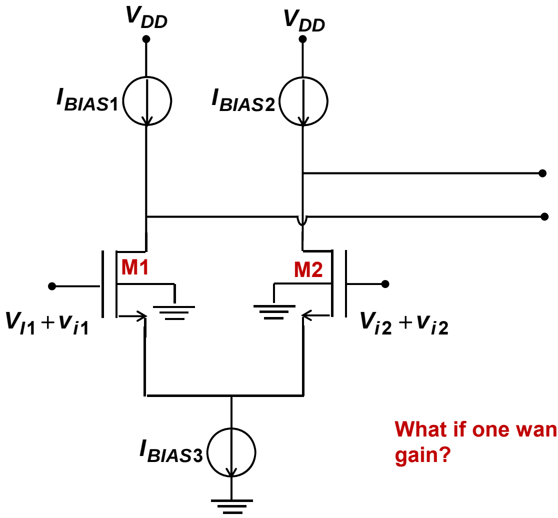
Lecture 20a

Circuit Topologies and Techniques: Opamps

In this lecture you will learn:

- Some circuit topologies and techniques
- Introduction to operational amplifiers

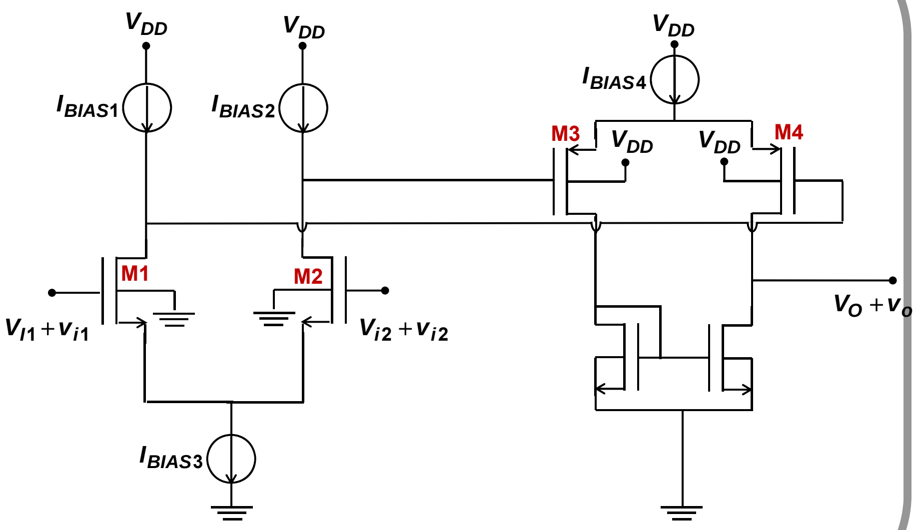
A Differential Amplifier



What if one wants larger differential gain?

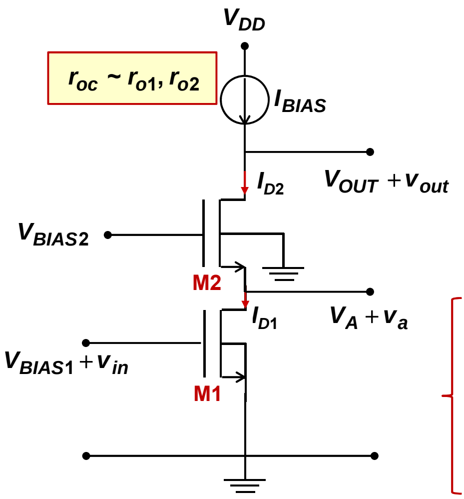
Large gain, small gain bandwidth (Miller effect), large input resistance, large output resistance

A Differential Amplifier Cascade



Very large gain, small gain bandwidth (Miller effect in both stages of the cascade), large input resistance, large output resistance, high CCMR

Telescopic Cascode Topology: Non-Ideal Current Source



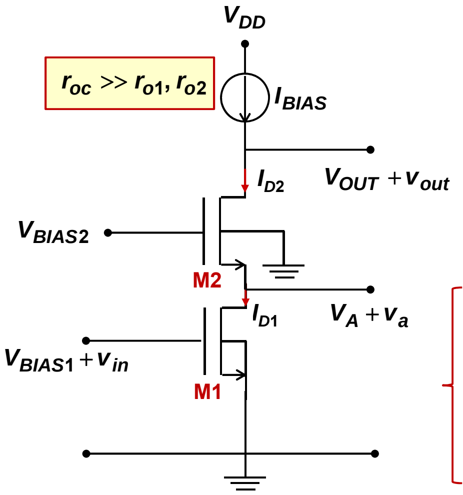
$r_{oc} \sim r_{o1}, r_{o2}$

$$\frac{v_{out}}{v_a} \approx (g_{m2}+g_{mb2})(r_{o2} \| r_{oc})$$

$$\begin{aligned}\frac{v_a}{v_{in}} &\approx -g_{m1}\left(r_{o1} \| \frac{1}{(g_{m2}+g_{mb2})}\left(1+\frac{r_{oc}}{r_{o2}}\right)\right)\\ &\sim -\frac{g_{m1}}{(g_{m2}+g_{mb2})}\left(1+\frac{r_{oc}}{r_{o2}}\right)\\ &\sim -2\end{aligned}$$

Large gain, large input resistance, large output resistance, output swing could be limited, large gain bandwidth (no Miller effect)

Telescopic Cascode Topology: More Ideal Current Source



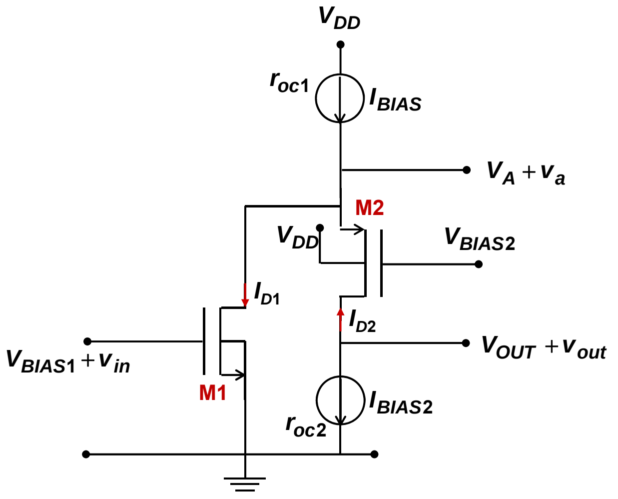
$r_{oc} >> r_{o1}, r_{o2}$

$$\frac{v_{out}}{v_a} \approx (g_{m2}+g_{mb2})(r_{o2} \| r_{oc})$$

$$\frac{v_a}{v_{in}} = -g_{m1}\left(r_{o1} \| \frac{1}{(g_{m2}+g_{mb2})}\left(1+\frac{r_{oc}}{r_{o2}}\right)\right)$$

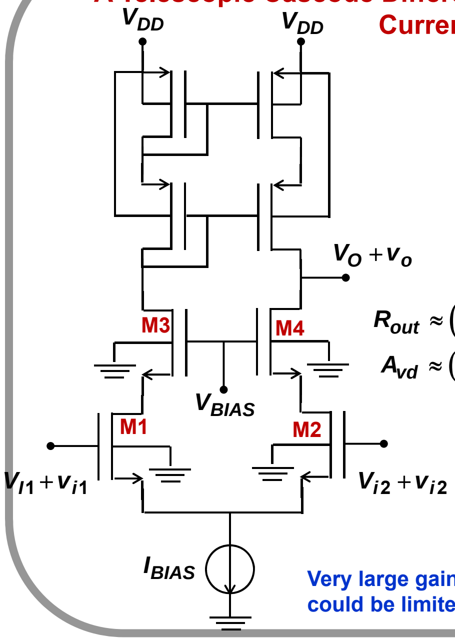
Very large gain, large input resistance, large output resistance, output swing could be limited, small gain bandwidth (Miller effect from CS stage)

Folded Cascode Topology



Easier to set input bias voltages than in the telescopic cascade, large output swing, more power dissipation than in the telescopic cascode

A Telescopic Cascode Differential Amplifier with a Cascode Current Mirror

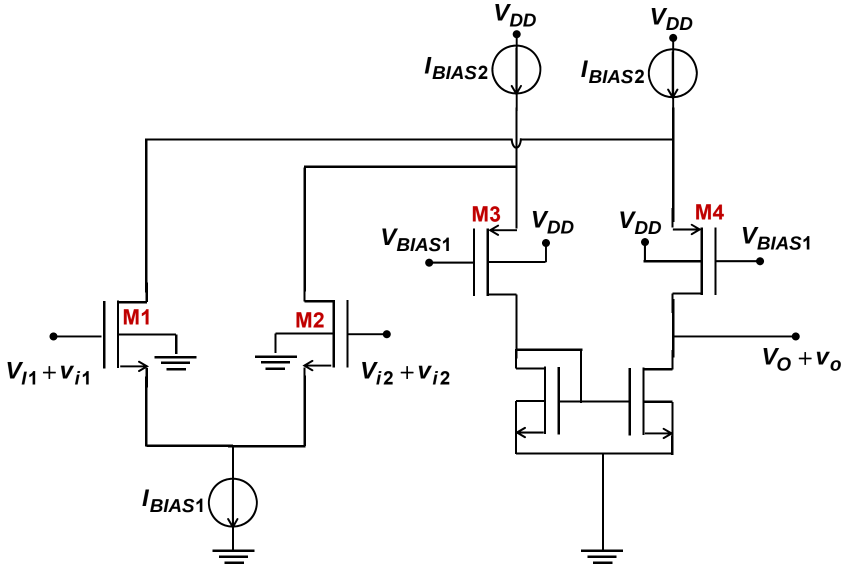


$$R_{out} \approx \left((g_{mn} + g_{mnb}) r_{on} r_{on}\right) \parallel \left((g_{mp} + g_{mpb}) r_{op} r_{op}\right)$$

$$A_{vd} \approx (g_{mn} + g_{mnb}) R_{out}$$

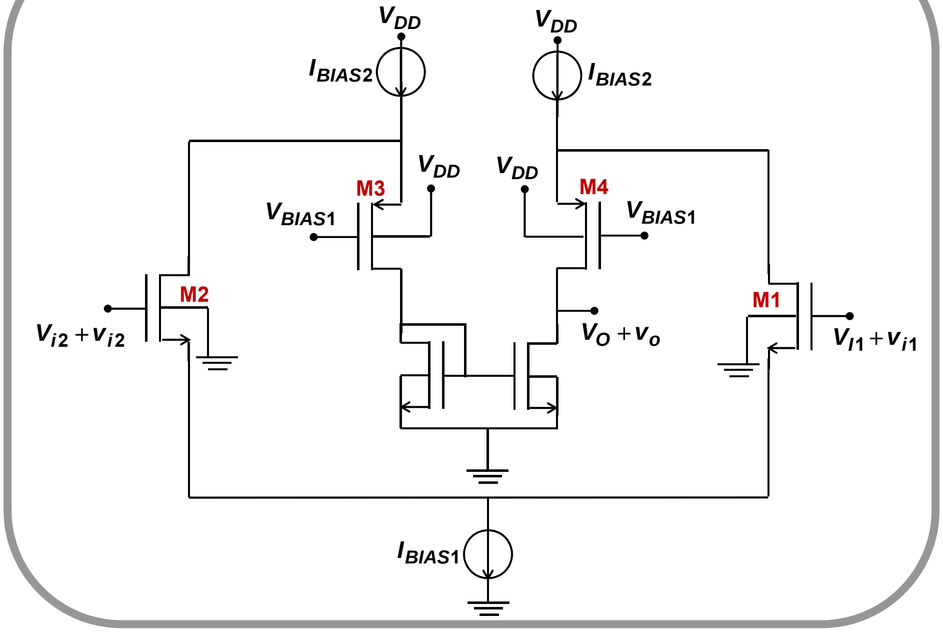
Very large gain, very large output resistance, output swing could be limited, small gain bandwidth (Miller effect)

A Folded Cascode Differential Amplifier with a Current Mirror

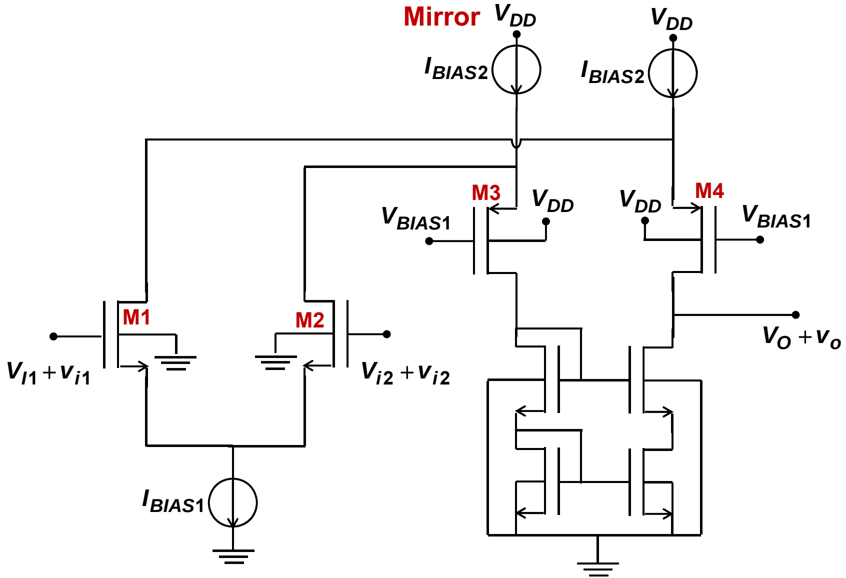


Large gain, large gain bandwidth, large output swing, large gain bandwidth (no Miller effect)

A Folded Cascode Differential Amplifier with a Current Mirror

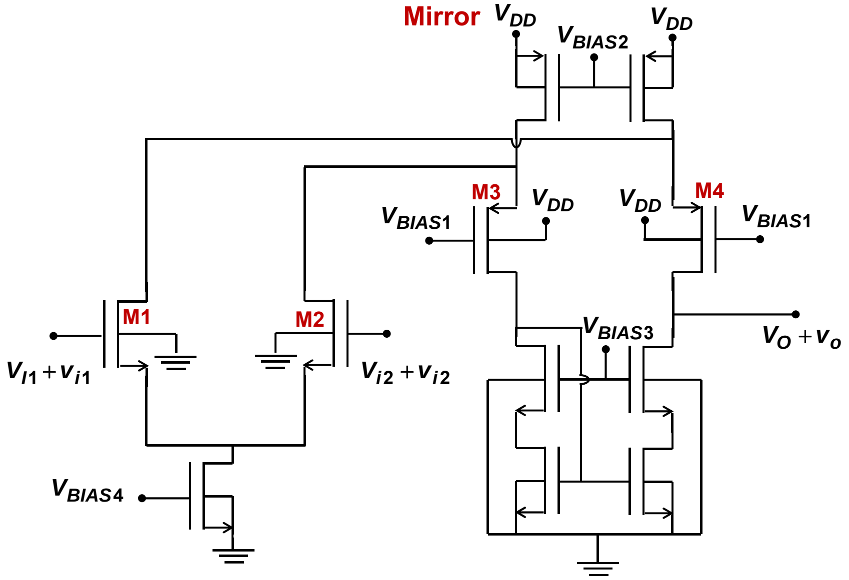


Folded Cascode Differential Amplifier with a Cascode Current Mirror

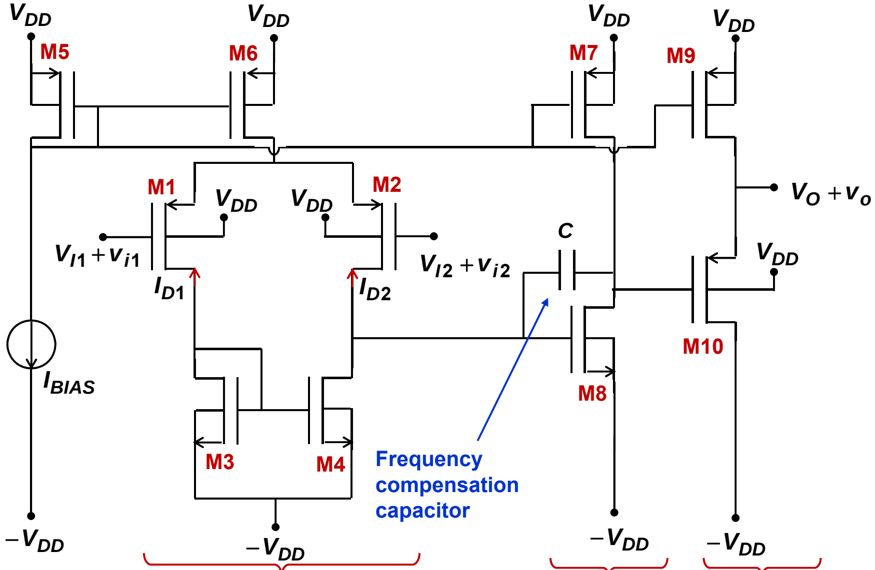


Very large gain, very large output resistance, decent output swing, small gain bandwidth (Miller effect)

Folded Cascode Differential Amplifier with a Cascode Current Mirror



A Complete Op-Amp (…… Almost)



Frequency compensation capacitor

Could be any one of the single-ended output differential stages we have discussed

CS gain stage

Low output resistance, CD output stage

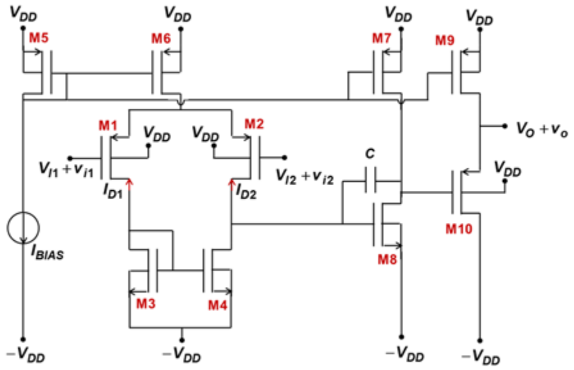
Lecture 20b

Negative Feedback, Stability, Gain Margins, Phase Margins

In this lecture you will learn:

- **Negative Feedback and Stability**
- **High Frequency Behavior of Amplifier Circuits**
- **Gain Margin, Phase Margin, and Stability**
- **Frequency Compensation**

A Complete Op-Amp

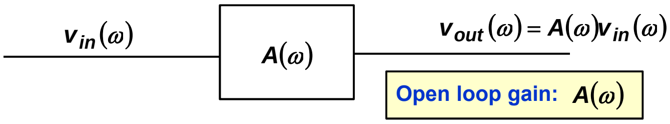


Stability problems: The output will be sensitive to the temperature and/or the power supply voltage.

As the temperature or the power supply fluctuates, the output is going to fluctuate.

Negative Feedback and Stability

Open loop system:

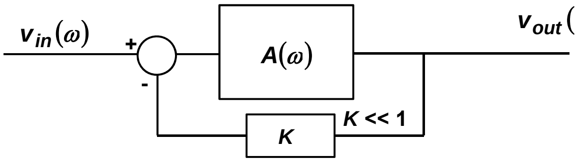


$v_{out}(\omega) = A(\omega) v_{in}(\omega)$

Open loop gain: $A(\omega)$

Stability problems: suppose the **open loop gain** is sensitive to the temperature or the power supply voltage. As the temperature or the power supply fluctuates, the output is going to fluctuate.

Closed loop system with negative feedback:



$$v_{out}(\omega) = \frac{A(\omega)}{1 + KA(\omega)} v_{in}(\omega)$$

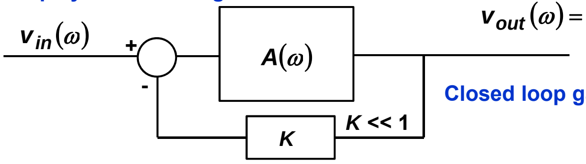
$$[v_{in}(\omega) - K v_{out}(\omega)] A(\omega) = v_{out}(\omega)$$

$$\Rightarrow v_{out}(\omega) = \frac{A(\omega)}{1 + KA(\omega)} v_{in}(\omega)$$

Closed loop gain: $\frac{A(\omega)}{1 + KA(\omega)}$

Negative Feedback and Stability

Closed loop system with negative feedback:



$$v_{out}(\omega) = \frac{A(\omega)}{1 + KA(\omega)} v_{in}(\omega)$$

Closed loop gain: $\frac{A(\omega)}{1 + KA(\omega)}$

If for small frequencies, assume $|A(\omega \sim 0)|$ >>>> 1 and $|KA(\omega \sim 0)|$ >> 1 :

Closed loop gain: $\frac{A(\omega \sim 0)}{1 + KA(\omega \sim 0)} \approx \frac{1}{K}$

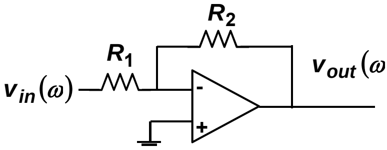
Stability problems resolved: Now as the temperature or the power supply fluctuates, the output is going to be much more stable (because it is almost independent of $A(\omega)$)!!

Negative feedback improves stability at the expense of gain

A **positive feedback** can lead to instability and/or oscillations!

Differential Amplifiers, Negative Feedback, and Stability

A high-gain differential amplifier is almost always operated using a negative feedback:



$$v_{out}(\omega) = A(\omega)\left[v_+(\omega) - v_-(\omega)\right]$$

$$v_{out}(\omega) = -v_{in}(\omega)\frac{R_2}{R_1}\frac{A(\omega)}{1+A(\omega)+\frac{R_2}{R_1}} = -v_{in}(\omega)\frac{\frac{R_2}{R_1}}{1+\frac{R_2}{R_1}}\frac{A(\omega)}{1+KA(\omega)}$$

$$\left[\; K = \frac{1}{1+\frac{R_2}{R_1}} \right.$$

If $|A(\omega \sim 0)| >>>> 1$, then:

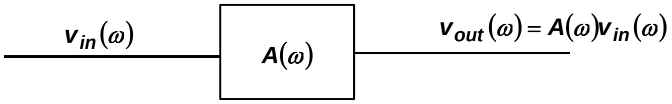
$$v_{out}(\omega) \approx -v_{in}(\omega)\frac{R_2}{R_1}$$

Negative feedback improves stability at the expense of gain

A positive feedback can lead to instability and/or oscillations!

Amplifier Gain: Frequency Response

Consider a differential amplifier:



$$v_{out}(\omega) = A(\omega)v_{in}(\omega)$$

The amplifier gain can be expressed (most generally) as:

$$A(\omega) = A_o\frac{(1+j\omega t_1)(1+j\omega t_2)(1+j\omega t_3)........}{(1+j\omega\tau_1)(1+j\omega\tau_2)(1+j\omega\tau_3)........}$$

$\longrightarrow$ **Multiple zeros**

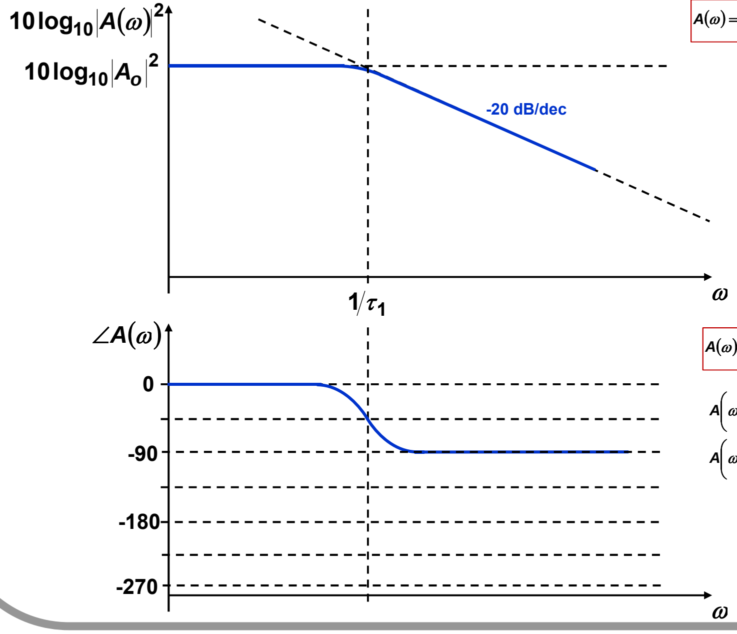
$\longrightarrow$ **Multiple poles**

Suppose, for simplicity, the amplifier gain can be expressed as:

$$A(\omega) = \frac{A_o}{(1+j\omega\tau_1)(1+j\omega\tau_2)(1+j\omega\tau_3)........}$$

$\longrightarrow$ **Multiple poles**

Magnitude and Phase of Response Functions: Single Pole Case



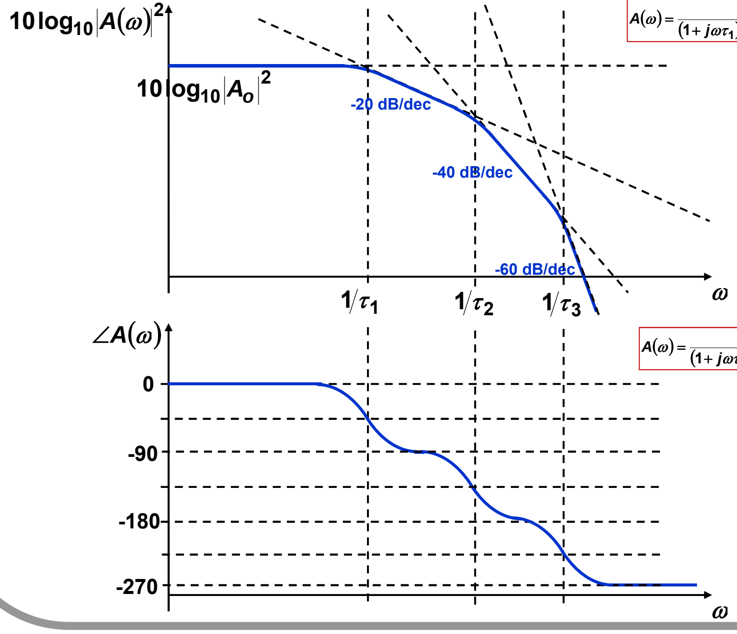
$$A(\omega)=\frac{A_o}{(1+j\omega\tau_1)}$$

$$A(\omega)=\frac{A_o}{(1+j\omega\tau_1)}$$

$$A\left(\omega << \frac{1}{\tau_1}\right)=A_o$$

$$A\left(\omega >> \frac{1}{\tau_1}\right)=-j\frac{A_o}{\omega\tau_1}$$

Magnitude and Phase of Response Functions: Multiple Pole Case

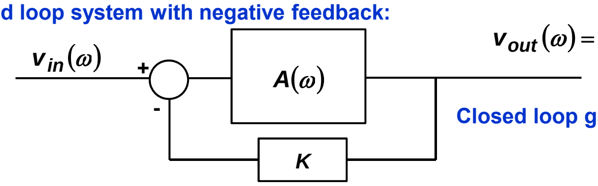


$$A(\omega)=\frac{A_o}{(1+j\omega\tau_1)(1+j\omega\tau_2)(1+j\omega\tau_3)}$$

$$A(\omega)=\frac{A_o}{(1+j\omega\tau_1)(1+j\omega\tau_2)(1+j\omega\tau_3)}$$

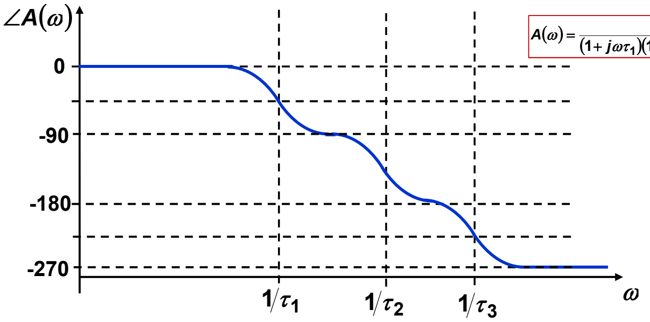
Negative Feedback and Positive Feedback

Closed loop system with negative feedback:



$$v_{out}(\omega) = \frac{A(\omega)}{1+KA(\omega)} v_{in}(\omega)$$

Closed loop gain: $\dfrac{A(\omega)}{1+KA(\omega)}$



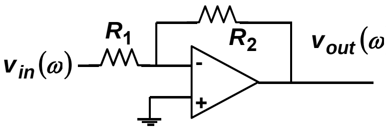
$$A(\omega) = \frac{A_o}{(1+j\omega\tau_1)(1+j\omega\tau_2)(1+j\omega\tau_3)}$$

At frequencies between $1/\tau_2$ and $1/\tau_3$, $\angle A(\omega)$ is 180-degrees

=> The feedback is positive, not negative!!!

Phase Response and Amplifier Stability

Consider a differential amplifier operated using a negative feedback:



$$v_{out}(\omega) = A(\omega)\left[v_+(\omega) - v_-(\omega)\right]$$

$$v_{out}(\omega) = -v_{in}(\omega)\frac{R_2}{R_1}\frac{A(\omega)}{1+A(\omega)+\frac{R_2}{R_1}} = -v_{in}(\omega)\frac{\frac{R_2}{R_1}}{1+\frac{R_2}{R_1}}\frac{A(\omega)}{1+KA(\omega)}$$

$$\left[K = \frac{1}{1+\frac{R_2}{R_1}} \right.$$

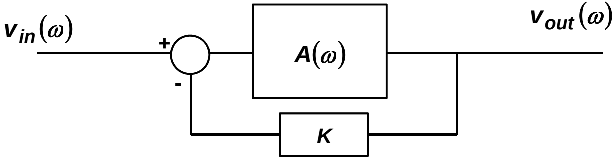
A positive feedback can happen at high frequencies when:

$$\angle A(\omega) \rightarrow -180^o$$

Denominator can become very small or zero!

Phase Response and Amplifier Stability

Closed loop system with feedback:



$$v_{out}(\omega) = \frac{A(\omega)}{1+KA(\omega)} v_{in}(\omega)$$

How to avoid unwanted output oscillations at the frequency ω at which $\angle A(\omega) = -180^{o}$??

$$v_{out}(\omega) = \frac{A(\omega)}{1+KA(\omega)} v_{in}(\omega) \rightarrow \frac{-|A(\omega)|}{1-K|A(\omega)|} v_{in}(\omega)$$

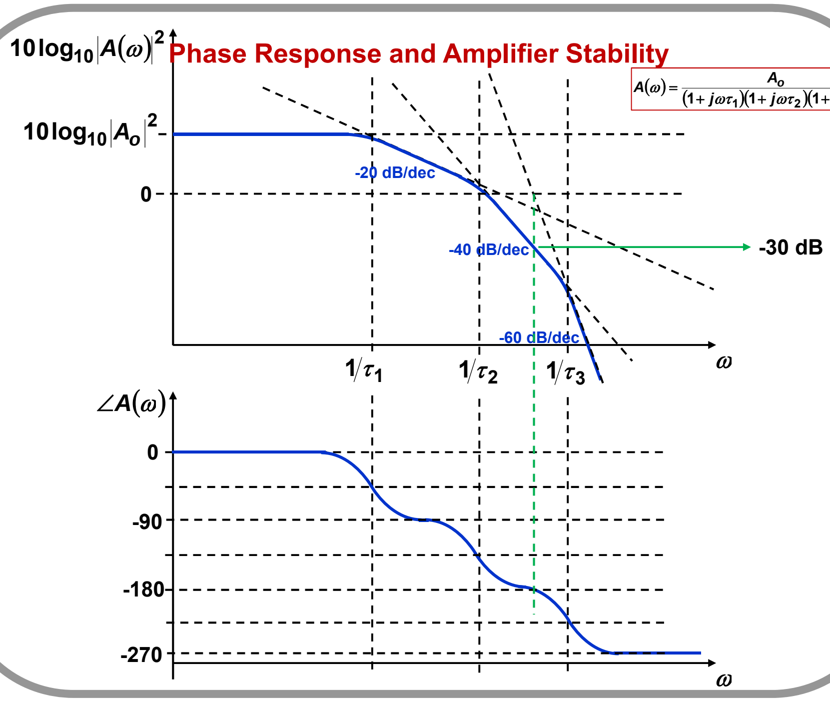
Output will be non-zero, even if the input is zero, if:

$$1-K|A(\omega)| = 0$$

$$\Rightarrow |A(\omega)| = \frac{1}{K} > 1$$

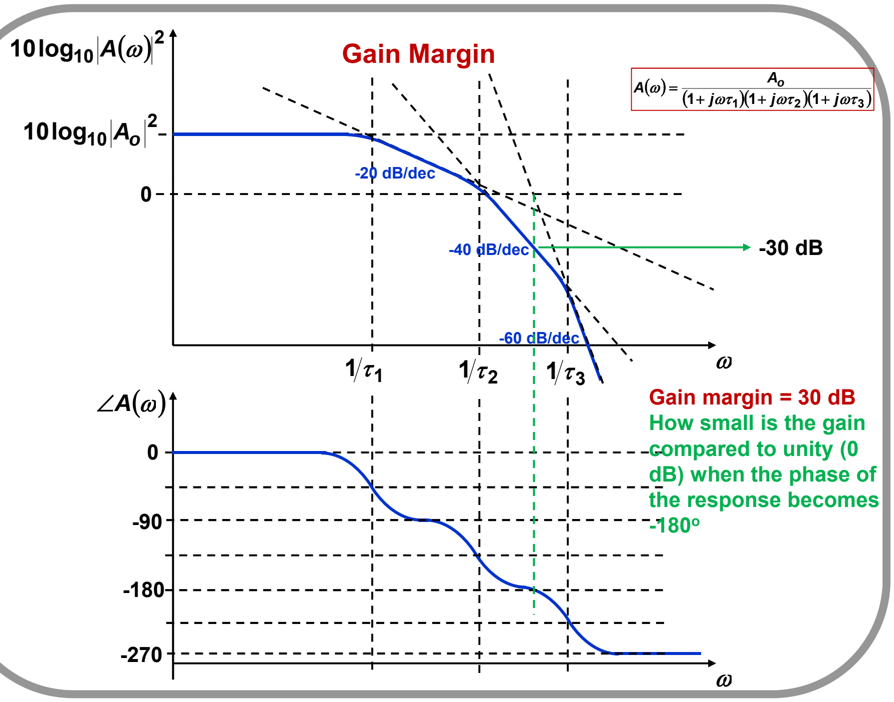
Solution:
To avoid this positive feedback from causing oscillations, the magnitude $|A(\omega)|$ of the gain must get much less than unity before $\angle A(\omega) = -180^{o}$

Phase Response and Amplifier Stability



$$A(\omega) = \frac{A_o}{(1+j\omega\tau_1)(1+j\omega\tau_2)(1+j\omega\tau_3)}$$

Gain Margin

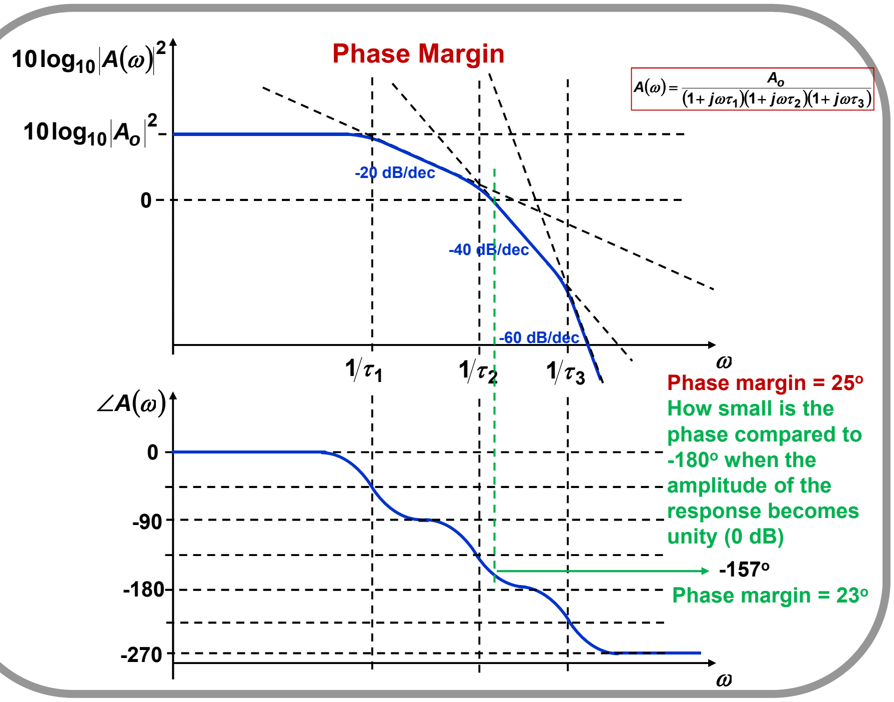


$$A(\omega)=\frac{A_o}{(1+j\omega\tau_1)(1+j\omega\tau_2)(1+j\omega\tau_3)}$$

Gain margin = 30 dB

How small is the gain compared to unity (0 dB) when the phase of the response becomes -180°

Phase Margin



$$A(\omega)=\frac{A_o}{(1+j\omega\tau_1)(1+j\omega\tau_2)(1+j\omega\tau_3)}$$

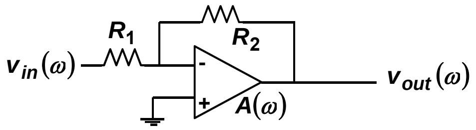
Phase margin = 25°

How small is the phase compared to -180° when the amplitude of the response becomes unity (0 dB)

Phase margin = 23°

Frequency Compensation

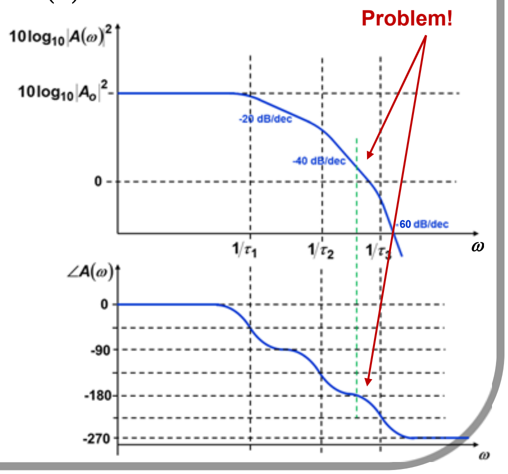
Consider a differential amplifier operated using a negative feedback:



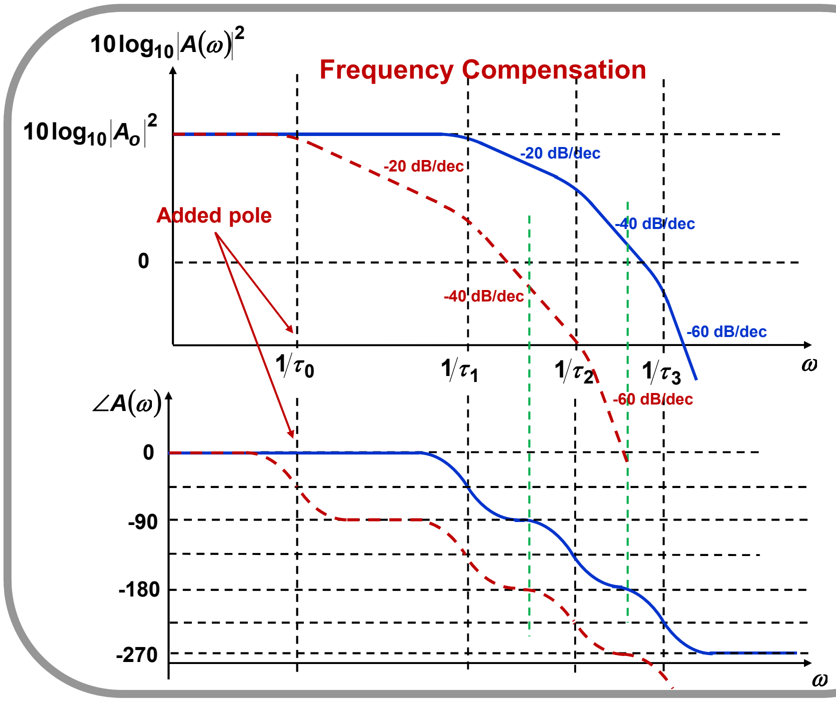
Very often, almost always in fact, when you are done designing the amplifier you figure out that you don't have enough gain and phase margins!!

How to solve this problem?

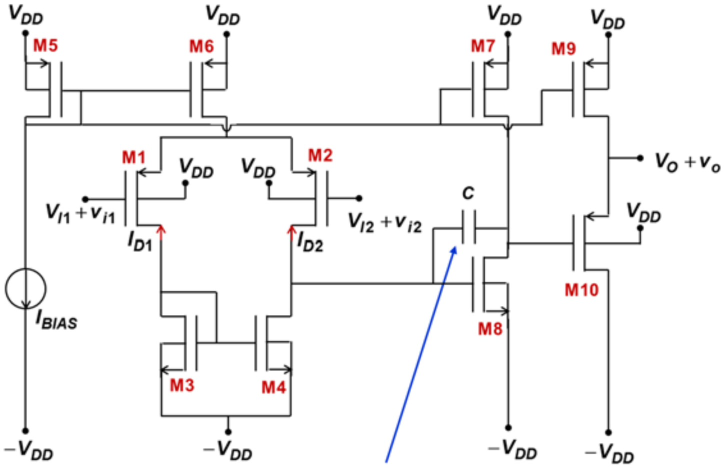
Frequency Compensation:
Add a low frequency pole inside $A(\omega)$ (by adding extra capacitors, for example), sacrifice bandwidth, but regain stability (PTO…)



Frequency Compensation

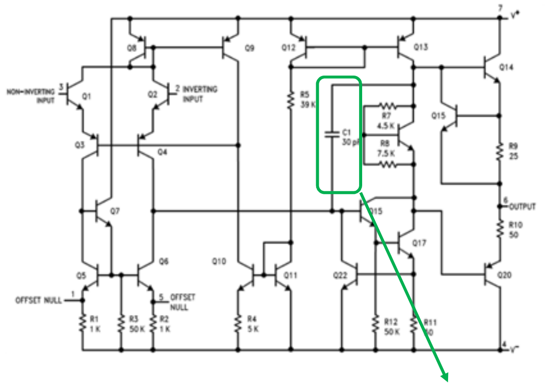


Frequency Compensation

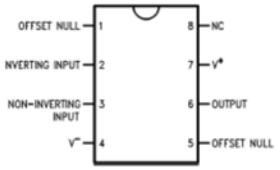


The frequency compensation capacitor is generally placed in the Miller position

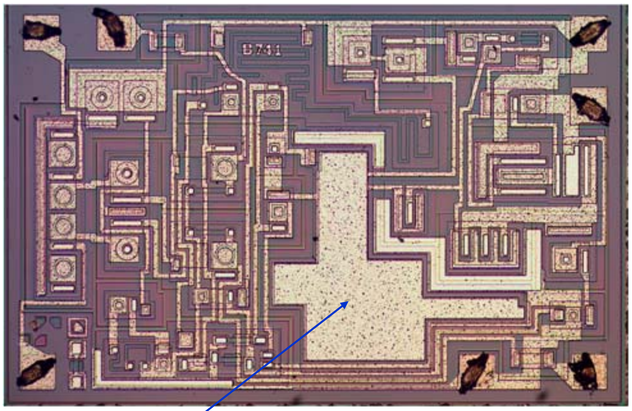
Texas Instruments LM 741 Operational Amplifier



Frequency Compensation capacitor



Texas Instruments LM 741 Operational Amplifier



Frequency compensation capacitor

It is weren't in the Miller position, it would need to be much larger!!