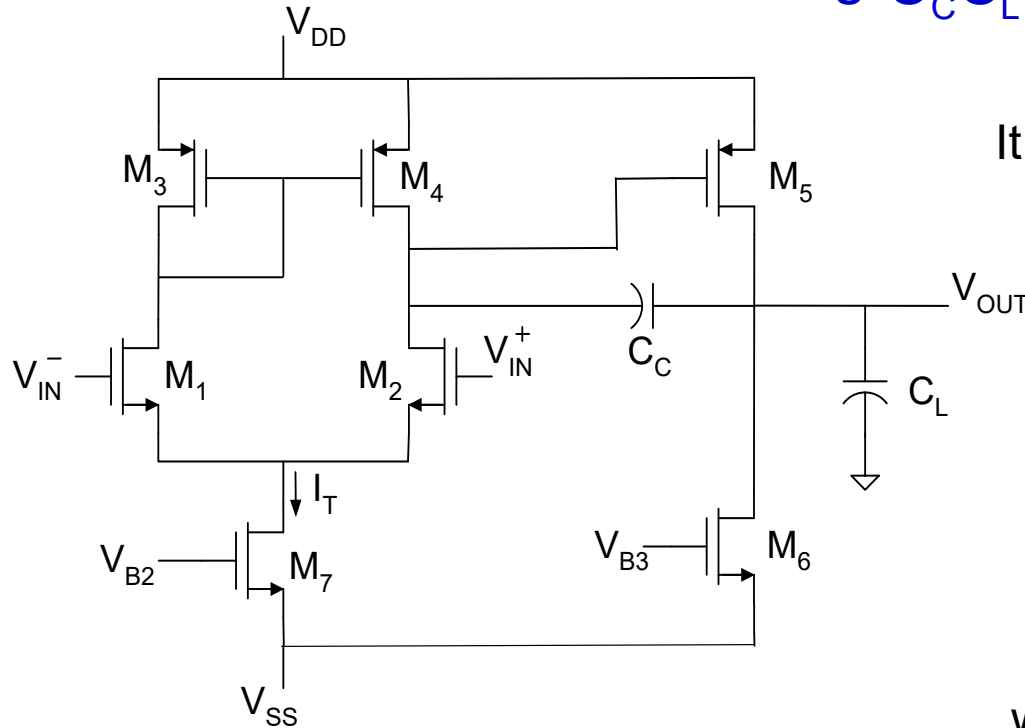
# Design of Two-Stage Op Amps

- Compensation is critical in two-stage op amps
- General approach to designing two-stage op amps is common even though significant differences in performance for different architectures
- Will consider initially the most basic two-stage op amp with internal Miller compensation

# Basic Two-Stage Op Amp

(with Miller compensation)

$$A_{FB}(s) \cong \frac{g_{md}(g_{m0} - sC_c)}{s^2 C_C C_L + s C_C (g_{m0} - \beta g_{md}) + \beta g_{md} g_{m0}}$$



It can be shown that

$$Q = \sqrt{\frac{C_L}{C_C}} \sqrt{\beta} \frac{\sqrt{g_{m0} g_{md}}}{g_{m0} - \beta g_{md}}$$

$$C_C = \frac{C_L \beta}{Q^2} \frac{g_{m0} g_{md}}{(g_{m0} - \beta g_{md})^2}$$

where  $g_{md} = g_{m1}$      $g_{m0} = g_{m5}$

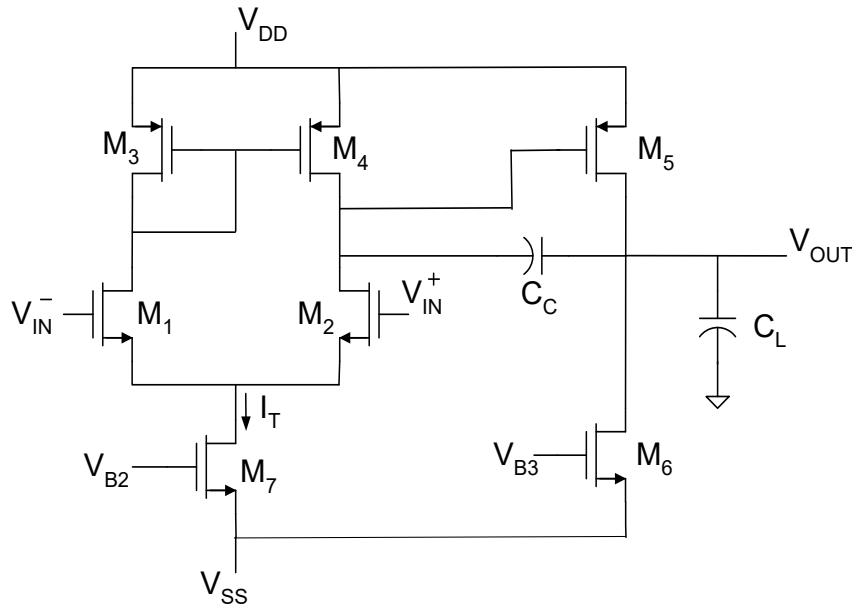
$g_{o0} = g_{o5} + g_{o6}$     and     $g_{od} = g_{o2} + g_{o4}$

What pole Q is desired?

$.707 < Q < 0.5$

What phase margin is desired?

# Basic Two-Stage Op Amp



Additional Performance Parameters  
(from earlier analysis)

$$A(s) \cong \frac{g_{md}(g_{m0} - sC_C)}{s^2 C_C C_L + sC_C g_{m0} + g_{oo} g_{od}}$$

$$A_0 \cong \frac{g_{md} g_{m0}}{g_{oo} g_{od}}$$

$$BW \cong |p_1| \cong \frac{g_{oo} g_{od}}{g_{m0} C_C}$$

$$GB \cong \frac{g_{md}}{C_C}$$

What is the SR?

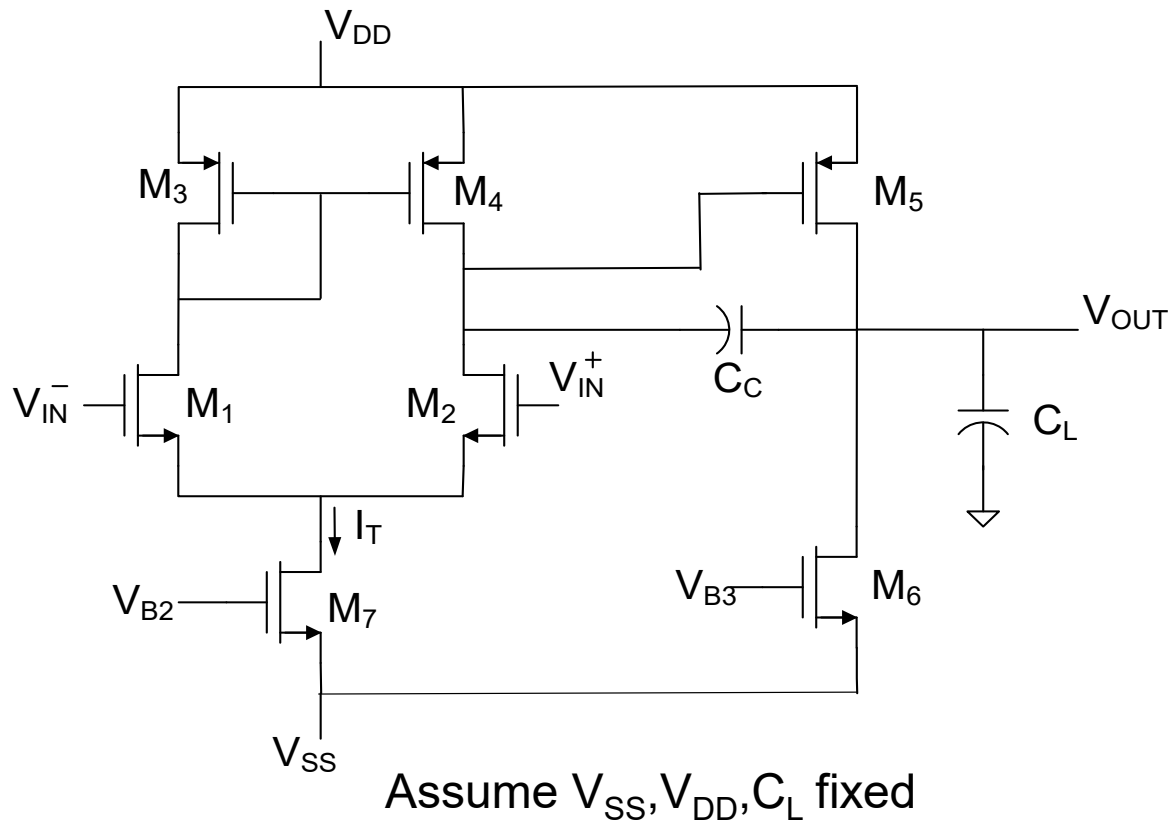
Voltage at output of first stage changes little compared to  $V_{OUT}$

$$SR = \left. \frac{dV_{OUT}}{dt} \right|_{\substack{I_{D4}=I_T \\ I_{D2}=0}} \cong \frac{dV_{C_C}}{dt} = \frac{I_T}{C_C}$$

$$SR \cong \frac{I_T}{C_C}$$



# Natural Parameter Space for the Two-Stage Amplifier Design



$$S_{\text{NATURAL}} = \{W_1, L_1, W_3, L_3, W_5, L_5, W_6, L_6, W_7, L_7, I_T, I_{D6}, C_c\}$$

# Design Degrees of Freedom

Total independent variables: 13

Degrees of Freedom: 13

If phase margin is considered a constraint

13 independent variables

1 constraint

12 degrees of freedom

# Observation:

W,L appear as W/L ratio in almost all characterizing equations

# Implication:

Degrees of Freedom are Reduced

$$S_{\text{NATURAL-REDUCED}} = \{(W/L)_1, (W/L)_3, (W/L)_5, (W/L)_6, (W/L)_7, I_{D6}, I_T, C_C\}$$

With phase margin constraint,

Degrees of freedom: 7

# Common Performance Parameters of Operational Amplifiers (may be more of interest)

Parameter	Description
$A_o$	Open-loop DC Gain
GB	Gain-Bandwidth Product
$\Phi_m$ (or Q)	Phase Margin (or pole Q)
SR	Slew Rate
$T_{SETTLE}$	Settling Time
$A_T$	Total Area
$A_A$	Total Active Area
P	Power Dissipation
$\sigma_{VOS}$	Standard Deviation of Input Referred Offset Voltage (often termed the input offset voltage)
CMRR	Common Mode Rejection Ratio
PSRR	Power Supply Rejection Ratio
$V_{imax}$	Maximum Common Mode Input Voltage
$V_{imin}$	Minimum Common Mode Output Voltage
$V_{omax}$	Maximum Output Voltage Swing
$V_{omin}$	Minimum Output Voltage Swing
$V_{noise}$	Input Referred RMS Noise Voltage
$S_v$	Input Referred Noise Spectral Density

# Common Performance Parameters

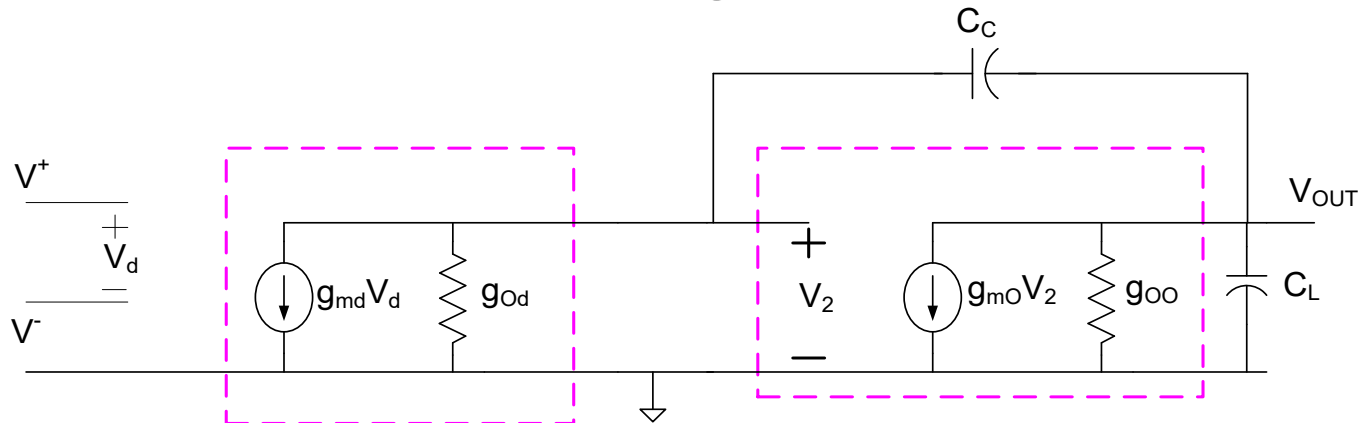
Total: 17

Performance parameters: 17

Degrees of freedom: 7

**System is Generally Highly Over Constrained !**

# Typical Parameter Space for a Two-Stage Amplifier

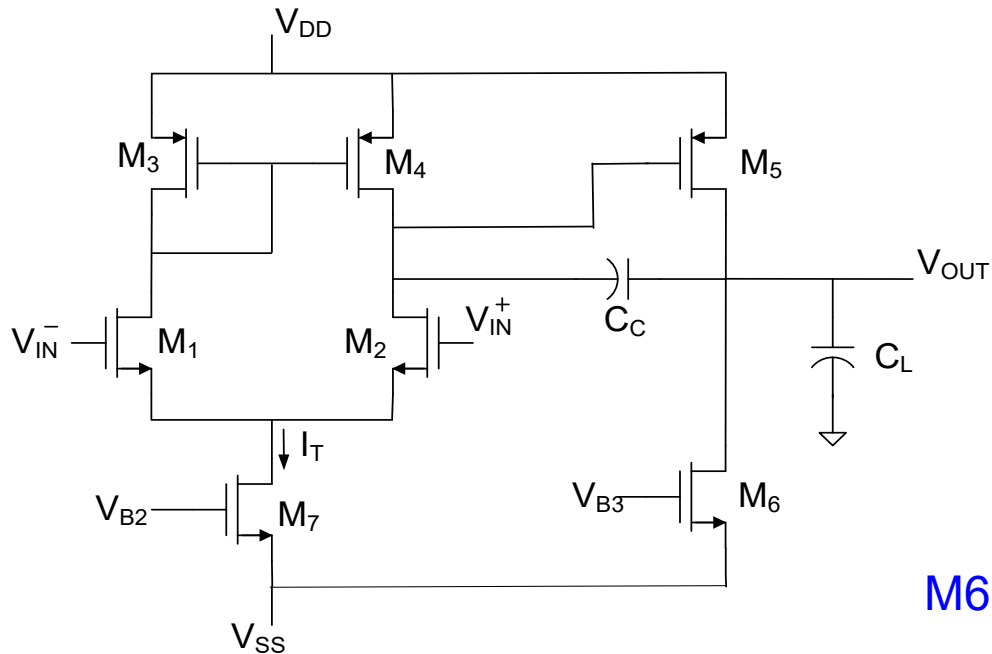


Small signal model of the two-stage operational amplifier

Small signal design parameters:

$$S_{\text{SMALL SIGNAL}} = \{g_{oo}, g_{od}, g_{mo}, g_{md}, C_C, g_{o2}, g_{o4}, g_{o5}, g_{o6}\}$$

# Signal Swing of Two-Stage Op Amp



$$SR \cong \frac{I_T}{C_C}$$

$$\text{M6: } V_{OUT} > V_{SS} + V_{EB6}$$

$$\text{M5: } V_{OUT} < V_{DD} - |V_{EB5}|$$

$$\text{M1: } V_{ic} < V_{DD} + V_{T1} - |V_{T3}| - |V_{EB3}|$$

$$\text{M2: } V_{ic} < V_{DD} + V_{T1} - |V_{T5}| - |V_{EB5}|$$

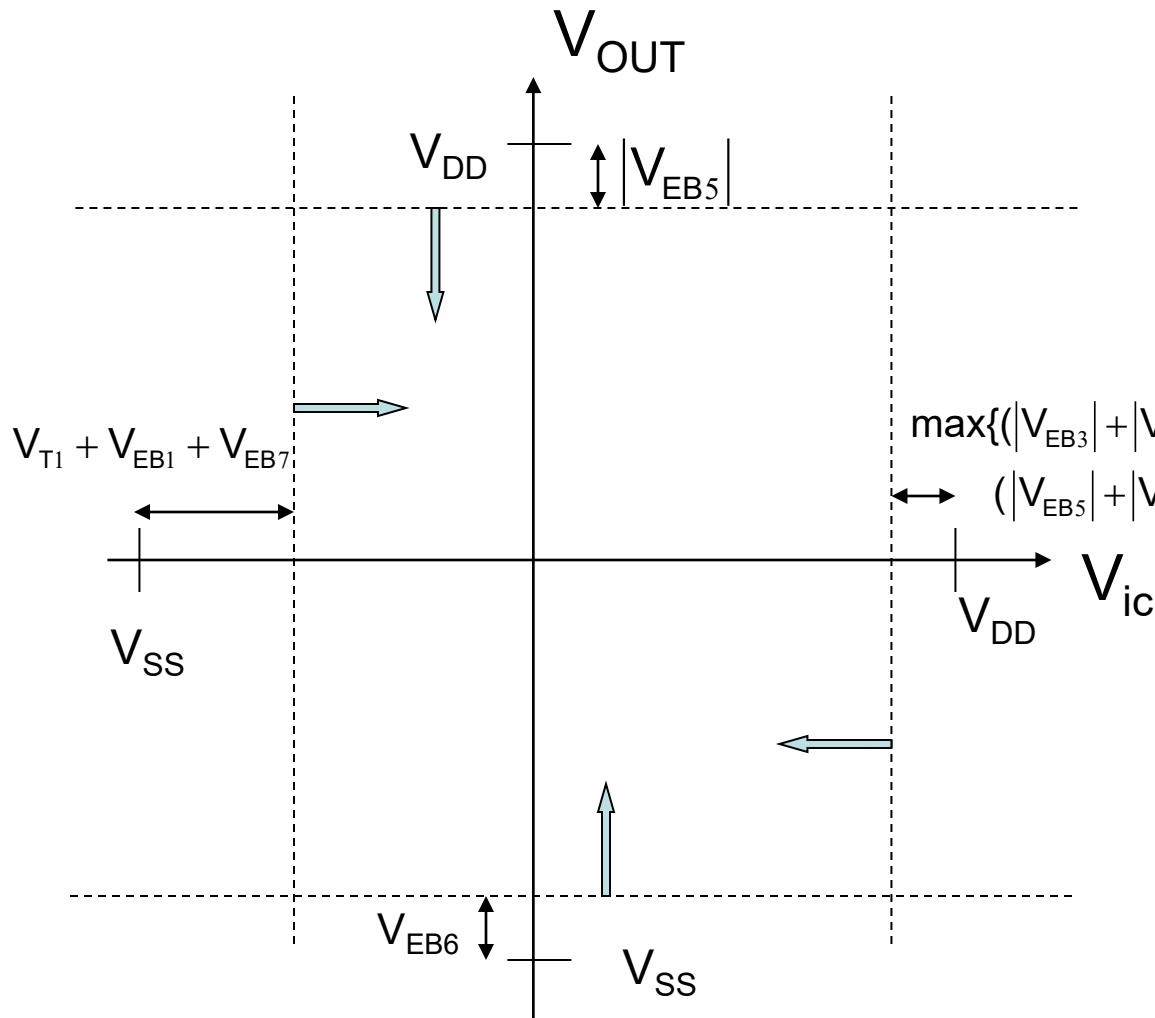
$$\text{M7: } V_{ic} > V_{T1} + V_{EB1} + V_{EB7} + V_{SS}$$

$$S_{\text{swing/Bias Related}} = \{ C_C, V_{EB1Q}, V_{EB3Q}, V_{EB5Q}, V_{EB6Q}, V_{EB7Q}, I_T \}$$



# Signal Swing of Two-Stage Op Amp

## Graphical Representation



$$V_{OUT} < V_{DD} - |V_{EB5}|$$

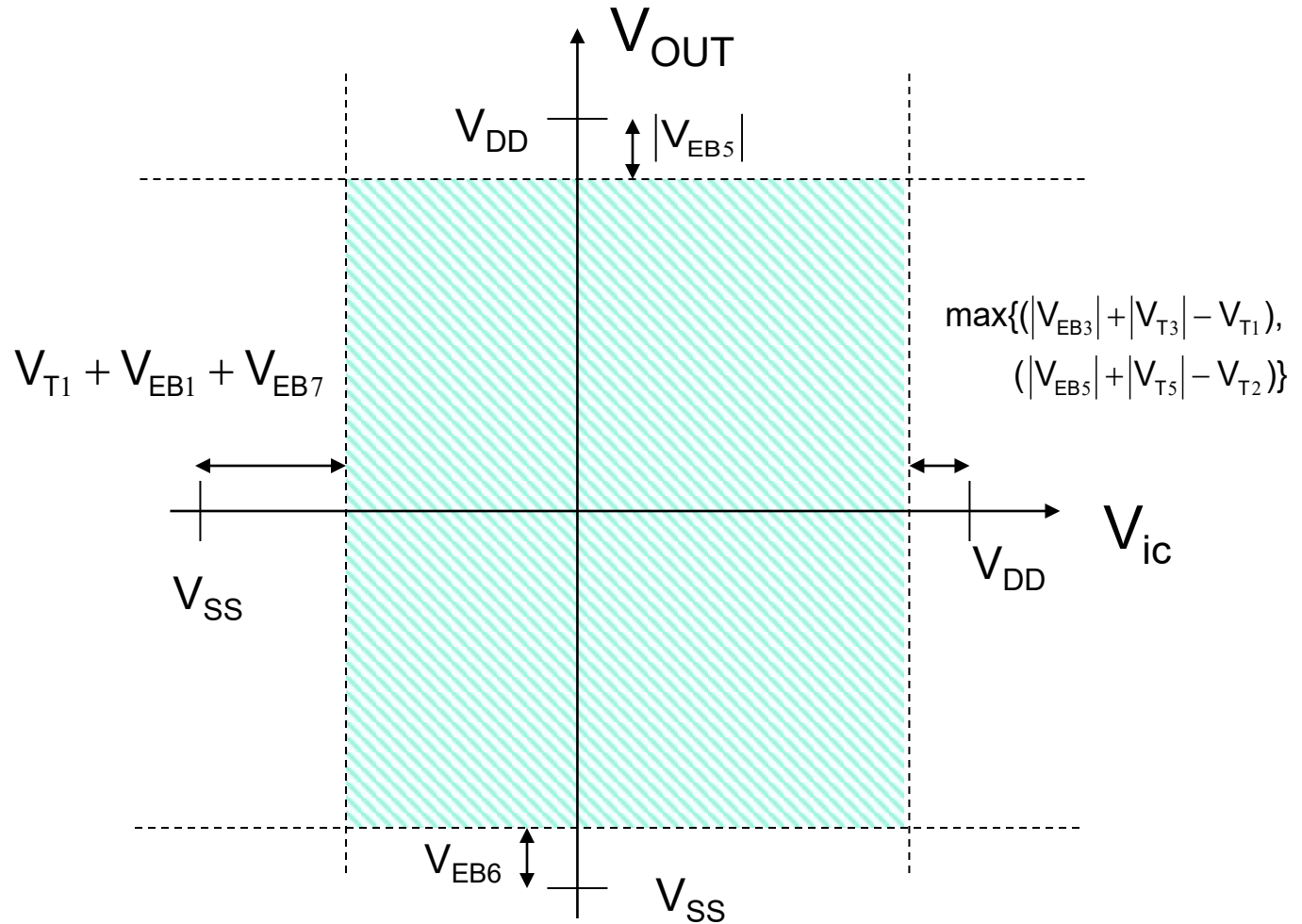
$$V_{OUT} > V_{SS} + V_{EB6}$$

$$V_{IC} > V_{T1} + V_{EB1} + V_{EB7} + V_{SS}$$

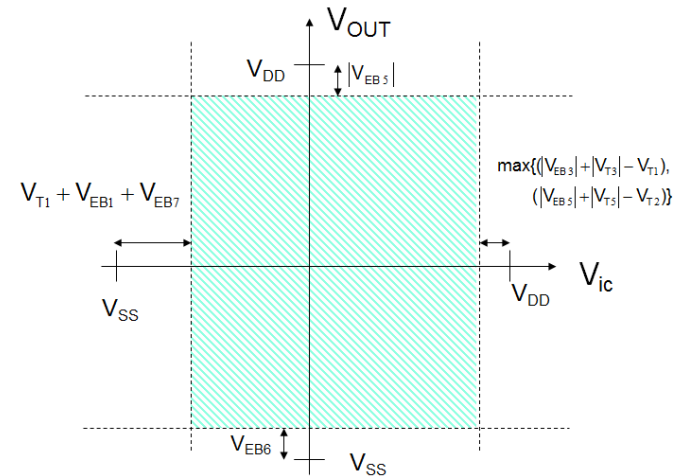
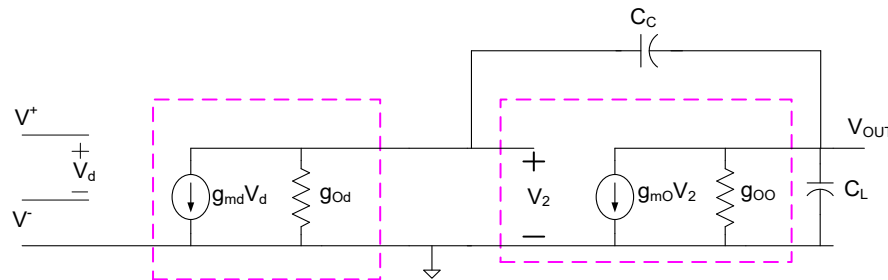
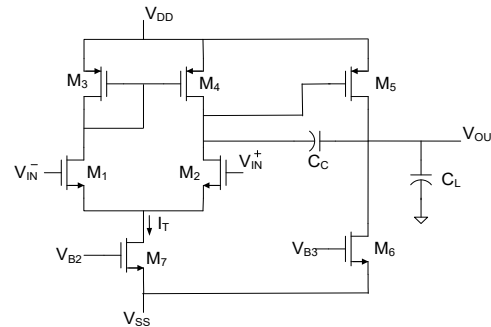
$$V_{IC} < V_{DD} + V_{T1} - |V_{T3}| - |V_{EB3}|$$

$$V_{IC} < V_{DD} + V_{T1} - |V_{T5}| - |V_{EB5}|$$

# Signal Swing of Two-Stage Op Amp



# Typical Parameter Space for a Two-Stage Amplifier



Augmented set of design parameters:

$$S_{\text{AUGMENTED}} = \{g_{oo}, g_{od}, g_{mo}, g_{md}, C_C, V_{EB1Q}, V_{EB3Q}, V_{EB5Q}, V_{EB6Q}, V_{EB7Q}, I_T, g_{o2}, g_{o4}, g_{o5}, g_{o6}\}$$

Parameters in this set are highly inter-related

# Performance Parameter Summary for 7T Miller Compensated Op Amp

$$A_o \cong \frac{g_{md}g_{mo}}{g_{oo}g_{od}} \quad SR \cong \frac{I_T}{C_C} \quad GB \cong \frac{g_{md}}{C_C}$$

$$V_{OMAX} = V_{DD} - |V_{EB5}| \quad V_{OMIN} = V_{SS} + V_{EB6}$$

$$V_{inMIN} = V_{T1} + V_{EB1} + V_{EB7} + V_{SS}$$

$$V_{inMAX} = V_{DD} - \max\{(|V_{EB3}| + |V_{T3}| - V_{T1}), (|V_{EB5}| + |V_{T5}| - V_{T2})\}$$

Constraint:

$$C_C = \frac{C_L \beta}{Q^2} \frac{g_{mo}g_{md}}{(g_{mo} - \beta g_{md})^2}$$

$$S_{AUGMENTED} = \{g_{oo}, g_{od}, g_{mo}, g_{md}, C_C, V_{EB1Q}, V_{EB3Q}, V_{EB5Q}, V_{EB6Q}, V_{EB7Q}, I_T, g_{o2}, g_{o4}, g_{o5}, g_{o6}\}$$

# Parameter Inter-dependence

$I_T$  affects

$$A_o \cong \frac{g_{md} g_{mo}}{g_{oo} g_{od}}$$
$$GB \cong \frac{g_{md}}{C_C}$$
$$SR \cong \frac{I_T}{C_C}$$
$$g_{md} \cong \frac{1}{2} \sqrt{\mu C_{OX} \frac{W_1}{L_1}} \sqrt{I_T}$$

The diagram illustrates the inter-dependence of circuit parameters. Blue arrows originate from the text "I\_T affects" and point to the terms  $g_{md}$ ,  $I_T$ , and  $g_{mo}$  in the equations above. This indicates that the tail current  $I_T$  influences the transconductance  $g_{md}$ , the signal rate  $SR$ , and the overall gain  $A_o$  through its effect on  $g_{mo}$ .

# A Set of Independent Design Parameters is Needed

Consider the Natural Reduced Parameter Set

$$\left\{ \frac{W_1}{L_1}, \frac{W_3}{L_3}, \frac{W_5}{L_5}, \frac{W_6}{L_6}, \frac{W_7}{L_7}, I_T, \theta \right\}$$

$$\theta = \frac{I_{D6Q}}{I_{Tot}} = \frac{P_2}{P}$$

$$I_{Tot} = I_T + I_{D6Q}$$

$$A_O \cong \frac{g_{md} g_{mo}}{g_{oo} g_{od}} \quad \Rightarrow \quad A_O = \frac{2\sqrt{2}C_{OX}\sqrt{\mu_n\mu_p}\sqrt{\frac{W_1W_5}{L_1L_5}}}{(\lambda_n + \lambda_p)^2 I_T \sqrt{\frac{W_6L_7}{W_7L_6}}}$$

## Consider the Natural Reduced Parameter Set

$$\left\{ \frac{W_1}{L_1}, \frac{W_3}{L_3}, \frac{W_5}{L_5}, \frac{W_6}{L_6}, \frac{W_7}{L_7}, I_T, \theta \right\}$$

$$GB \cong \frac{g_{md}}{C_C} \quad \Rightarrow \quad GB = \frac{\sqrt{\frac{\mu_n C_{OX} W_1}{L_1}} \sqrt{I_T}}{C_C}$$

$$SR \cong \frac{I_T}{C_C}$$

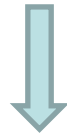
Constraint:

$$C_C = \frac{C_L \beta}{Q^2} \frac{g_{mo} g_{md}}{(g_{mo} - \beta g_{md})^2} \quad \Rightarrow \quad C_C = \frac{C_L \beta}{Q^2} \frac{\sqrt{\mu_n \mu_p} \sqrt{2 \frac{W_1 W_5 W_6 L_7}{L_1 L_5 L_6 W_7}}}{\left( \sqrt{2 \mu_p \frac{W_5 W_6 W_7}{L_5 L_6 L_7}} - \beta \sqrt{\mu_n \frac{W_1}{L_1}} \right)^2}$$

## Consider the Natural Reduced Parameter Set

$$\left\{ \frac{W_1}{L_1}, \frac{W_3}{L_3}, \frac{W_5}{L_5}, \frac{W_6}{L_6}, \frac{W_7}{L_7}, I_T, \theta \right\}$$

$$V_{\text{inMIN}} = V_{T1} + V_{EB1} + V_{EB7} + V_{SS}$$



$$V_{\text{imin}} = V_{T1} + \sqrt{\frac{I_T L_1}{\mu_n C_{OX} W_1}} + \sqrt{\frac{2I_T L_7}{\mu_n C_{OX} W_7}} + V_{SS}$$

Expressions for remainder of signal swings are particularly complicated !



# Observation

- Even the most elementary performance parameters require very complicated expressions when the natural design parameter space is used
- Strong simultaneous dependence on multiple natural design parameters
- Interdependence and notational complexity obscures insight into performance and optimization

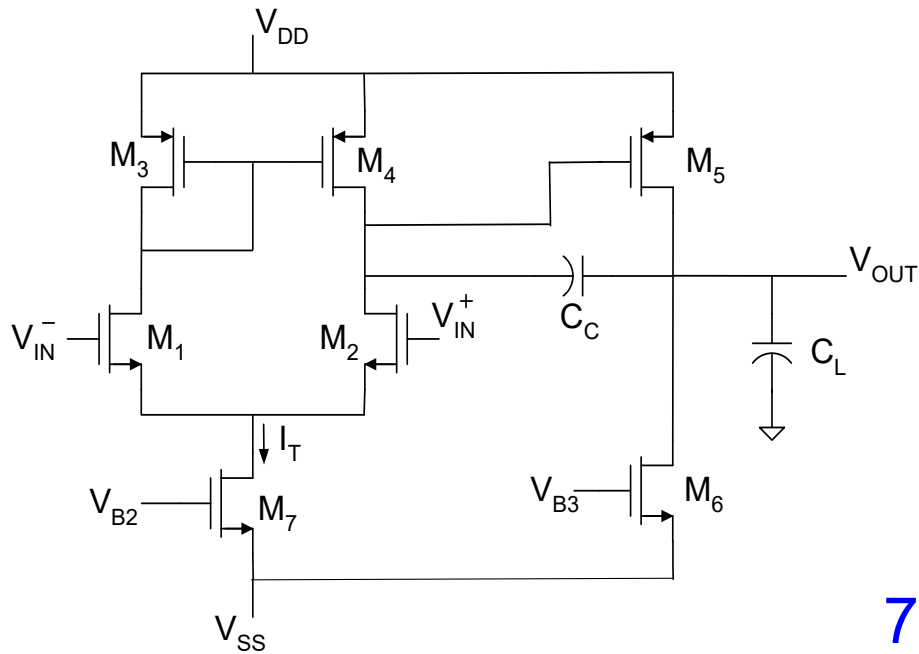
# Practical Set of Design Parameters

$$S_{\text{PRACTICAL}} = \{P, \theta, V_{\text{EB}1}, V_{\text{EB}3}, V_{\text{EB}5}, V_{\text{EB}6}, V_{\text{EB}7}\}$$

7 degrees of freedom!

- $P$  : total power dissipation
- $\theta$  = fraction of total power in second stage
- $V_{\text{EB}k}$  = excess bias voltage for the  $k^{\text{th}}$  transistor
- Phase margin constraint assumed (so  $C_C$  not shown in DoF)

# Basic Two-Stage Op Amp



7 Degrees of Freedom


$\{P, \theta, V_{EB1}, V_{EB3}, V_{EB5}, V_{EB6}, V_{EB7}\}$



$\left\{ \frac{W_1}{L_1}, \frac{W_3}{L_3}, \frac{W_5}{L_5}, \frac{W_6}{L_6}, \frac{W_7}{L_7}, I_T, \theta \right\}$

# Relationship Between the Practical Parameters and the Natural Design Parameters

$$\{P, \theta, V_{EB1}, V_{EB3}, V_{EB5}, V_{EB6}, V_{EB7}\}$$

$$\left\{ \frac{W_1}{L_1}, \frac{W_3}{L_3}, \frac{W_5}{L_5}, \frac{W_6}{L_6}, \frac{W_7}{L_7}, I_T, \theta \right\}$$


$$I_T = \frac{P(1-\theta)}{V_{DD}}$$

$$I_{DQi} \in \left\{ I_T, \frac{I_T}{2}, \frac{\theta P}{V_{DD}} \right\}$$

$$\left( \frac{W}{L} \right)_i \cong \frac{2I_{DQi}}{\mu_i C_{OX} V_{EBi}^2}$$

# A Set of Independent Design Parameters is Needed

## Consider Practical Parameter Set

$$\{P, \theta, V_{EB1}, V_{EB3}, V_{EB5}, V_{EB6}, V_{EB7}\}$$

$$A_o = \frac{4}{(\lambda_n + \lambda_p)^2 V_{EB1} |V_{EB5}|}$$

$$GB = \frac{P(1-\theta)}{V_{DD} V_{EB1} C_C} = \frac{PQ^2 (2\theta V_{EB1} - \beta(1-\theta) |V_{EB5}|)^2}{C_L \beta 2\theta V_{EB1}^2 |V_{EB5}| V_{DD}}$$

$$SR = \frac{PQ^2 (2\theta V_{EB1} - \beta(1-\theta) |V_{EB5}|)^2}{C_L \beta 2\theta V_{EB1} |V_{EB5}| V_{DD}}$$

Constraint:

$$C_C = \frac{C_L 2\theta(1-\theta)\beta}{Q^2} \frac{V_{EB1} |V_{EB5}|}{(V_{EB1} 2\theta - \beta |V_{EB5}| (1-\theta))^2}$$

## Observation:

$$GB = \frac{P(1-\theta)}{V_{DD}V_{EB1}C_C} = \frac{PQ^2(2\theta V_{EB1} - \beta(1-\theta)|V_{EB5}|)^2}{C_L\beta 2\theta V_{EB1}^2|V_{EB5}|V_{DD}}$$

$$SR = \frac{PQ^2(2\theta V_{EB1} - \beta(1-\theta)|V_{EB5}|)^2}{C_L\beta 2\theta V_{EB1}|V_{EB5}|V_{DD}}$$

GB and SR are inter-related for this Op Amp

$$SR = V_{EB1} \bullet GB$$

Could have made this observation in the other parameter domains as well !

# A Set of Independent Design Parameters is Needed

Consider Practical Parameter Set

$$\{P, \theta, V_{EB1}, V_{EB3}, V_{EB5}, V_{EB6}, V_{EB7}\}$$

$$V_{OMAX} = V_{DD} - |V_{EB5}|$$

$$V_{OMIN} = V_{SS} + V_{EB6}$$

$$V_{inMIN} = V_{T1} + V_{EB1} + V_{EB7} + V_{SS}$$

$$V_{inMAX} = V_{DD} - \max\{(|V_{EB3}| + |V_{T3}| - V_{T1}), (|V_{EB5}| + |V_{T5}| - V_{T2})\}$$

All expressions are quite manageable in the practical parameter domain except for the GB expression

# Characteristics of the Practical Design Parameter Space

- Minimum set of independent parameters
- Results in major simplification of the key performance parameters
- Provides valuable insight which makes performance optimization more practical



# Design Assumptions

- Assume the following system parameters:

$$V_{DD} = 3.3 \text{ V}$$

$$C_L = 1 \text{ pF}$$

- Typical 0.35um CMOS process
- Simulation corner: typ/55°C/3.3V

# Example for Design Procedure

Given specifications:

$$A_0: 66\text{dB}$$

$$\text{GB}: 5\text{MHz}$$

$$V_{\text{OMIN}}=0.25\text{V}$$

$$V_{\text{OMAX}}=3.1\text{V}$$

$$V_{\text{INMIN}}=1.1\text{V}$$

$$V_{\text{INMAX}}=3\text{V}$$

$$P=0.17\text{mw}$$

$$\beta=1 \quad \text{with pole } Q=.707$$

Assume:  $V_{\text{TN}} = 0.6$ ,  $V_{\text{TP}} = -0.7$ ,  $\lambda_n=0.04$ ,  $\lambda_p=0.18$

7 constraints (in addition to  $\varphi_m$ ) and 7 degrees of freedom

# Example for Design Procedure

1. Choose channel length

2.  $V_{EB3}, V_{EB5}, V_{EB6}$

~~{P,  $\theta, V_{EB1}, V_{EB3}, V_{EB5}, V_{EB6}, V_{EB7}$ }~~

$$V_{imax} = V_{DD} + V_{EB3} + V_{T1} + V_{T3}$$

$$V_{omax} = V_{DD} + V_{EB5}$$

$$V_{omin} = V_{EB6}$$

3.  $V_{EB1}$

$$A_O = \frac{4}{(\lambda_n + \lambda_p)^2 V_{EB1} |V_{EB5}|}$$

~~{P,  $\theta, V_{EB1}, V_{EB3}, V_{EB5}, V_{EB6}, V_{EB7}$ }~~

4.  $V_{EB7}$

$$V_{imin} = V_{EB1} + V_{EB7} + V_{T1}$$

~~{P,  $\theta, V_{EB1}, V_{EB3}, V_{EB5}, V_{EB6}, V_{EB7}$ }~~

5. Choose P to satisfy power constraint

~~{P,  $\theta, V_{EB1}, V_{EB3}, V_{EB5}, V_{EB6}, V_{EB7}$ }~~

(note this step could have occurred earlier since P is one of the design variables)

# Example for Design Procedure

6. Choose  $\theta$  to meet GB constraint

(the expression for GB really contains only one unknown at this stage,  $\theta$ , though expression is not explicit since  $\theta$  also appears in  $C_C$ )

~~$\{P, \theta, V_{EB1}, V_{EB3}, V_{EB5}, V_{EB6}, V_{EB7}\}$~~

$$GB = \frac{P(1-\theta)}{V_{DD}V_{EB1}C_C}$$

Must solve nonlinear equation in  $\theta$

7. Compensation capacitance  $C_C$

$$C_C = \frac{C_L \beta}{Q^2} 2\theta(1-\theta) \frac{V_{EB1}|V_{EB5}|}{(V_{EB1}2\theta - \beta V_{EB5}(1-\theta))^2}$$

8. Calculate all transistor sizes

$$I_T = \frac{P(1-\theta)}{V_{DD}}$$

$$I_{5Q} = \frac{P\theta}{V_{DD}}$$

$$\frac{W_k}{L_k} = \frac{2I_{Dk}}{\mu_k C_{OX} V_{EBk}^2}$$

9. Implement structure, simulate, and make modifications if necessary guided by where deviations may occur

Note: It may be necessary or preferable to make some constraints an inequality

Note: Specifications may be over-constrained or have no solution

Note: Sequence of steps may change with different requirements for this amplifier

# Example for Design Procedure

Summary of Design Procedure for This Set of Specifications and this Architecture:

1. Choose channel length
2. Select:  $V_{EB3}$ ,  $V_{EB5}$ ,  $V_{EB6}$
3. Select:  $V_{EB1}$
4. Select:  $V_{EB7}$
5. Choose  $P$  to satisfy power constraint
6. Choose  $\theta$  to meet GB constraint
7. Compensation capacitance  $C_C$
8. Calculate all transistor sizes
9. Implement structure, simulate, and make modifications if necessary  
guided by where deviations may occur

Note: Though not shown, this design procedure was based upon looking at the set of equations that must be solved and developing a sequence to solve these equations. It may not always be the case that equations can be solved sequentially.

Note: Different specification requirements (constraints) will generally require a different design procedure

# Example for Design Procedure

Design results in this example in practical parameter domain

VEB1	0.207102
VEB3	-0.2
VEB5	-0.2
VEB6	0.25
VEB7	0.292898
P	.17mW
Th	0.51

$A_0$ : 66dB  
 GB: 5MHz  
 $V_{OMIN}$ =0.25V  
 $V_{OMAX}$ =3.1V  
 $V_{INMIN}$ =1.1V  
 $V_{INMAX}$ =3V  
 P=0.17mw  
 $\beta=1$  with pole Q=.707

Design results in natural parameter domain (with  $L=2\mu\text{m}$ ):

$M_{1,2}$ W/L	$M_{3,4}$ W/L	$M_5$ W/L	$M_6$ W/L	$M_7$ W/L	P	$\theta$	$C_c$
13/2	24.5/2	54/2	17.4/2	17.4/2	0.17mW	.51	3.7pF

Spice simulation results:

A0	GB	P	Phase margin
65dB	5.2MHz	.17mW	45.4 degrees

May need to tweak  $C_c$  to obtain desired pole Q or other settling characteristics

# Spreadsheet for Design Space Exploration

<b>Settling Characteristics of Two-Stage Operational Amplifier</b>																					
<b>Process Parameters</b>																					
uCoxn		9E-05		In		0.02		Power		0.01											
uCoxp		5E-05		Ip		0.1		CT		1E-12											
Vtn		0.768						Vdd		4											
Vtp		0.774																			
<b>Design Parameters</b>					<b>Performance Characteristics</b>						<b>Input Range</b>				<b>Output Range</b>		<b>Device Sizing</b>				
VEB1	VEB2	VEB5	VEB6	VEB7	h	Ao	GB	ISS(mA)	CC	Vmin	Vmax	Vmin	Vmax	W/L1	W/L2	W/L5	W/L6	W/L7			
0.5	0.5	0.5	0.25	0.25	0.5	1111	8.3E+08	1.67	4E-12	1.52	4.27	0.25	3.5	72.5	148.1	148.1	289.9	579.7			
1	0.5	0.5	0.25	0.25	0.5	556	1.9E+09	1.67	8.9E-13	2.02	4.27	0.25	3.5	18.1	148.1	148.1	289.9	579.7			
2	1	0.5	0.25	0.25	0.5	278	2.6E+09	1.67	3.3E-13	3.02	3.77	0.25	3.5	4.5	37.0	148.1	289.9	579.7			
0.5	1	0.5	0.25	0.25	0.5	1111	8.3E+08	1.67	4E-12	1.52	3.77	0.25	3.5	72.5	37.0	148.1	289.9	579.7			
1	2	0.5	0.25	0.25	0.5	556	1.9E+09	1.67	8.9E-13	2.02	2.77	0.25	3.5	18.1	9.3	148.1	289.9	579.7			
2	2	0.5	0.25	0.25	0.5	278	2.6E+09	1.67	3.3E-13	3.02	2.77	0.25	3.5	4.5	9.3	148.1	289.9	579.7			
0.5	0.5	1	0.25	0.25	0.5	556	ERR	1.67	ERR	1.52	4.27	0.25	3	72.5	148.1	37.0	289.9	579.7			
1	0.5	1	0.25	0.25	0.5	278	4.2E+08	1.67	4E-12	2.02	4.27	0.25	3	18.1	148.1	37.0	289.9	579.7			
2	1	1	0.25	0.25	0.5	139	9.4E+08	1.67	8.9E-13	3.02	3.77	0.25	3	4.5	37.0	37.0	289.9	579.7			
0.5	1	1	0.25	0.25	0.5	556	ERR	1.67	ERR	1.52	3.77	0.25	3	72.5	37.0	37.0	289.9	579.7			
1	2	1	0.25	0.25	0.5	278	4.2E+08	1.67	4E-12	2.02	2.77	0.25	3	18.1	9.3	37.0	289.9	579.7			
2	2	1	0.25	0.25	0.5	139	9.4E+08	1.67	8.9E-13	3.02	2.77	0.25	3	4.5	9.3	37.0	289.9	579.7			
0.5	0.5	2	0.25	0.25	0.5	278	8.3E+08	1.67	4E-12	1.52	4.27	0.25	2	72.5	148.1	9.3	289.9	579.7			
1	0.5	2	0.25	0.25	0.5	139	ERR	1.67	ERR	2.02	4.27	0.25	2	18.1	148.1	9.3	289.9	579.7			

# Summary

1. Determination of Design Space and Degrees of Freedom Often Useful for Understanding the Design Problem
2. Analytical Expressions for Key Performance Parameters give Considerable Insight Into Design Potential
3. Natural Design Parameters Often Not Most Useful for Providing Insight or Facilitating Optimization
4. Concepts Readily Extend to other Widely Used Structures





Stay Safe and Stay Healthy !

End of Lecture 17