Lecture – 17 Date: 27.10.2016

- Feedback and Properties, Types of Feedback
- Amplifier Stability
- Gain and Phase Margin Modification

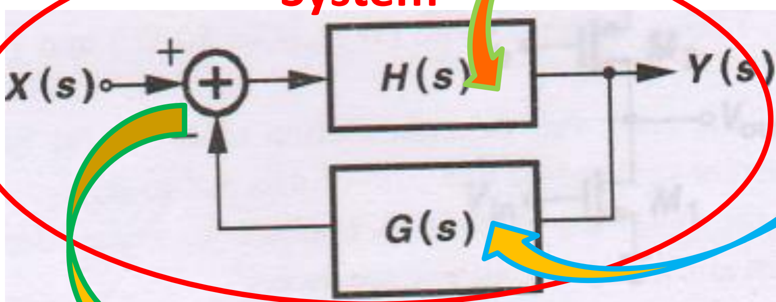
Feedback

General Considerations:

Negative Feedback System

Feedforward Network

Feedback Network



Subtraction at this node makes this system negative feedback

Open Loop Transfer Function

$$Y(s) = H(s)\left[X(s) - G(s)Y(s)\right]$$

Error Signal or Compensation Signal

$$\frac{Y(s)}{X(s)} = \frac{H(s)}{1 + G(s)H(s)}$$

Closed Loop Transfer Function

Open-Loop Transfer Function

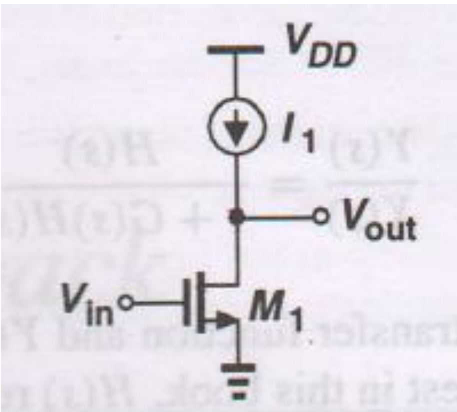
In our discussion: H(s) represents an amplifier and G(s) is a frequency-independent quantity representing the feedback network

Elements of Feedback System:

(a) The feed forward amplifier [H(s)] ; (b) A means of sensing the output; (c) The feedback network [G(s)] ; (d) A means of generating the feedback error [X(s) – G(s)Y(s)]

Properties of Feedback Circuits

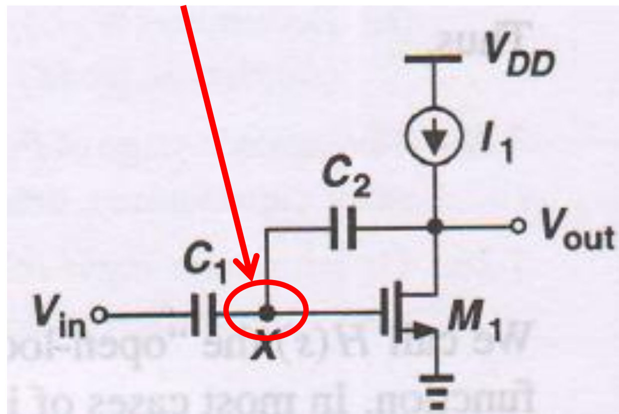
1. Gain Desensitization



$$\frac{V_{out}}{V_{in}} = -g_{m1} r_{o1}$$

Dependent on process parameters, temperature, bias etc.

Node generating error term



$$\frac{V_{out}}{V_{in}} = -\frac{1}{\left(1+\frac{1}{g_{m1} r_{o1}}\right)\frac{C_2}{C_1} + \frac{1}{g_{m1} r_{o1}}}$$

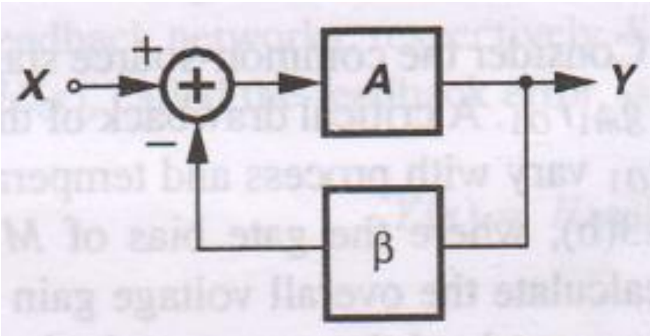
For large $g_{m1} r_{o1}$

$$\frac{V_{out}}{V_{in}} \cong -\frac{C_1}{C_2}$$

The closed-loop gain is much less sensitive to device parameters

Feedback makes gain of this CS stage independent of process and temperature

Properties of Feedback Circuits (contd.)



$$\frac{Y}{X} = \frac{A}{1+A\beta} = \frac{1}{\beta}\frac{1}{\left(1+\frac{1}{A\beta}\right)}$$

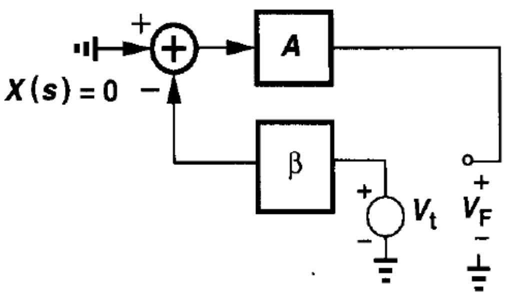
$$\frac{Y}{X} \cong \frac{1}{\beta}\left(1-\frac{1}{A\beta}\right)$$

The impact of variations in A on the closed loop gain is insignificant

- The quantity βA (loop gain) is critical for any feedback system → higher the βA, less sensitive is the closed loop gain to the variations of A
- Accuracy of the closed loop gain improves by maximizing either A or β
- β increases → closed loop gain decreases → means a trade-off exist between precision and the closed loop gain

Properties of Feedback Circuits (contd.)

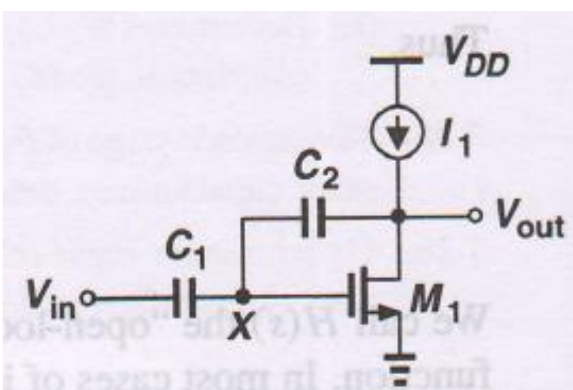
Loop Gain Calculation

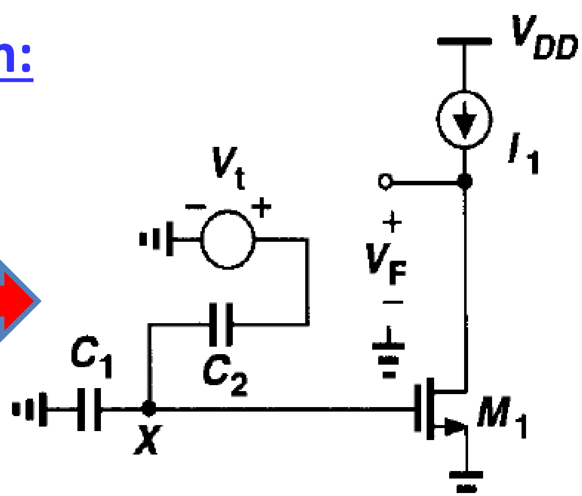


- Set the main input to zero
- Break the loop at some point
- Inject a test signal ‘while maintaining the direction and polarity’
- Follow the signal around the loop and obtain the expression/value

$$V_t \beta(-1) A = V_F \quad \Rightarrow \quad \therefore \frac{V_F}{V_t} = -\beta A$$

Example: Calculate Loop Gain:

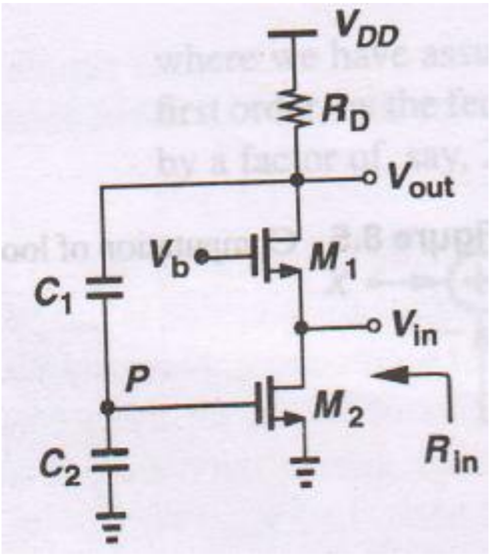




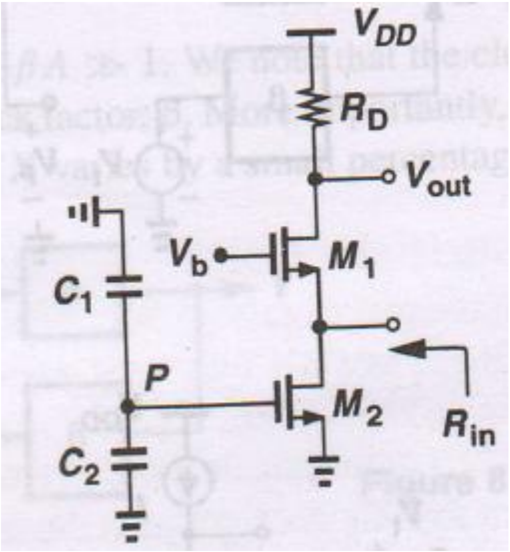
$$\therefore \frac{V_F}{V_t} = -\frac{C_2}{C_1 + C_2} g_{m1} r_{o1}$$

Properties of Feedback Circuits (contd.)

2. Input Impedance Modification



Lets check input impedance with and without feedback

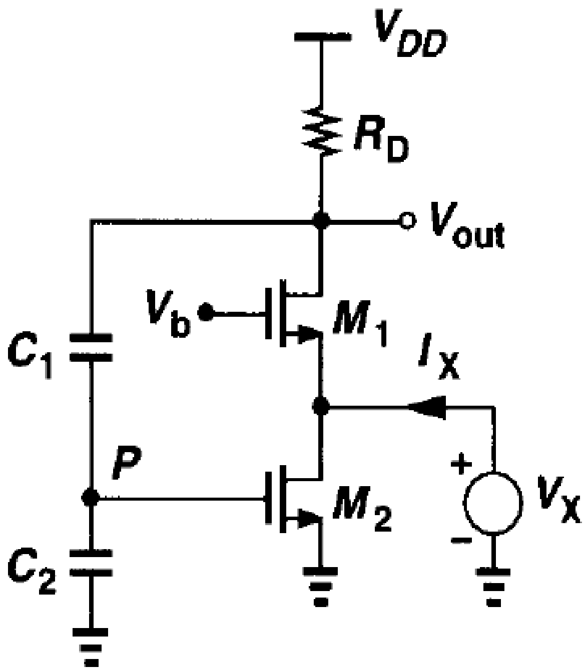


CG stage (M_1) → capacitive divider senses V_{out} and applies it to gate of current source (M_2) → M_2 returns a current feedback signal to the input of M_1

$$R_{in,open} = \frac{1}{g_{m1} + g_{mb1}}$$

Assumption: no channel-length modulation present

Properties of Feedback Circuits (contd.)



$$\frac{V_X}{I_X} = R_{in,closed} = \frac{1}{g_{m1}+g_{mb1}} \frac{1}{1+g_{m2}R_D\frac{X_{C1}}{X_{C1}+X_{C2}}}$$

$$R_{in,closed} = R_{in,open}\frac{1}{1+g_{m2}R_D\frac{X_{C1}}{X_{C1}+X_{C2}}}$$

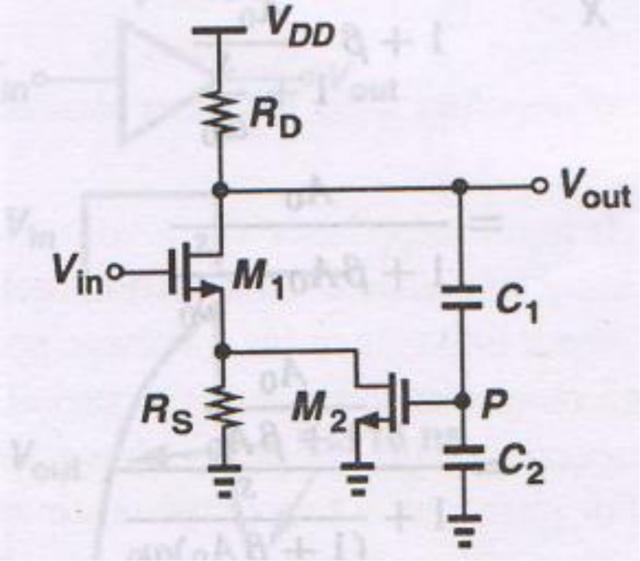
Loop Gain

Feedback reduces the input impedance in this instance → quite useful circuit topology

Four Elements of Feedback: feed-forward amplifier consists of M_1 and R_D, the output is sensed by C_1 and C_2, the feedback network comprise of C_1, C_2, and M_2, subtraction occurs in current domain at the input

Properties of Feedback Circuits (contd.)

3. Output Impedance Modification



$$R_{out,open} = R_D$$

$$R_{out,closed} = \frac{R_D}{1 + \frac{g_{m2} R_S (g_{m1} + g_{mb1}) R_D}{(g_{m1} + g_{mb1}) R_S} \frac{X_{C1}}{X_{C1} + X_{C2}}}$$

Loop Gain

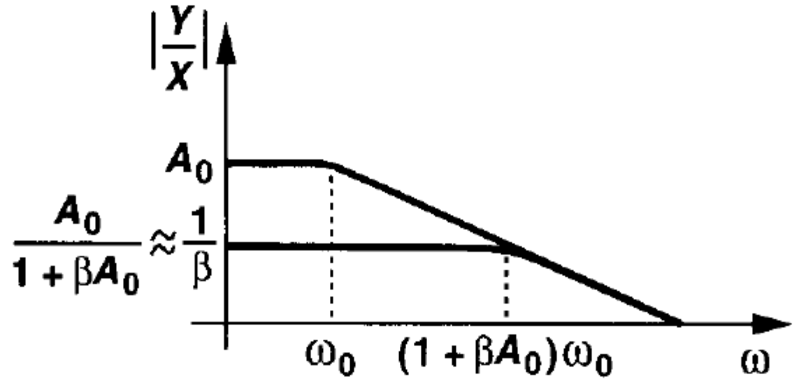
Can you identify if this is a positive feedback or negative feedback circuit? Why?

Properties of Feedback Circuits (contd.)

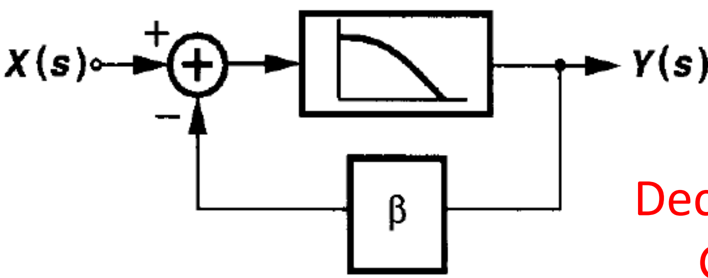
4. Bandwidth Modification

One pole transfer function:

$$A(s) = \frac{A_0}{1+\frac{s}{\omega_0}}$$



One pole transfer function of a closed-loop system:



$$\frac{Y}{X}(s) = \frac{\dfrac{A_0}{1+\frac{s}{\omega_0}}}{1+\beta\dfrac{A_0}{1+\frac{s}{\omega_0}}}$$

Decreased Gain

$$\frac{Y}{X}(s) = \frac{\dfrac{A_0}{1+\beta A_0}}{1+\dfrac{s}{(1+\beta A_0)\omega_0}}$$

Constant GBW

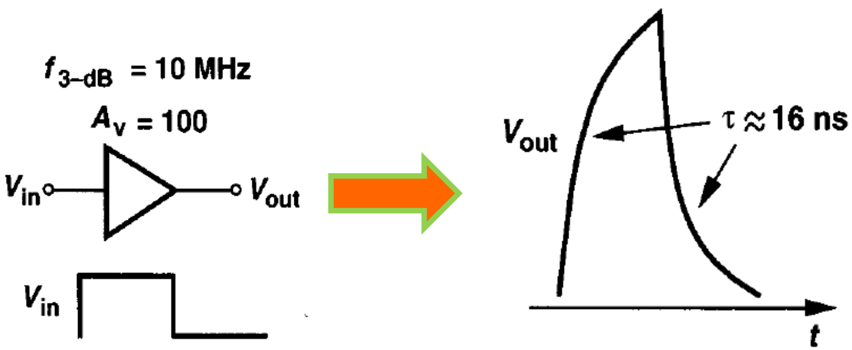
High pole frequency

↔Increased Bandwidth

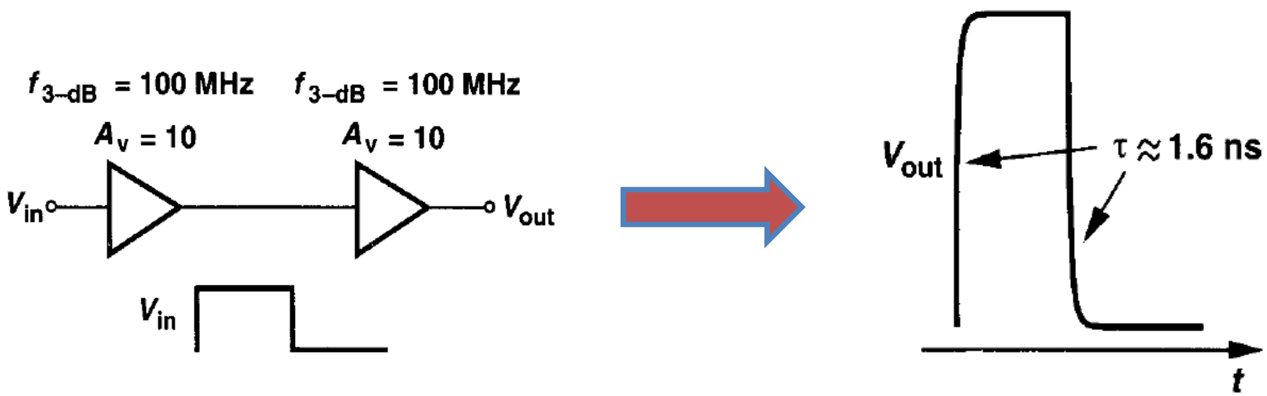
Properties of Feedback Circuits (contd.)

4. Bandwidth Modification

- GBW of a single pole system doesn't change with feedback. But how to improve the speed of the system with high gain?
- Suppose we need to amplify a 20 MHz square wave by a factor of 100 and maximum bandwidth but we only have single pole amplifier with an open-loop gain of 100 and 3-dB bandwidth of 10 MHz.



Apply feedback in such a way that the gain and bandwidth are modified to 10 and 100 MHz. Then use two stage amplification to achieve the desired.

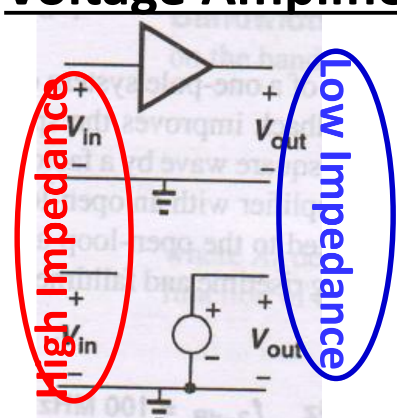


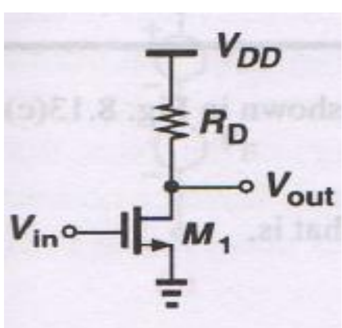
Types of Amplifiers

Type: Based on the type of parameters (current or voltage) they sense at the input and the type of parameters (current or voltage) they produce at the output

- **Amplifier sensing voltage at the input: exhibit high input impedance (as a voltmeter)**
- **Amplifier sensing current at the input: exhibit low input impedance (as an ammeter)**
- **Amplifier sensing voltage at the output: exhibit low output impedance (as a voltage source)**
- **Amplifier sensing current at the output: exhibit high output impedance (as a current source)**

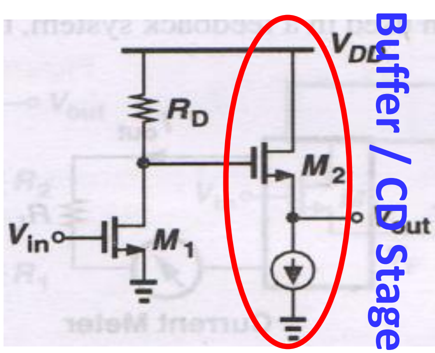
Voltage Amplifier





CS Amplifier

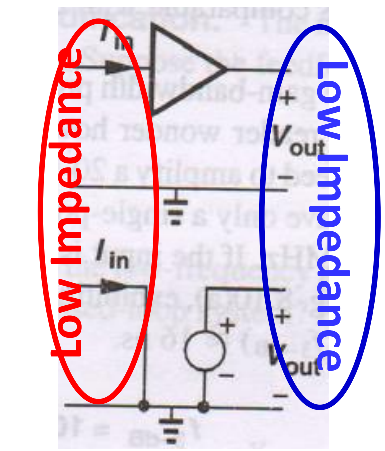
Possess Relatively High Output Impedance

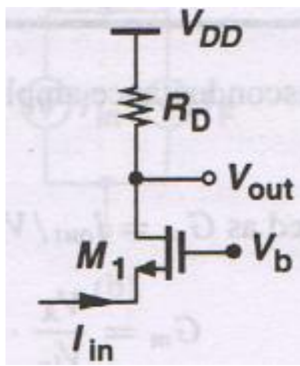


CS Amplifier with a buffer

Types of Amplifiers (contd.)

Transimpedance Amplifier

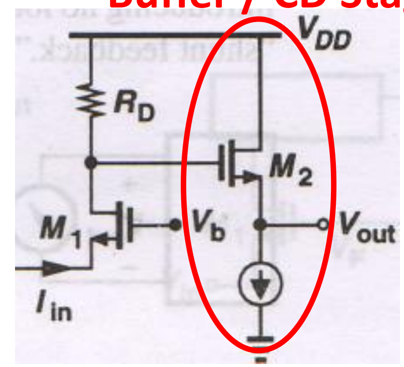




CG Amplifier

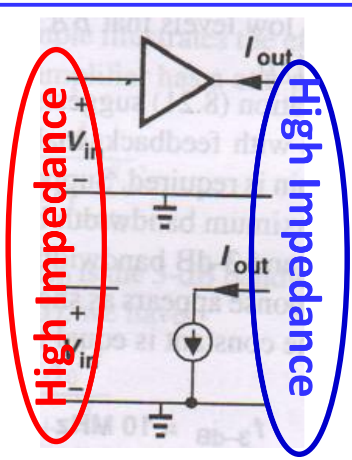
Possess Relatively High Output Impedance

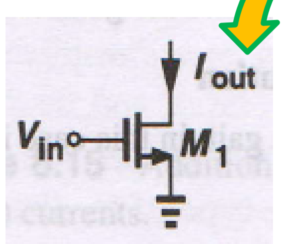
Buffer / CD Stage



CG Amplifier with a buffer

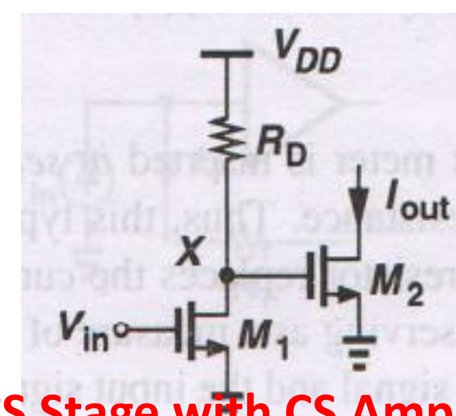
Transconductance Amplifier





CS Stage

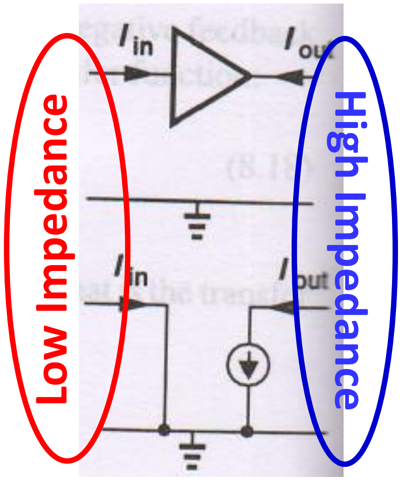
Less control on input impedance

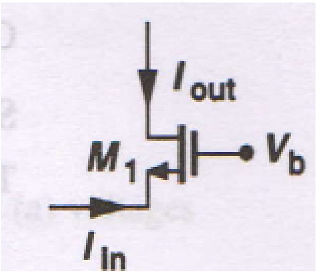


CS Stage with CS Amplifier at the input

Types of Amplifiers (contd.)

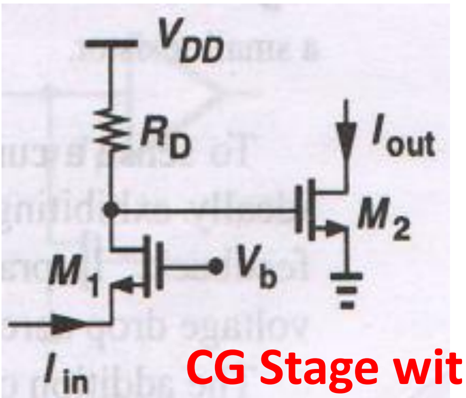
Current Amplifier





CG Stage

Less control on input impedance



CG Stage with CG Amplifier at the input

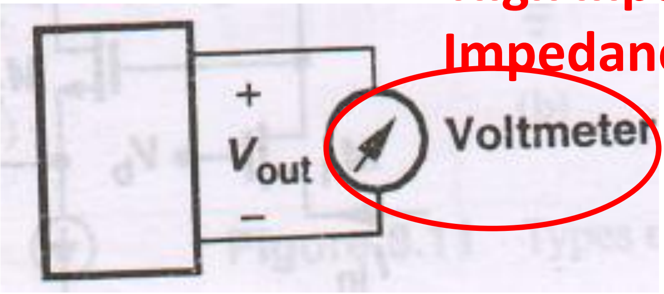
Sense and Return Mechanism

- Placing a circuit in the feedback requires sensing the output signal and then returning a fraction to the input
- Voltage and Current as input and output quantities provide 4 different possibilities for feedback circuit (sense and return circuit)
- Voltage-Voltage: both the input and output of the feedback circuit is voltage
- Voltage-Current: input of feedback is voltage and output is current
- Current-Voltage: input of feedback is current and output is voltage
- Current-Current: both the input and output of feedback circuit is current

Sense and Return Mechanism (contd.)

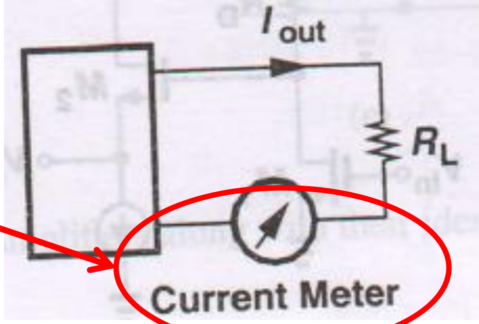
To sense a voltage:

High Input Impedance

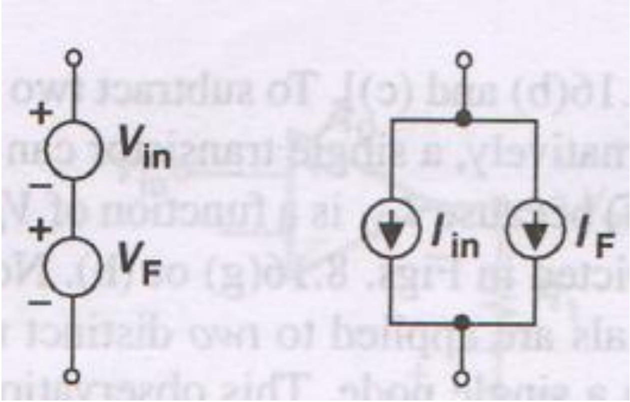


To sense a current:

Low Input Impedance



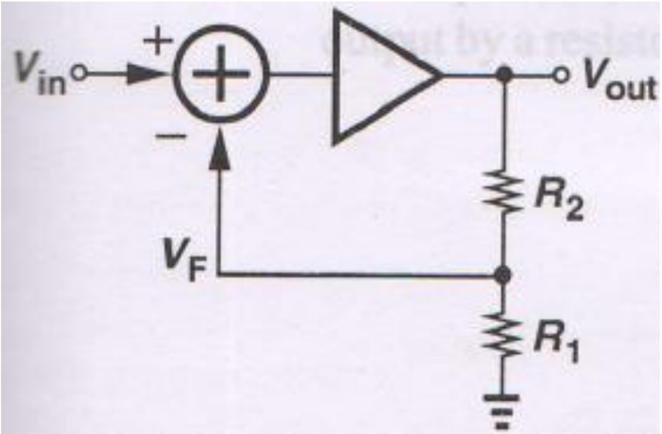
- The addition/subtraction at the input can be done in current or voltage domain: (a) currents are added by placing them in parallel; (b) voltages are added by placing them in series



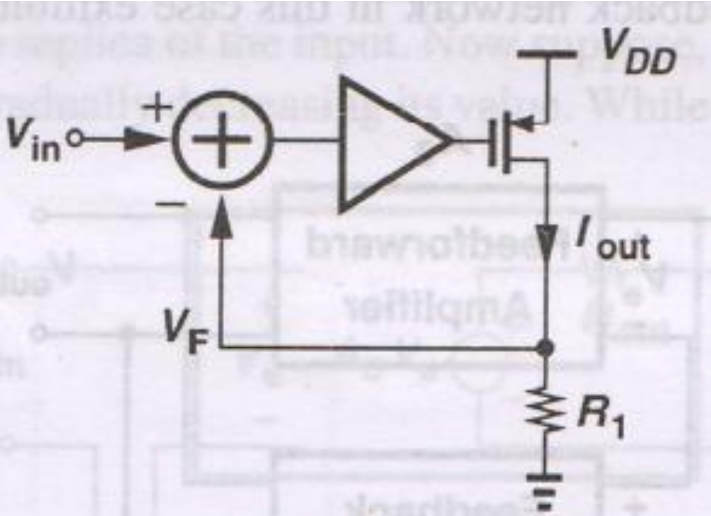
The sense and return mechanism ideally do not affect the operation of feed-forward amplifier → in practical circuits they do introduce loading effects

Sense and Return Mechanism (contd.)

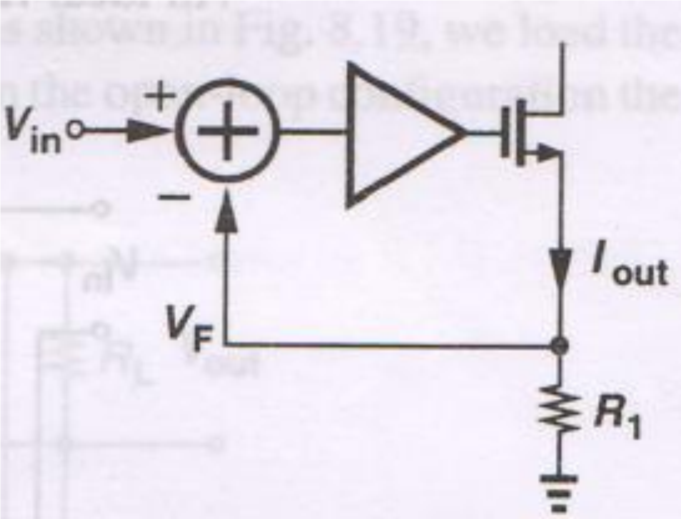
Practical Implementations of Sensing:



Voltage Sensing



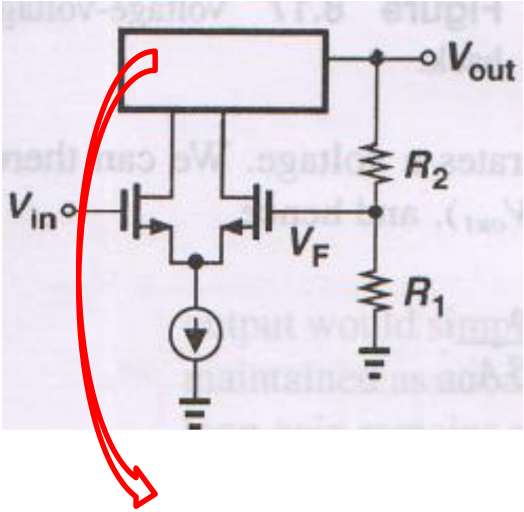
Current Sensing

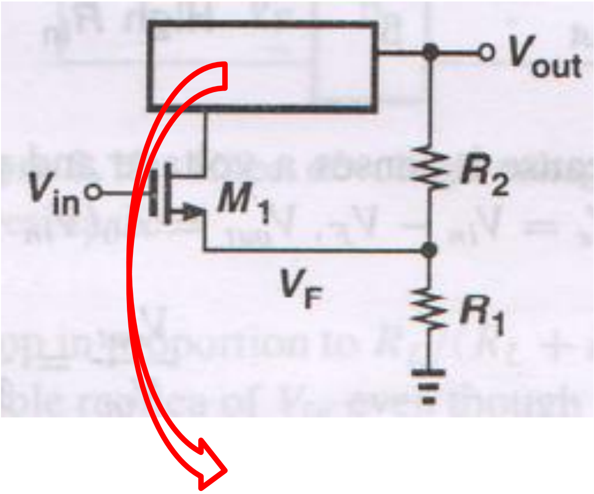


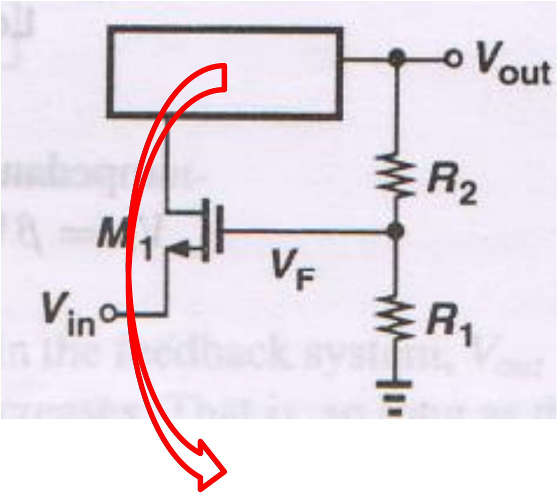
Current Sensing

Sense and Return Mechanism (contd.)

Practical Implementations of Voltage Subtraction:







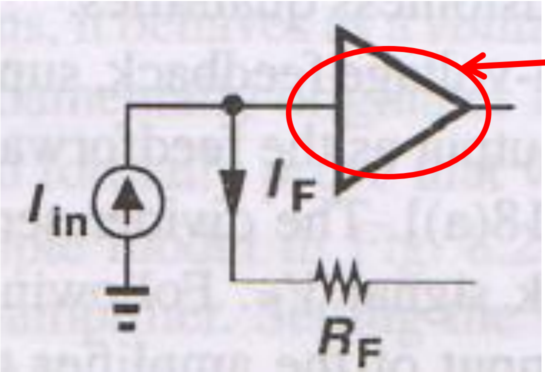
Provides the amplified version of difference between V_{in} and the portion of V_{out}

This CS stage provides output in terms of voltage difference V_{in} - V_F

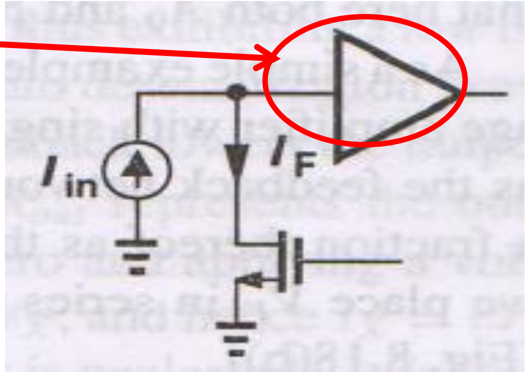
This CG stage provides output in terms of voltage difference V_{in} - V_F

Sense and Return Mechanism (contd.)

Practical Implementations of Current Subtraction:



Feed-forward Amplifier



Important: voltage subtraction happens when they are applied to two distinct nodes whereas current subtraction happens when they are applied to a single node → a precursor to feedback topologies

Feedback Topologies

- **Voltage-Voltage Feedback (also called Shunt-Series Feedback):** both the input and output of the feedback circuit is voltage
- **Voltage-Current Feedback (also called Shunt-Shunt Feedback):** input of feedback is voltage and output is current
- **Current-Voltage (also called Series-Series Feedback):** input of feedback is current and output is voltage
- **Current-Current (also called Series-Shunt Feedback):** both the input and output of feedback circuit is current

Voltage – Voltage Feedback

Sensed Quantity is Voltage

Voltmeter Type Characteristics

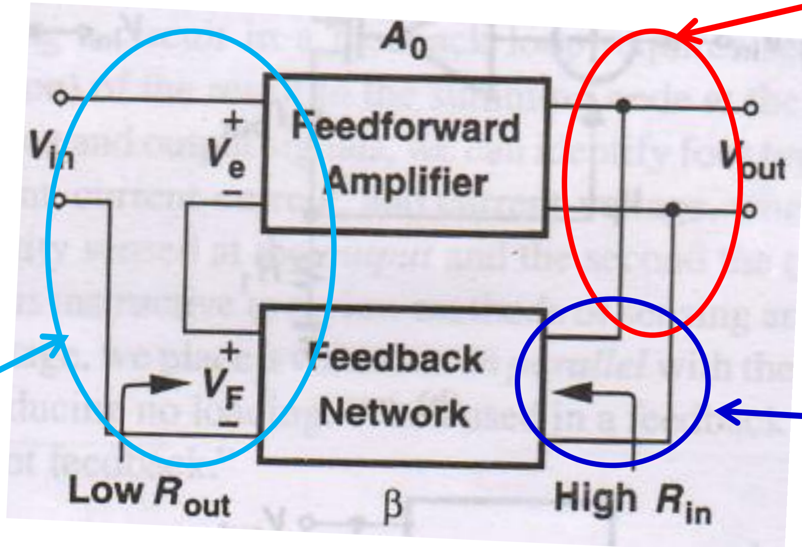
Returned Quantity is Voltage

Should be added/subtracted in series

Voltage-Voltage Feedback

Increased Input Impedance

Subtracted in series



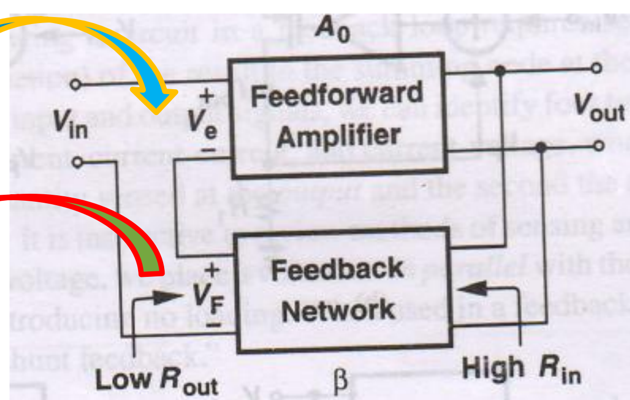
Voltmeter Type Connection → Parallel Sensing

Reduced Output Impedance

This high impedance is in parallel to the feedforward amplifier

$$V_e = V_{in} - V_F$$

$$V_F = \beta V_{out}$$

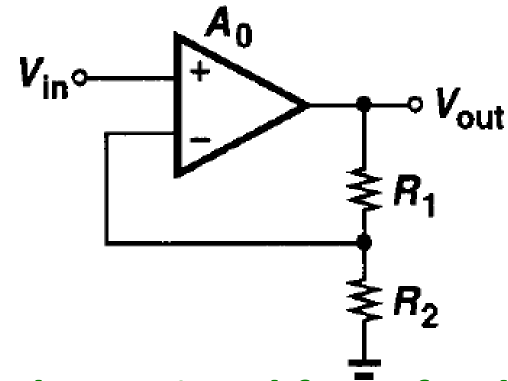


$$V_{out} = A_0 V_e = A_0\left(V_{in} - \beta V_{out}\right)$$

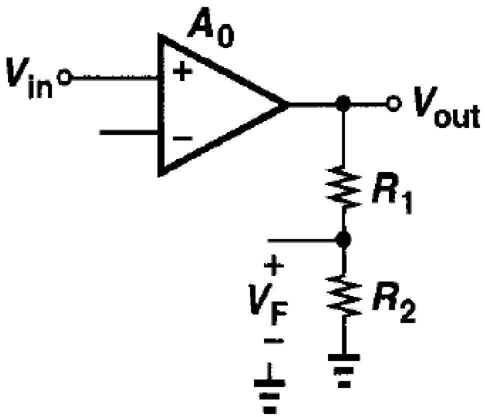
$$\Rightarrow \frac{V_{out}}{V_{in}} = \frac{A_0}{1+\beta A_0}$$

Closed loop gain → modified gain → smaller !!!

Voltage-Voltage Feedback (contd.)



Example: Voltage-Voltage Feedback



For voltage sensing – parallel to the output node of this differential input but single ended output amplifier

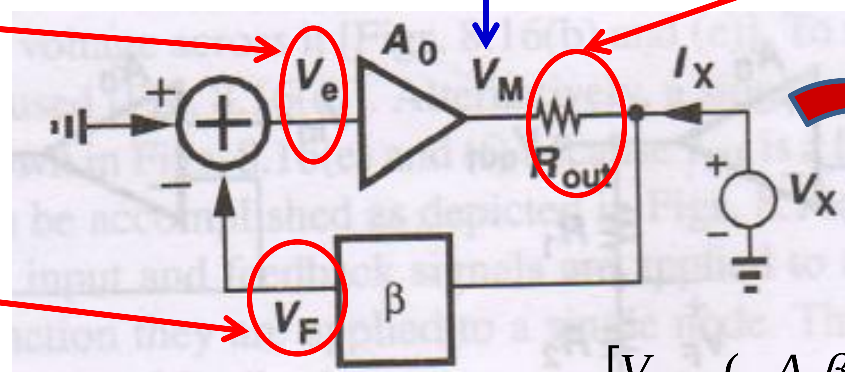
The voltage signal from feedback network is fed to the other input node of the differential amplifier

$$V_M = A_0 V_e = -A_0 \beta V_X$$

Open-Loop Output Impedance

$$V_e = -V_F = -\beta V_X$$

Output Impedance:



$$V_F = \beta V_X$$

$$I_X = \frac{[V_X - (-A_0 \beta V_X)]}{R_{out}}$$

$$\Rightarrow R_{out,closed} = \frac{V_X}{I_X} = \frac{R_{out}}{1 + A_0 \beta}$$

Reduced Closed-Loop Output Impedance

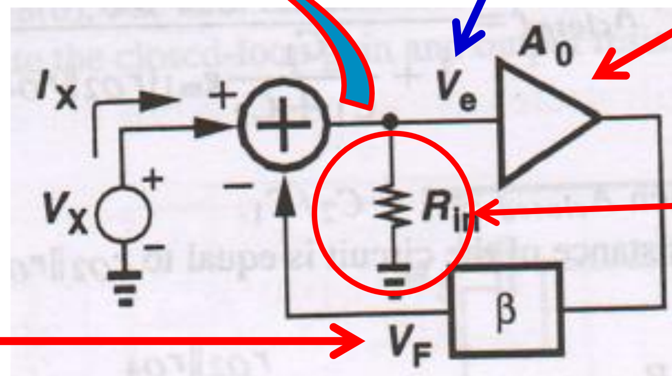
Voltage-Voltage Feedback (contd.)

$V_e = V_X - V_F$

$V_e = I_X R_{in}$

$A_0 I_X R_{in}$

Input Impedance:



Open-Loop Input Impedance

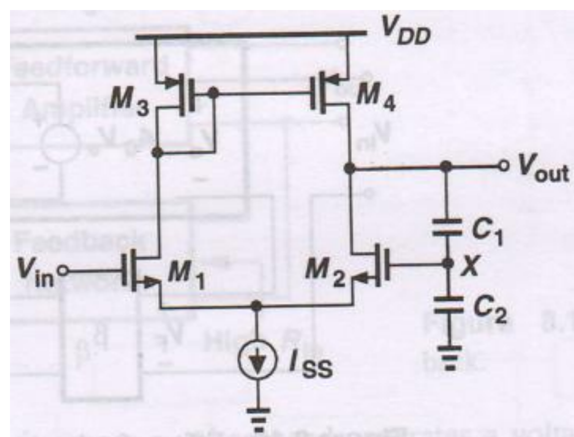
$V_F = \beta A_0 I_X R_{in}$

$$\Rightarrow V_e = V_X - V_F = V_X - \beta A_0 I_X R_{in} = I_X R_{in}$$

$$\therefore R_{in,closed} = \frac{V_X}{I_X} = R_{in}\left(1 + \beta A_0\right)$$

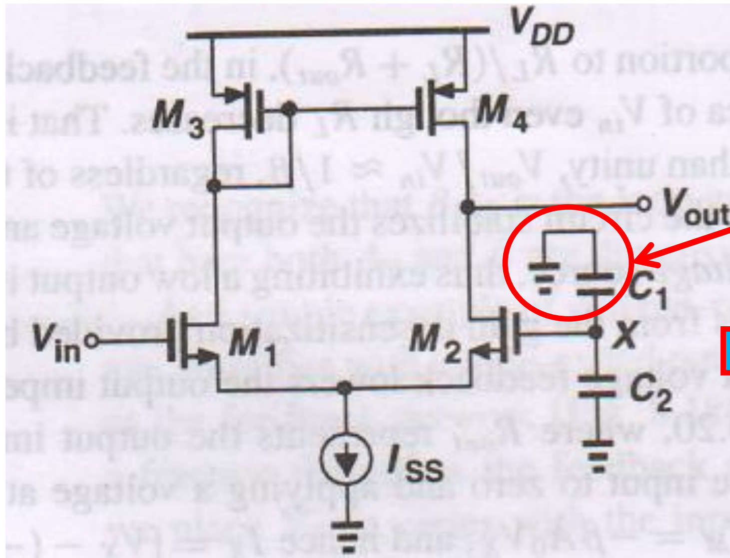
Increased Input Impedance

Example: calculate gain and output impedance of this circuit:



Voltage-Voltage Feedback (contd.)

Step-1: determine open-loop voltage gain

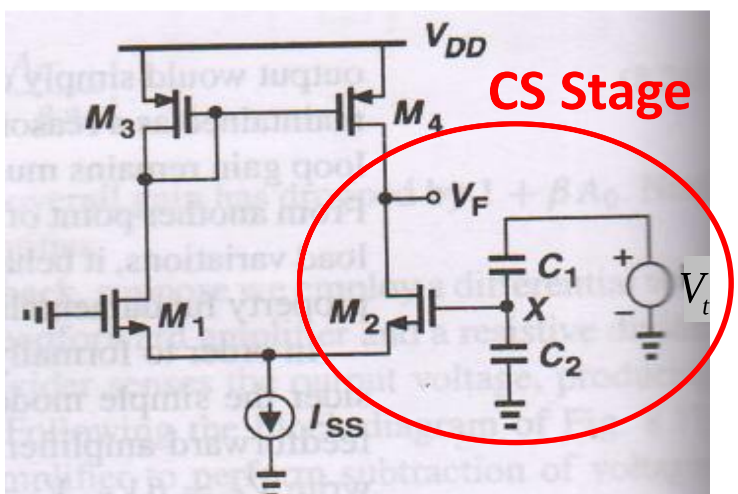


Grounding ensures there is no voltage feedback

Open-loop gain is:

$$A_0 = g_{m1}\left(r_{o2} \| r_{o4}\right)$$

Step-2: determine the loop gain



Drain Current

Output impedance

$$V_F = -V_t \frac{C_1}{C_1 + C_2} g_{m1}\left(r_{o2} \| r_{o4}\right)$$

Therefore,

$$\beta A_0 = \frac{C_1}{C_1 + C_2} g_{m1}\left(r_{o2} \| r_{o4}\right)$$

Voltage-Voltage Feedback (contd.)

$$\Rightarrow A_{closed} = \frac{A_0}{1+\beta A_0} = \frac{g_{m1}\left(r_{o2} \| r_{o4}\right)}{1+\frac{C_1}{C_1+C_2} g_{m1}\left(r_{o2} \| r_{o4}\right)}$$

- **For $\beta A_0 >> 1$,**

$$A_{closed} \simeq \frac{g_{m1}\left(r_{o2} \| r_{o4}\right)}{\frac{C_1}{C_1+C_2} g_{m1}\left(r_{o2} \| r_{o4}\right)} = 1+\frac{C_2}{C_1}$$

- **The closed-loop output impedance,**

$$R_{out,closed} = \frac{R_{out,open}}{1+\beta A_0} = \frac{\left(r_{o2} \| r_{o4}\right)}{1+\frac{C_1}{C_1+C_2} g_{m1}\left(r_{o2} \| r_{o4}\right)}$$

- **For $\beta A_0 >> 1$,**

$$R_{out,closed} \simeq \left(1+\frac{C_2}{C_1}\right)\frac{1}{g_{m1}}$$

Relatively Smaller Value

Stability Issues in Feedback Amplifiers

- **The generic closed-loop transfer function:**

$$A_{closed}(j\omega) = \frac{A_0(s)}{1 + A_0(s)\beta(s)}$$

It is assumed that both the open-loop gain and the feedback gain is frequency dependent

At low frequencies:

- β(s) is assumed as a constant value and A_0(s) is also assumed as a constant value → the loop gain becomes constant → obviously this happens for any direct-coupled amplifier with poles and zeros present at high frequency → the loop gain (Aβ) should be positive value for negative feedback

At high frequencies: $$A_{closed}(j\omega) = \frac{A_0(j\omega)}{1 + A_0(j\omega)\beta(j\omega)}$$

- **Therefore it is apparent that the loop gain is:**

$$L(j\omega) = A_0(j\omega)\beta(j\omega) = |A_0(j\omega)\beta(j\omega)| e^{j\varphi(\omega)}$$

Phase Angle ($e^{j\varphi(\omega)}$), **Magnitude** ($|A_0(j\omega)\beta(j\omega)|$)

It is real with negative sign at the frequency when φ(ω) is 180° → **If for ω=ω_1, the loop gain is less than unity** → **What happens to stability?**

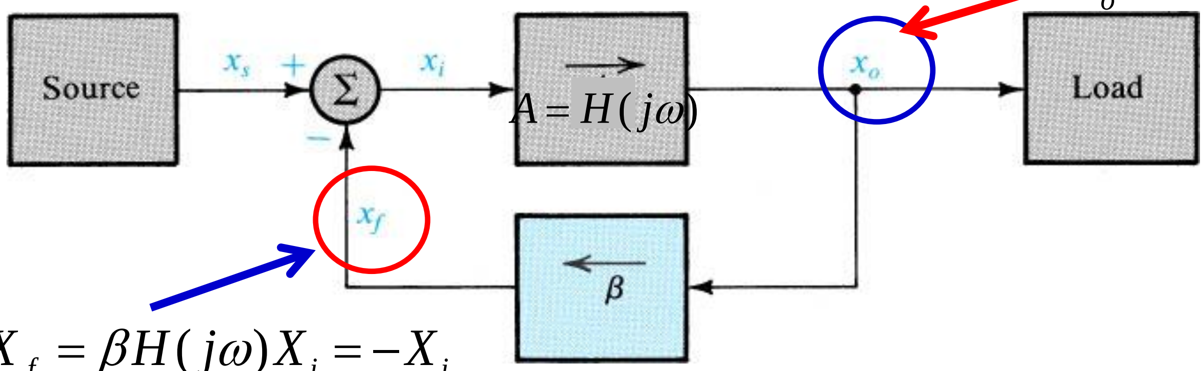
Stability Issues in Feedback Amplifiers (contd.)

At high frequencies:

If at $\omega=\omega_1$, the loop gain (L) is equal to unity with negative sign → Closed-loop gain will be infinite → even for zero input there will be some output → an oscillation condition!!!

For no input: (just excited by some noise)

$$X_o = H(j\omega)X_i$$



$$X_f = \beta H(j\omega)X_i = -X_i$$

Provides a positive feedback which can sustain oscillation

Summary:

- The phase angle of the loop gain equals -180^{O}
- The magnitude of the loop gain is either unity or greater than unity

Both exist together to cause oscillation → Barkhausen Criterion

Stability Issues in Feedback Amplifiers (contd.)

Boundary Condition:

$$|\beta H(j\omega_1)| = 1$$
$$\angle \beta H(j\omega_1) = -180^\circ$$

Notice that the total phase shift around the loop at ω_1 is 360^O because negative feedback itself introduces 180^O

360^O phase shift is necessary for oscillation since the feedback signal must add in phase to the original noise to allow oscillation

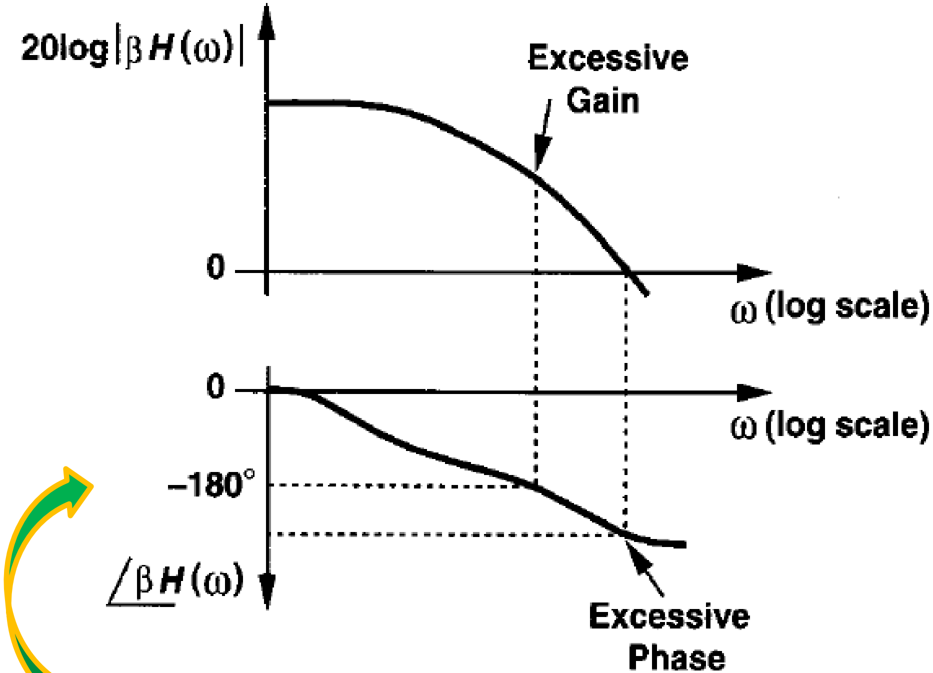
Similarly, a loop gain of unity (or greater) is also required to enable growth of the oscillation amplitude

Summary

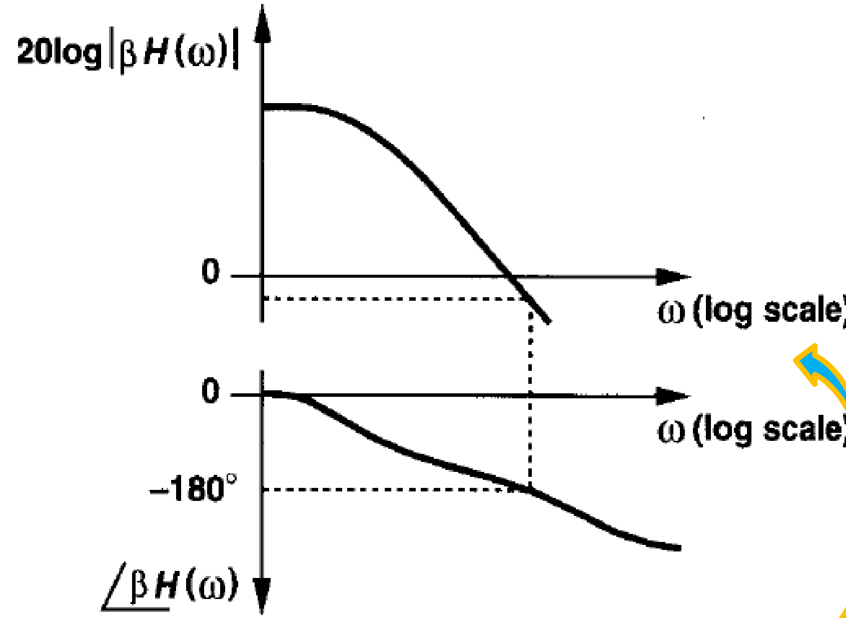
A negative feedback system may oscillate at ω_1 if:

- **the phase shift around the loop at this frequency is so much that the feedback becomes positive, and**
- **the loop gain is still enough to allow signal buildup**

Stability Issues in Feedback Amplifiers (contd.)



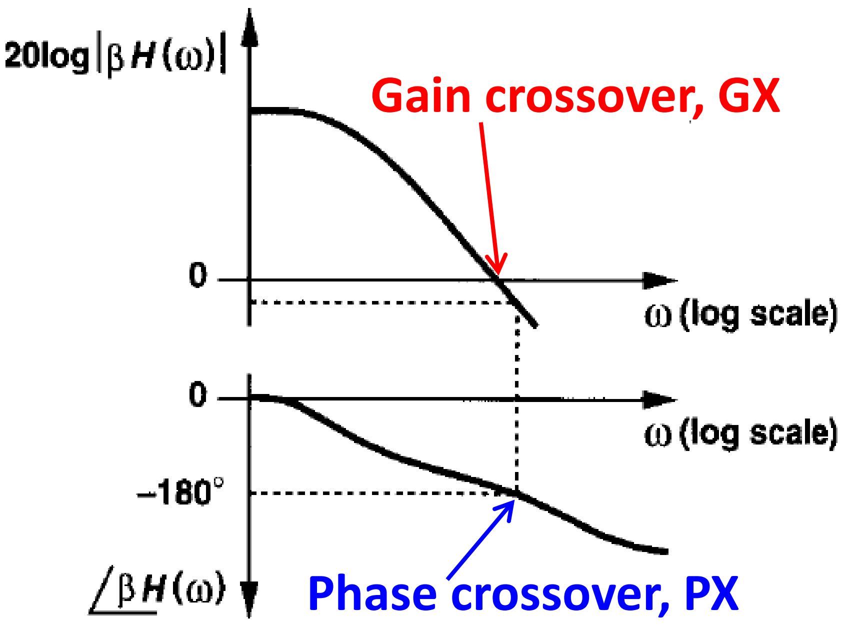
Unstable System



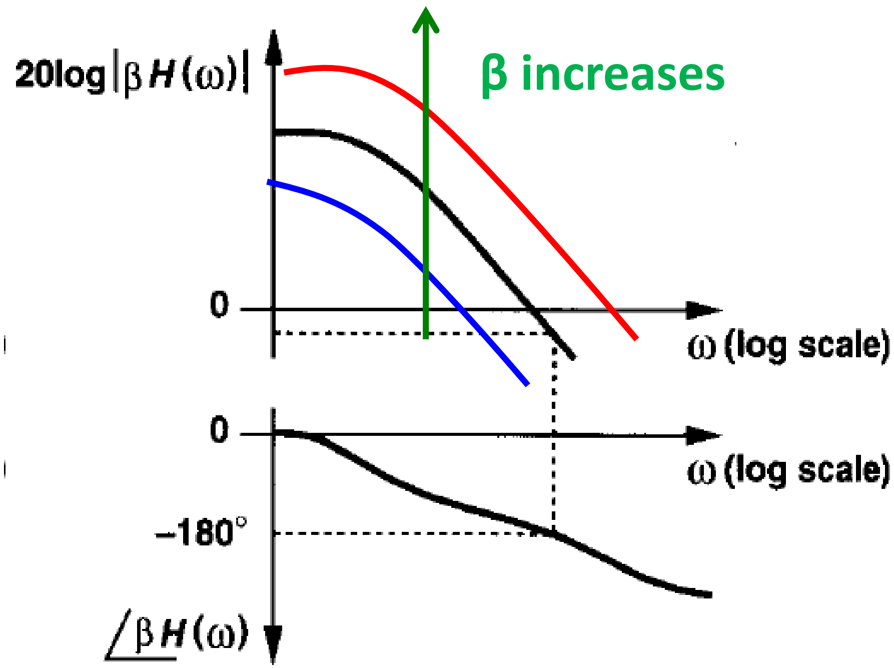
Stable System

To make the system stable, the idea is to minimize the total phase shift so that for |βH|=1, <βH is still more positive than -180^{O}

Stability Issues in Feedback Amplifiers (contd.)



- For a unity gain (β=1) Feedback

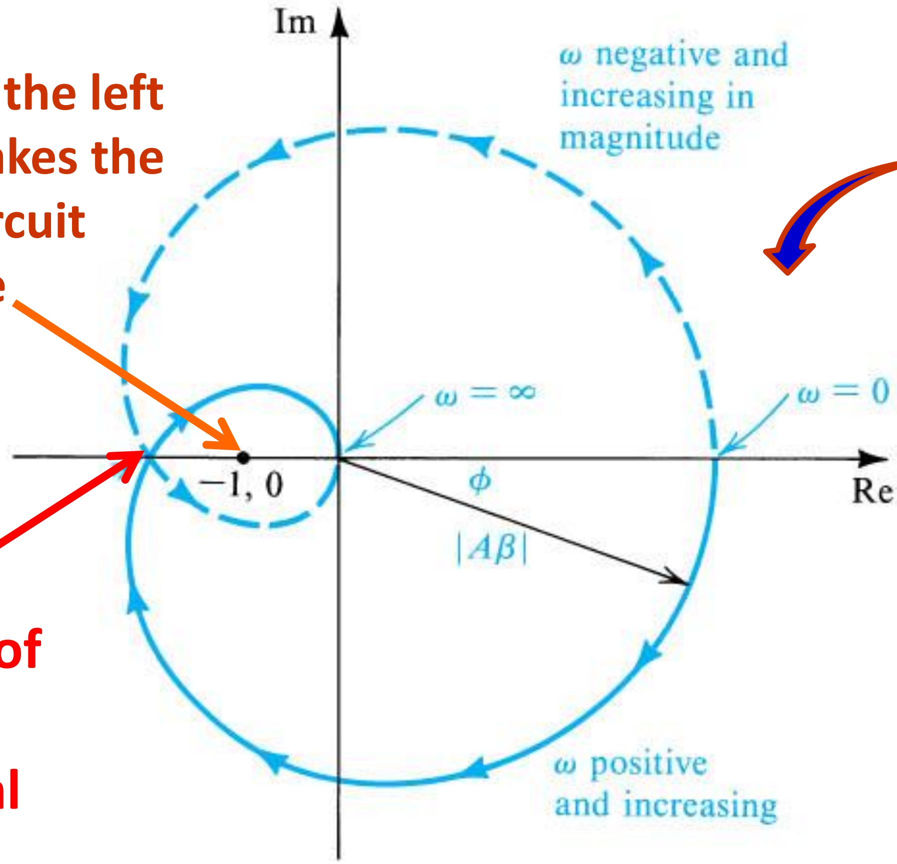


If β is reduced (i.e., less feedback is applied), the magnitude plot will shift down → essentially moves GX closer to origin → in turn makes the system more stable

Stability Issues in Feedback Amplifiers (contd.)

Stability Test: Nyquist Plot

Intersection on the left of this point makes the feedback circuit unstable



Polar plot of loop gain with varying frequency

Intersection of |Hβ| with negative real axis: $\omega=\omega_1$

Stability Issues in Feedback Amplifiers (contd.)

Stability and Pole Location → the transient response of an amplifier with a pole pair $s_p = \sigma_p \pm j\omega_p$ subjected to disturbance will show a transient response:

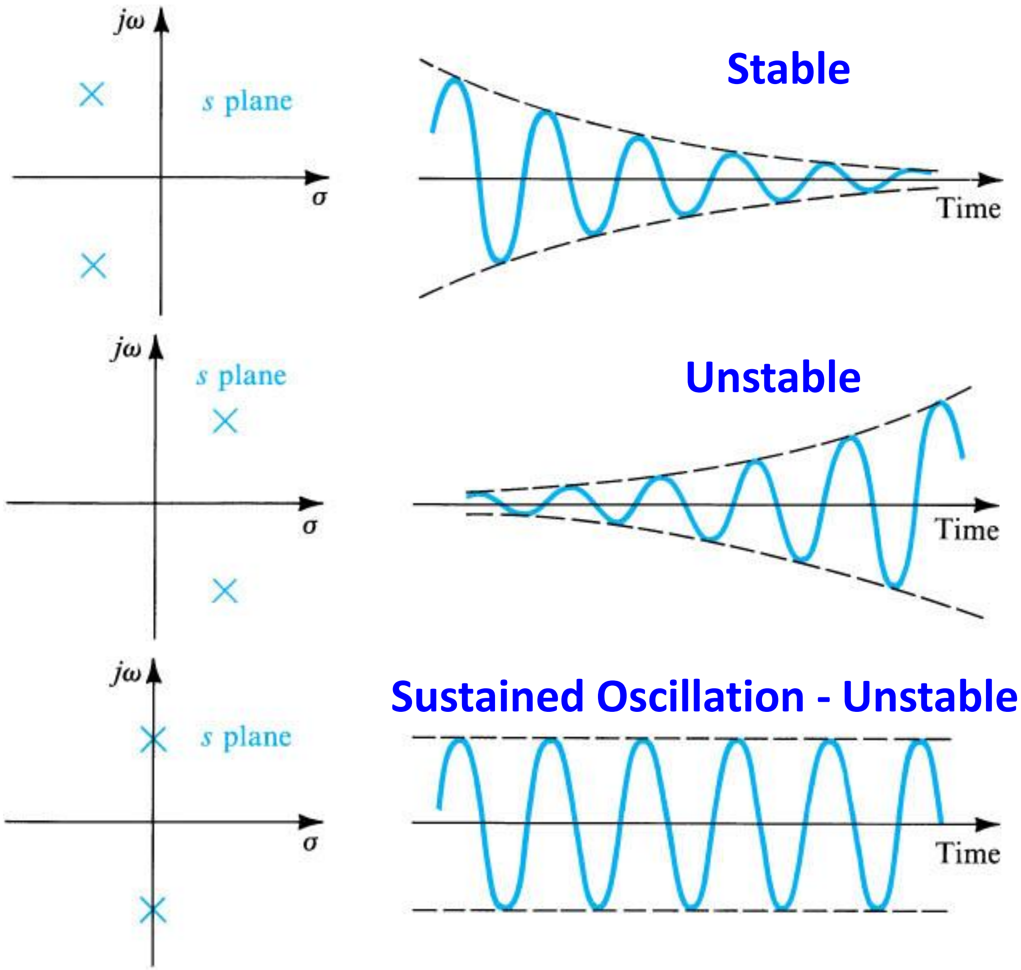
$$x(t) = e^{\sigma_p t}\left[e^{+j\omega_p t} + e^{-j\omega_p t}\right] = 2e^{\sigma_p t}\cos(\omega_p t)$$

Envelope **Sinusoid**

- For poles in right half of the s-plane the oscillations will grow exponentially considering that σ_p will be positive
- For poles with $\sigma_p = 0$, the oscillation will be sustained
- For poles in the left half of the s-plane, the term σ_p will be negative and therefore the oscillation will decay exponentially towards zero

Stability Issues in Feedback Amplifiers (contd.)

Stability and Pole Location



Negative σ_p

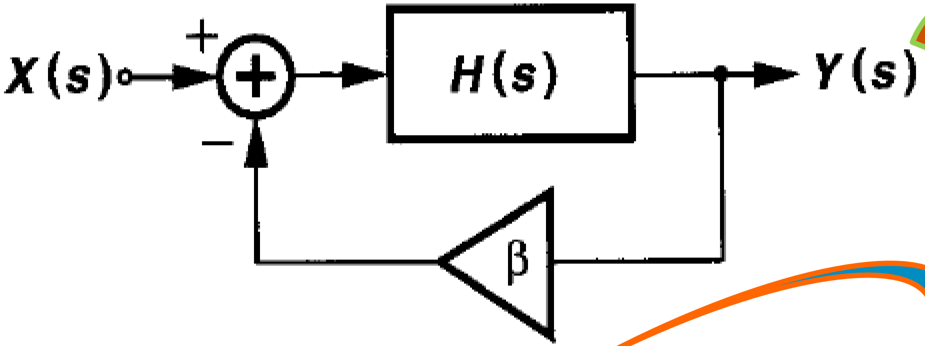
Positive σ_p

Zero σ_p

Obviously, the presence of zeros have been ignored

Poles of the Feedback Amplifier

- Study of single-pole feedforward amplifier



Closed-loop transfer function

$$A_{closed}(s) = \frac{Y}{X}(s) = \frac{H(s)}{1+\beta H(s)}$$

Where, $H(s) = \dfrac{A_0}{(1+s/\omega_p)}$

Then the closed-loop transfer function becomes

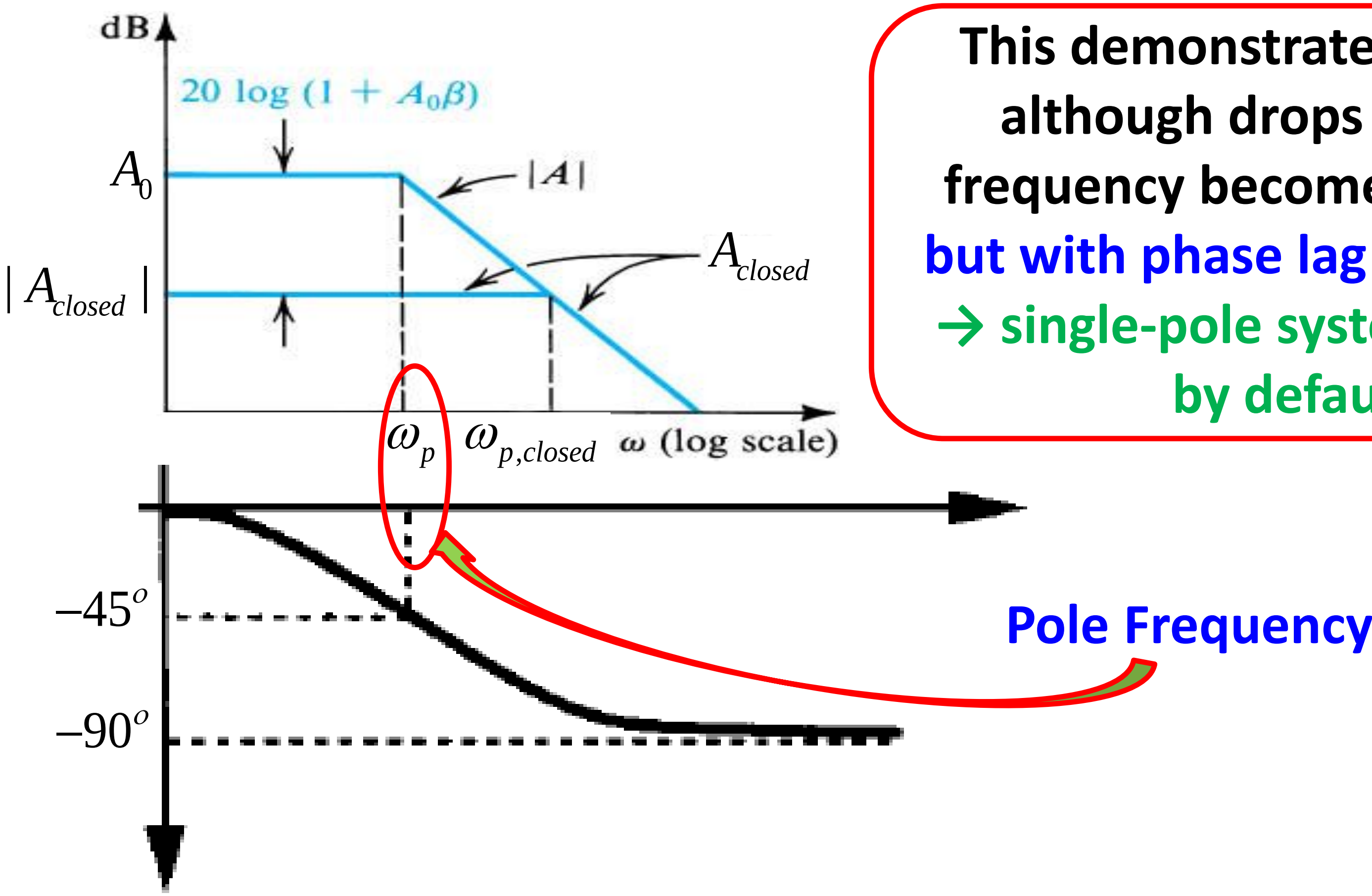
$$A_{closed}(s) = \frac{A_0/(1+A_0\beta)}{1+s/\omega_P(1+A_0\beta)}$$

It is apparent that the feedback moves the pole frequency from ω_p to:

$$\omega_{p,closed} = \omega_p(1+A_0\beta)$$

Amplifier with a Single Pole (contd.)

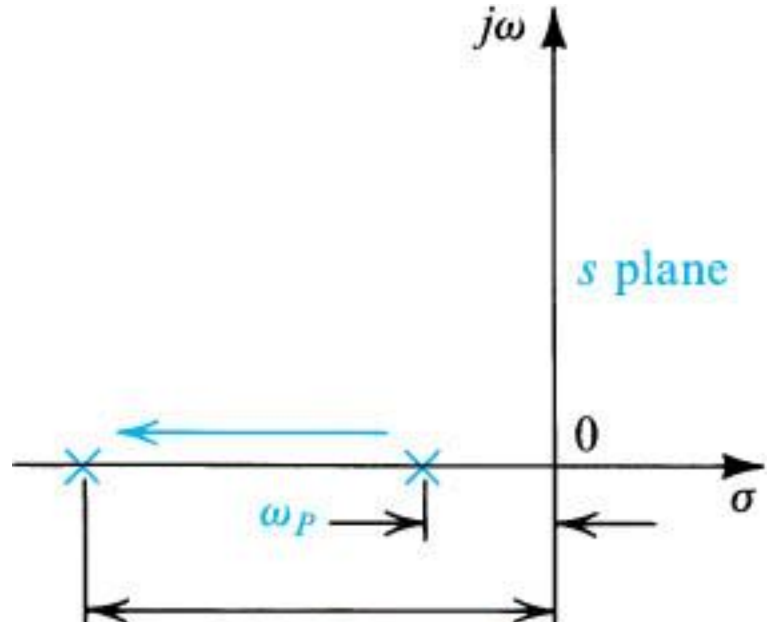
- The frequency response of amplifier with and without feedback



This demonstrates that gain although drops and pole frequency becomes bigger → but with phase lag of only -90° → single-pole system is stable by default

Amplifier with a Single Pole (contd.)

Root Locus



$$\omega_{p,closed} = \omega_p(1 + A_0\beta)$$

The original pole and its movement with feedback

It is apparent that the pole never enters the right half of the s-plane → unconditionally stable scenario!

Amplifier with Two Poles

- Open-loop transfer function of an amplifier with two pole is given as:

$$A(s) = \frac{A_0}{(1+s/\omega_{P1})(1+s/\omega_{P2})}$$

  - The closed-loop poles are obtained from:

$$1 + A(s)\beta = 0 \qquad \Rightarrow s^2 + s(\omega_{P1} + \omega_{P2}) + (1 + A_0\beta)\omega_{P1}\omega_{P2} = 0$$

  - Therefore the closed-loop poles are:

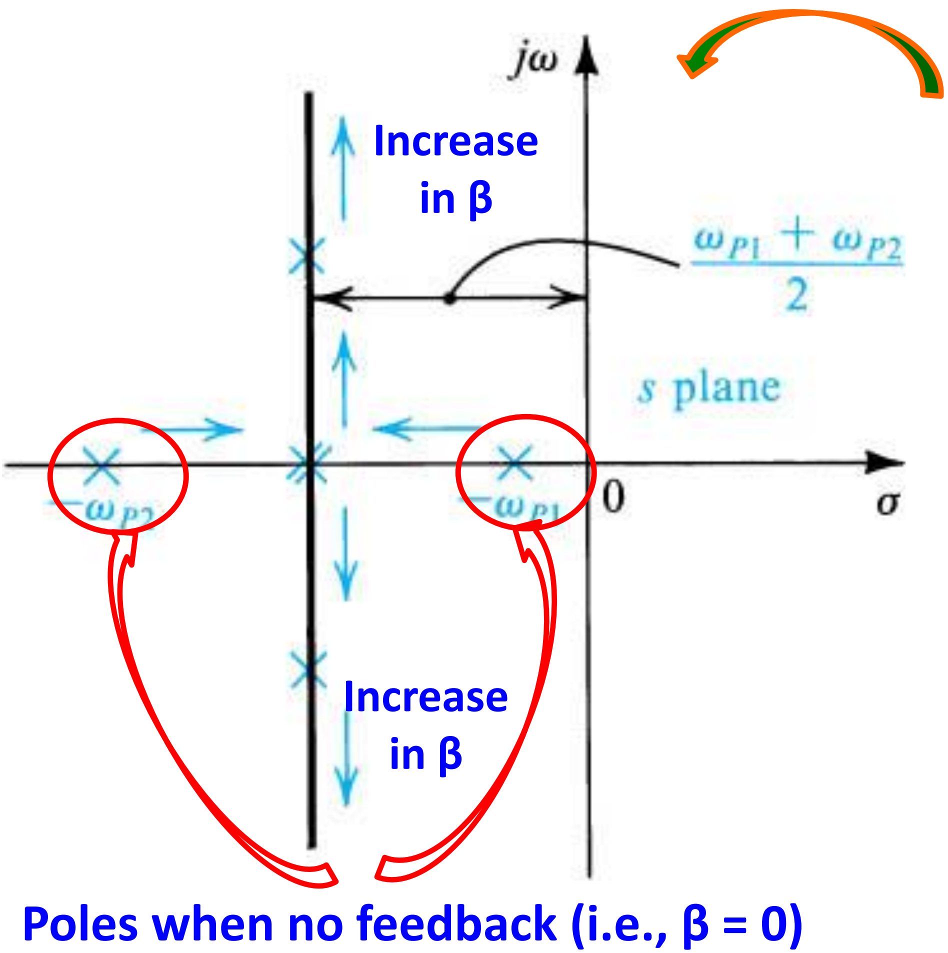
$$s = -\frac{1}{2}(\omega_{P1} + \omega_{P2}) \pm \frac{1}{2}\sqrt{(\omega_{P1} + \omega_{P2})^2 - 4(1 + A_0\beta)\omega_{P1}\omega_{P2}}$$

- As the loop gain $A_0\beta$ is increased from zero, the poles come closer
- At certain $A_0\beta$ the poles will coincide
- Further increase in $A_0\beta$ make poles complex conjugate which move along a vertical line

Amplifier with Two Poles (contd.)

Root-locus Diagram

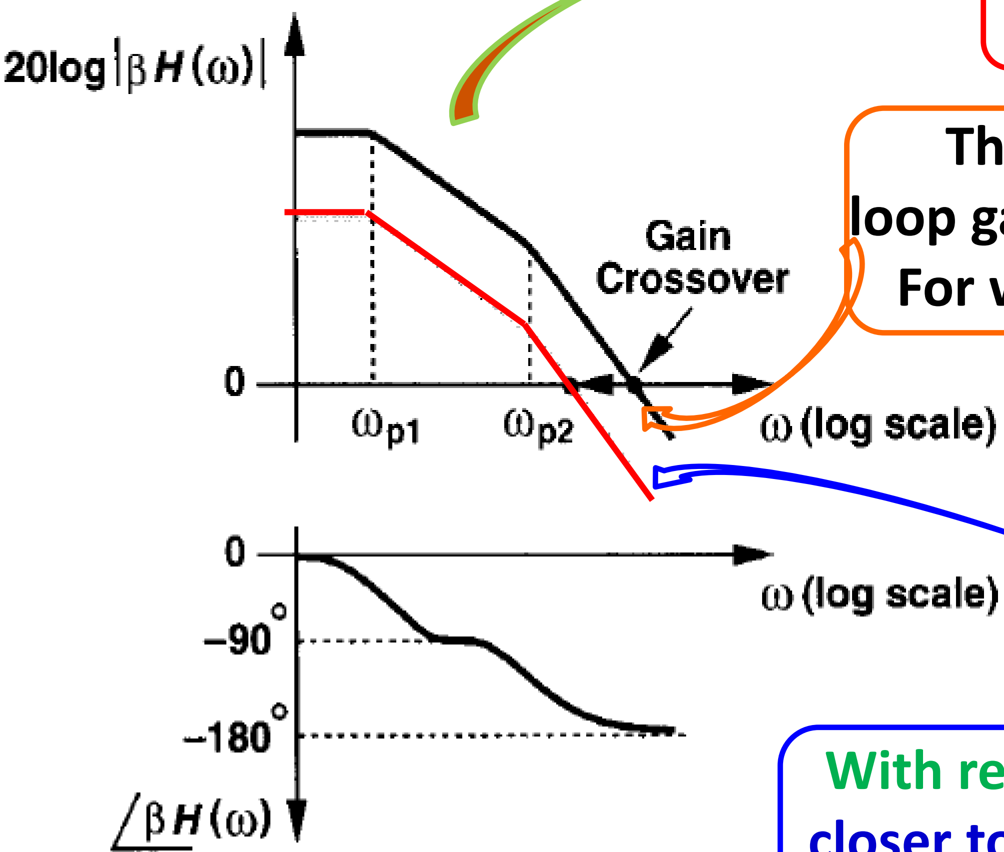
$$s = -\frac{1}{2}(\omega_{P1} + \omega_{P2}) \pm \frac{1}{2}\sqrt{(\omega_{P1} + \omega_{P2})^2 - 4(1 + A_0\beta)\omega_{P1}\omega_{P2}}$$



- Root-locus shows that the poles never enter the right half of s-plane
  - Unconditionally stable !!!
- Reason is simple: the maximum phase shift of A(s) is -180^O (-90^O per pole) [that too when $\omega_p \rightarrow \infty$]
- There is no finite frequency at which the phase shift reaches -180^O → therefore no polarity reversal of feedback

Amplifier with Two Poles (contd.)

Frequency Response



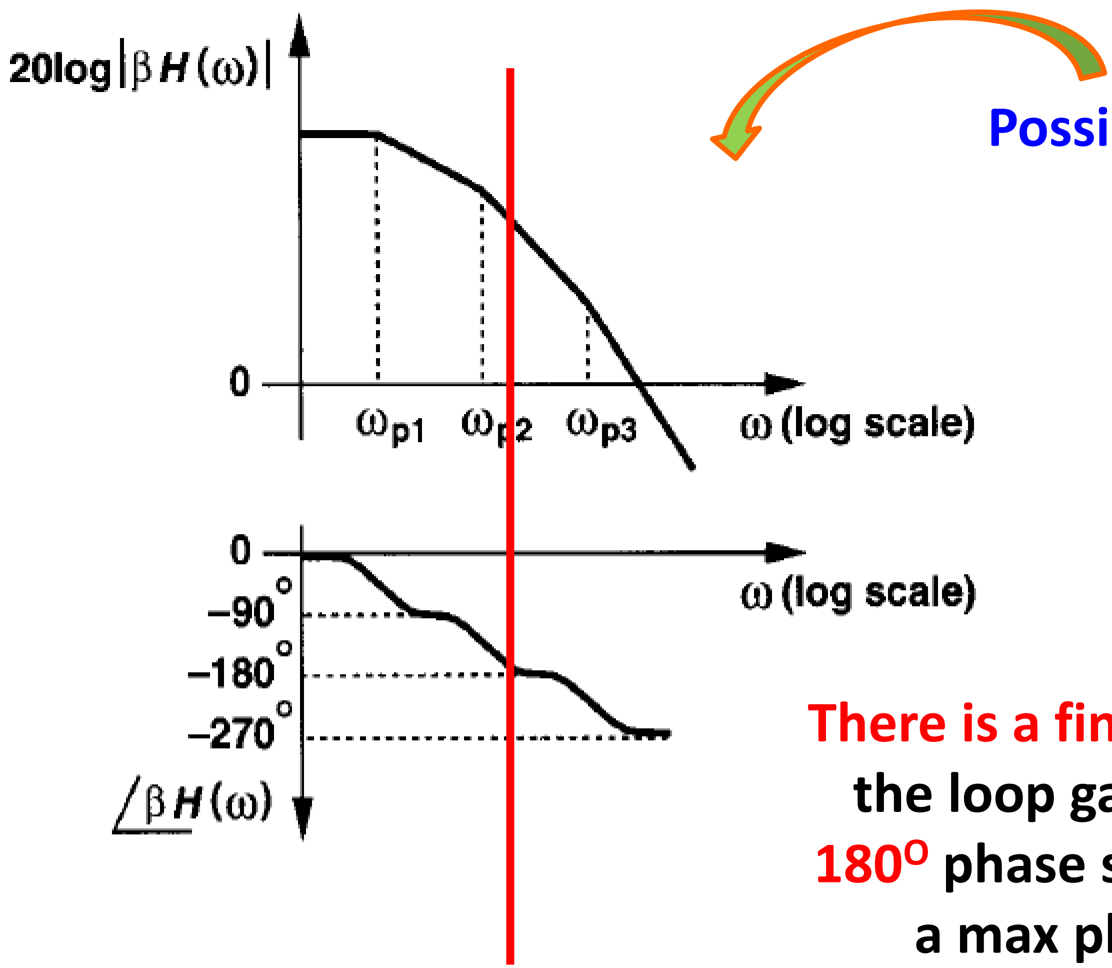
GX happens before PX → unconditionally stable

The system is stable since the loop gain is less than 1 at a frequency For which the angle(βH(ω))=-180.

With reduced feedback → GX moves closer to origin → doesn't affect PX → the system becomes more stable

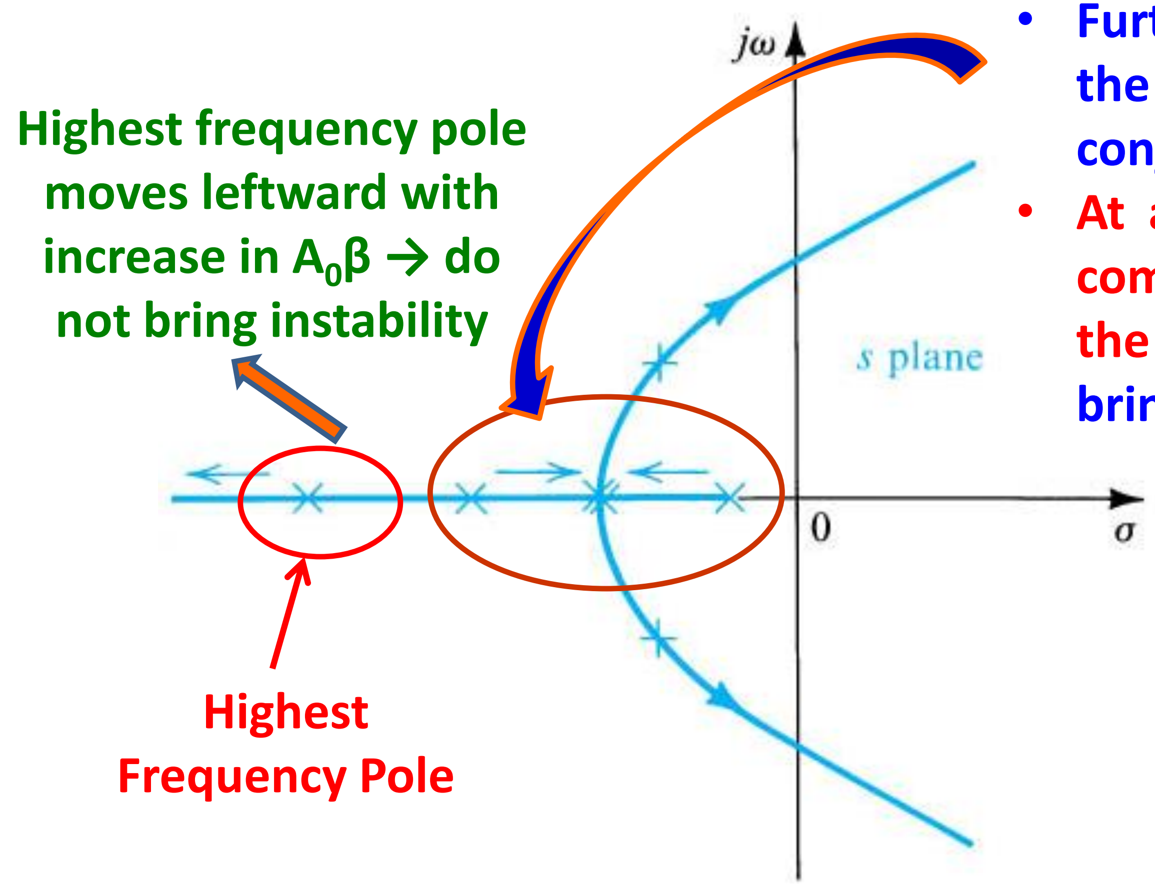
Amplifier with Three Poles

Frequency Response



There is a finite frequency at which the loop gain can be more than 180^{O} phase shift (3 poles can bring a max phase shift of 270^{O})

Amplifier with Three Poles



- Increase in $A_0\beta$ bring the other two poles together
- Further increase in $A_0\beta$ make the poles complex and then conjugate
- At a definite $A_0\beta$ the pair of complex-conjugate poles enter the right half of s-plane $\rightarrow$ bring instability!!!

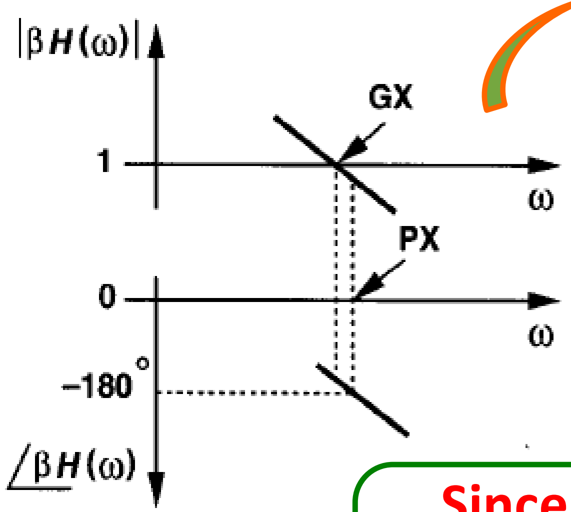
Amplifier with Three Poles (contd.)

- In order to maintain the stability of amplifiers it is imperative to keep loop gain $A_0\beta$ smaller than the value corresponding to the poles entering right half s-plane
- In terms of Nyquist diagram, the critical value of $A_0\beta$ is that for which the diagram passes through the (-1, 0) point
- Reducing $A_0\beta$ below this value causes the Nyquist plot to shrink → the plot intersects the negative real axis to the right of (-1, 0) point → indicates stable amplifier
- Increasing $A_0\beta$ above this value causes expansion of Nyquist plot → plot encircles the (-1, 0) point → unstable performance

Case Study: Relative Location of GX and PX

- **Case 1: <βH(jω$_p$)=-175^o**
- **Case 2: <βH(jω$_p$) such that GX<<PX**
- **Case 3: <βH(jω$_p$)=-135^o**

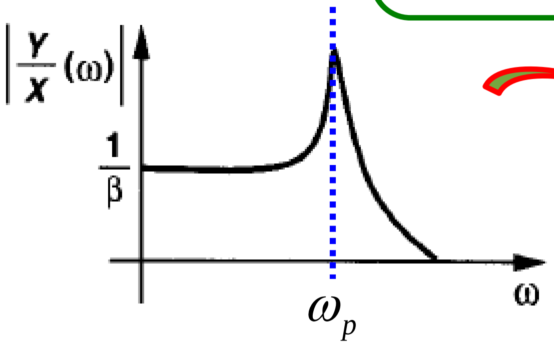
Case 1: $<\beta H(j\omega_p)=-175^o$

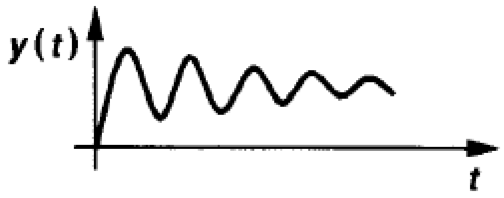


$$\frac{Y}{X}(j\omega_p)=\frac{H(j\omega_p)}{1+\beta H(j\omega_p)} \Rightarrow \frac{Y}{X}(j\omega_p)=\frac{\frac{1}{\beta}e^{-j175^o}}{1+\frac{1}{\beta}e^{-j175^o}}$$

$$\therefore \frac{Y}{X}(j\omega_p)\approx\frac{11.5}{\beta}$$

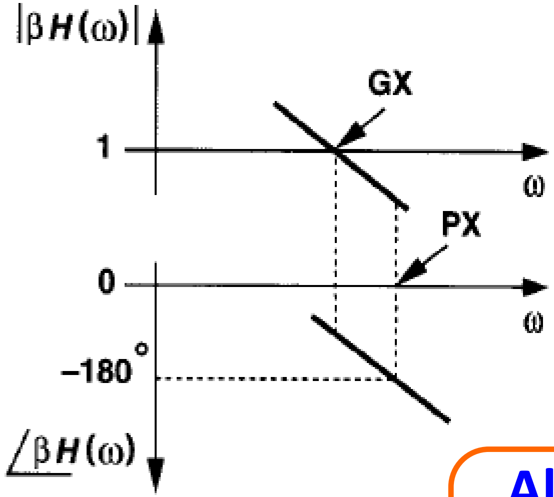
Since at low frequencies, |Y/X| = 1/β: the closed loop freq response exhibits a sharp peak in the vicinity of $\omega=\omega_p$





The system is technically stable, but it suffers from ringing

Case 2: <βH(jω$_p$) such that GX<<PX



Higher is the spacing between GX and PX (while GX remains below PX), the more stable is the system

Alternatively, phase of βH at the GX frequency can serve as the measure of stability: the smaller <βH at GX, the more stable the system

Leads to the concept of phase margin (PM)

$$PM = 180^o + \angle \beta H(\omega_1)$$

Where, ω_1 is the GX frequency

Case 3: <βH(jω1)=-135

- **How much PM is adequate?**

$$PM = 45^o$$

$$\angle \beta H(\omega_1) = -135^o$$

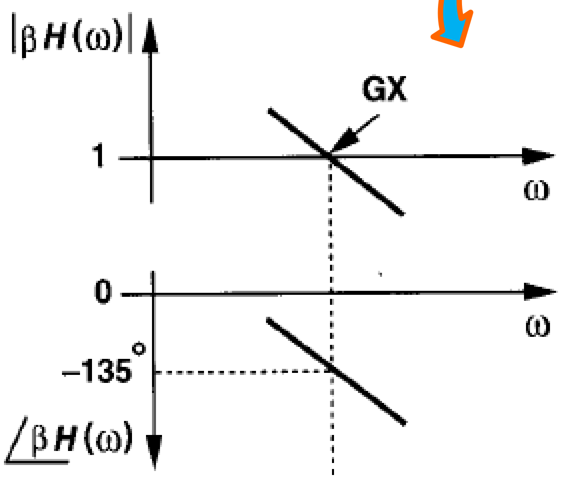
$$|\beta H(\omega_1)| = 1$$

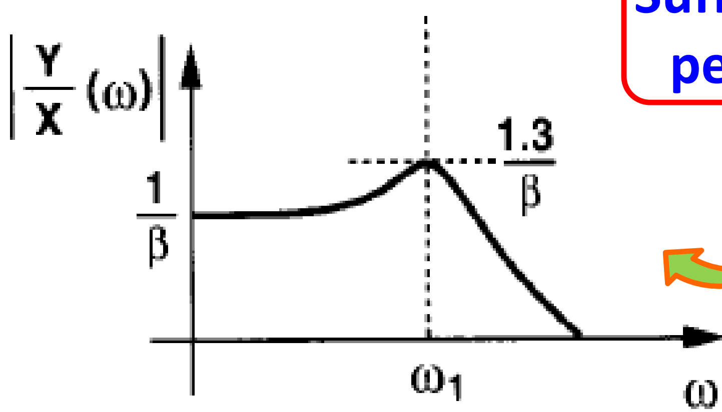
$$\frac{Y}{X}(j\omega_1) = \frac{H(j\omega_1)}{1 + 1\times e^{-j135^o}}$$

Closed-Loop

$$\left|\frac{Y}{X}\right| = \frac{1.3}{\beta}$$

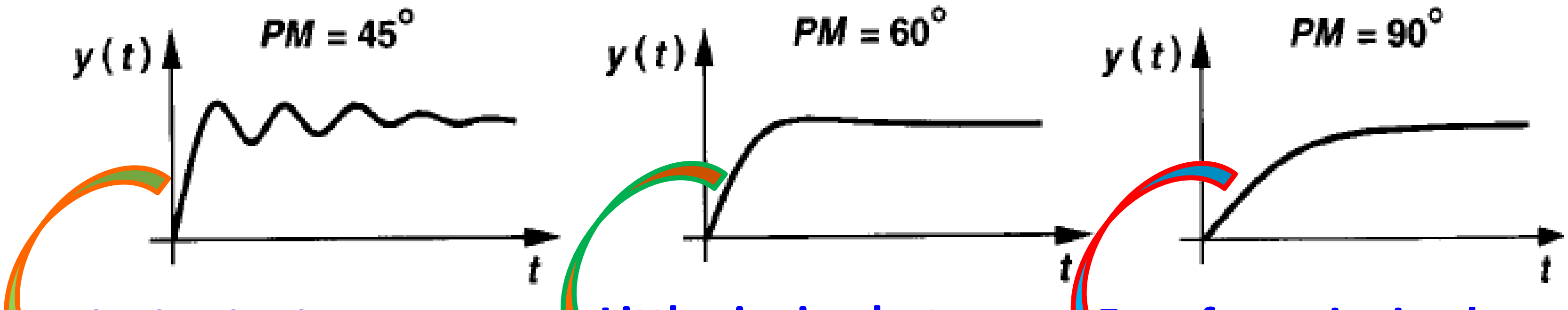
Suffers a 30% peak at ω_1





Case 3: <βH(jω1)=-135

- Peaking is associated with ringing in time domain



Ringing in time domain

Little ringing but fast settling

Free from ringing but slow settling

You design your system to achieve PM of around 60^{o}

Caution

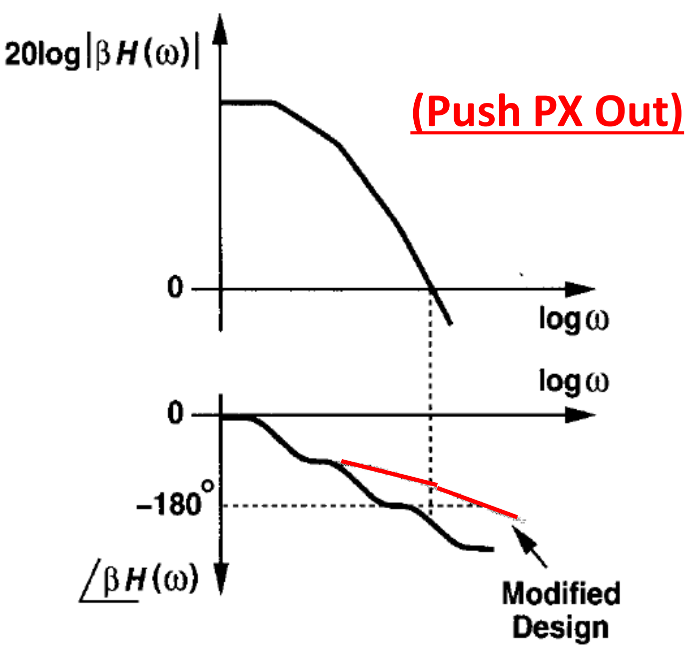
- PM is useful for small signal analysis.
- For large signal step response of a feedback system, the nonlinear behavior is usually such that a system with satisfactory PM may still exhibit excessive ringing.
- Transient analysis should be used to analyze large signal response.

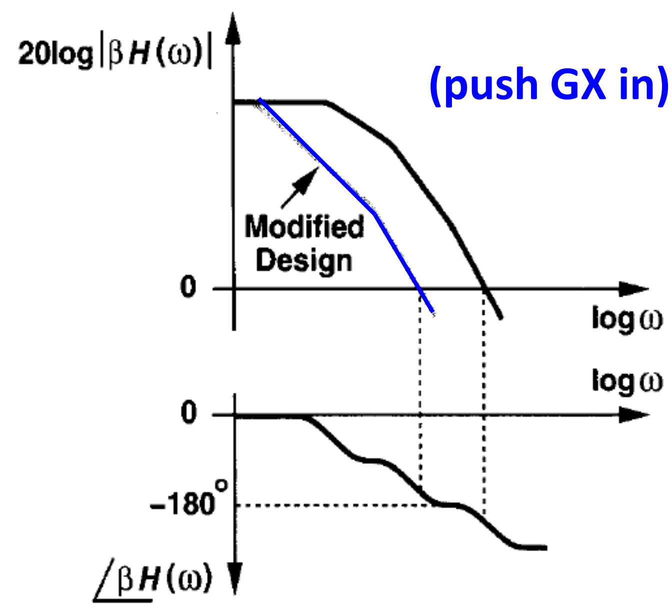
Frequency Compensation

- Open loop transfer function is modified such that the closed-loop circuit is stable and the time response is well behaved

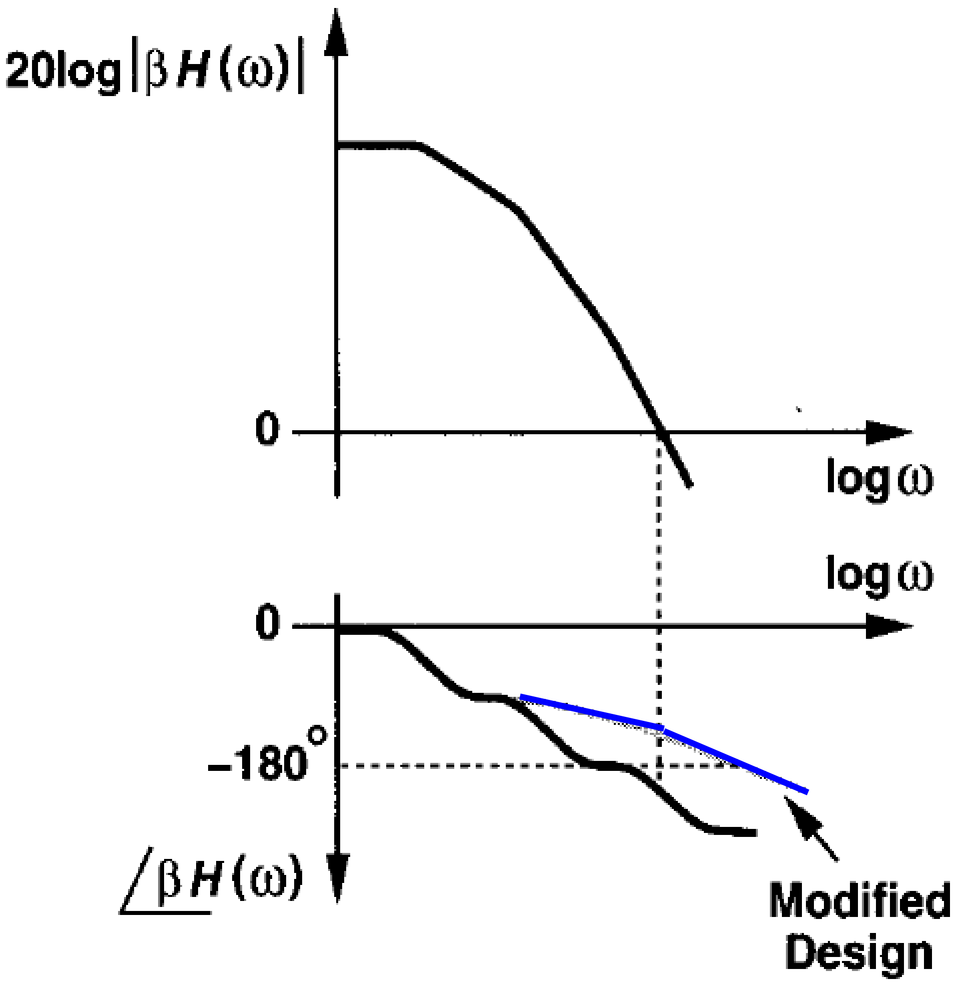
- Reason for frequency compensation:
  - $|\beta H(\omega)|$ does not drop to unity when $\angle\beta H(\omega)$ reaches -180°.

- Possible Solutions:



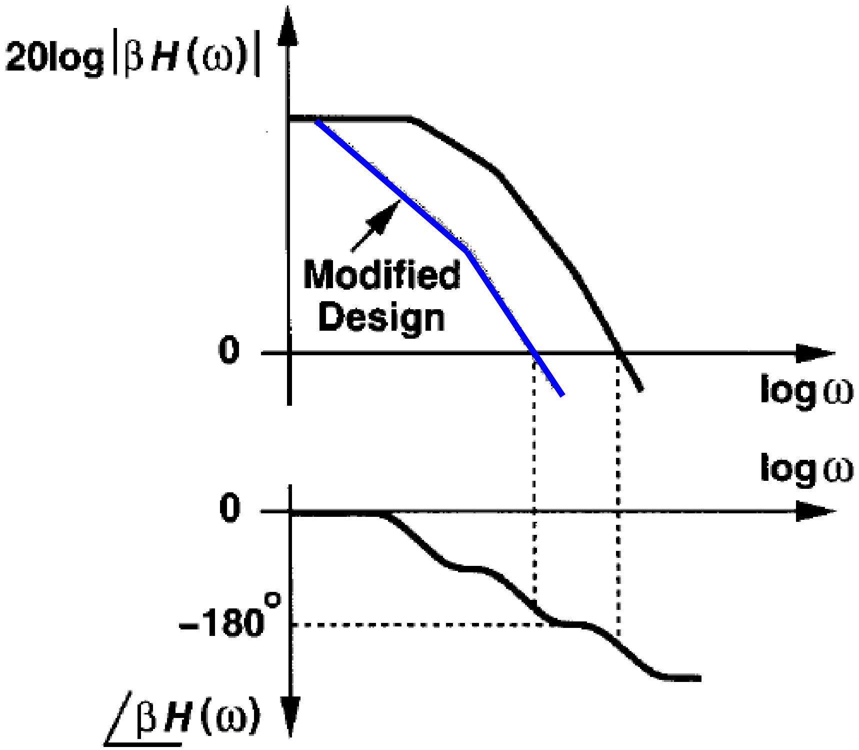


Option 1: Push PX OUT



- Minimize the # of poles
- What's the problem?
  - Each stage contributes a pole.
- Reduction in # of stages implies difficult trade-off of gain versus output swings.

Option 2: Push GX In



Problem:

Bandwidth is sacrificed for stability

Typical Approach

- Minimize the number of poles first to push PX out
- Use compensation to move the GX towards the origin next