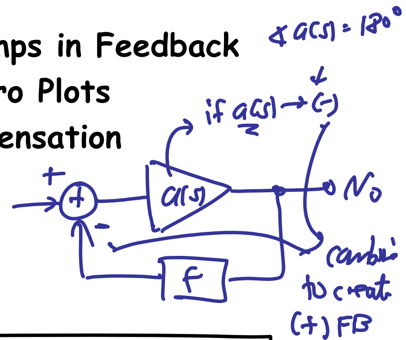
- **Announcements**:
  - Evening lecture today, 7 p.m., in 289 Cory
  - You should be finished with a draft design of your op amp project by now
- **Today**:
  - Stability of Op Amps in Feedback
  - Review of Pole/Zero Plots
  - Methods for Compensation
    - Narrowbanding
    - Pole-Splitting




Last Time –

**Stability of FB Ckt. Using a Single Pole Op Amp**

For a single pole op amp: $a(s) = \dfrac{a_o}{1 - \frac{s}{p_1}} \equiv$ op amp transfer function

Thus: closed loop Xfer Fcn

$$A(s) = \frac{a(s)}{1 + a(s)f} = \frac{a_o}{1 + a_o f} \cdot \frac{1}{1 - \frac{s}{p_1(1 + a_o f)}}$$

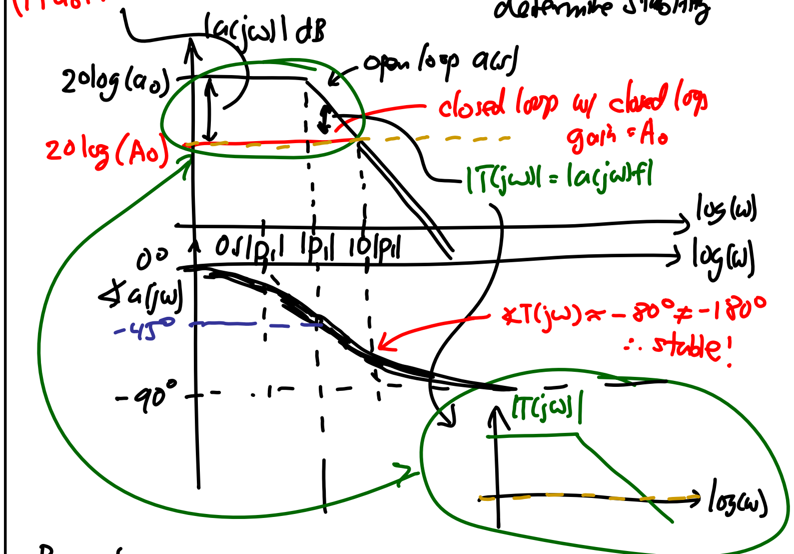
($p_1(1+a_o f)$ ← much higher 3dB freq.)

$A_o$ = closed loop dc gain → $(1 + a_o f) \approx a_o f$ × smaller than $a_o$ $= \frac{1}{f}$

$T_o = a_o f$ = loop gain (defined at dc)

$T(s) = a(s) f$ = loop transmission (defined for general frequencies)

Bode Plot: → use to determine ∡a(s)f when $|a(s)f| = 1$ ← then can determine stability




Remarks:

① For the case of a single pole op amp, FB can never reach ∡T(jω) = −180°! (90° is the limit!)

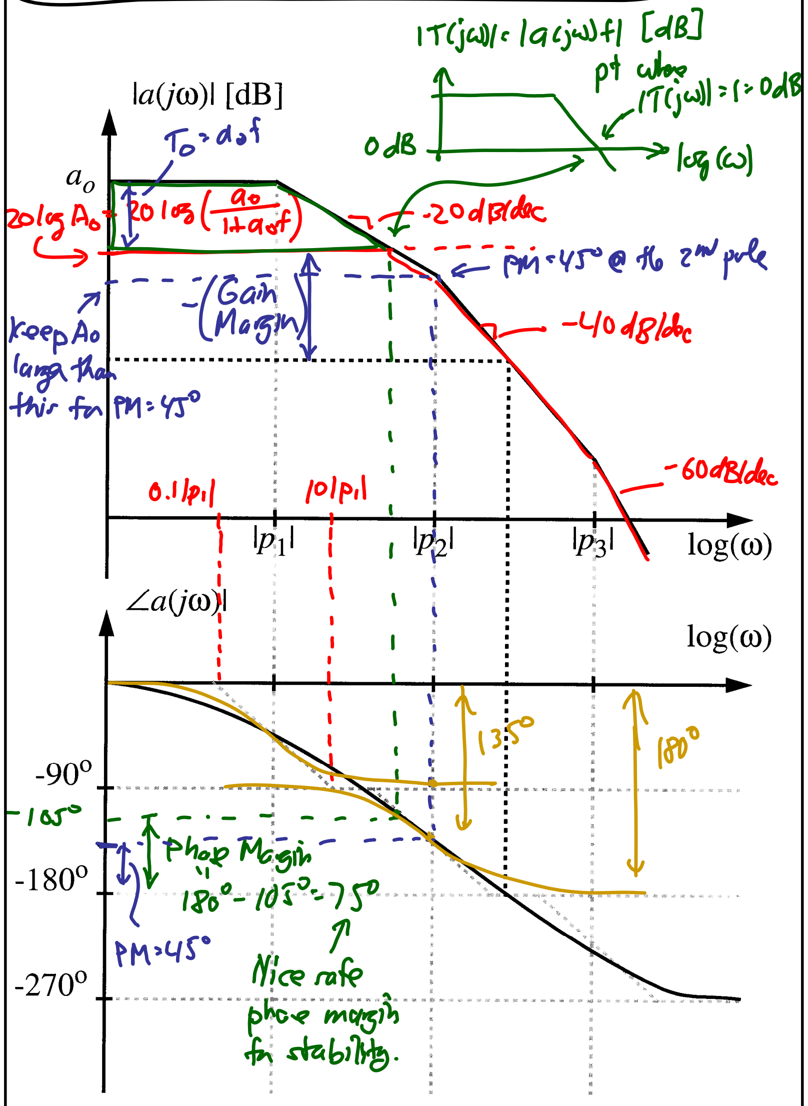
② Thus, an op amp FB ckt. w/ f = const. and using a single-pole op amp is always stable!

↓

But add a few non-dominant poles → then instability is possible! since now, ∡T(jω) can reach −180°!

Can best visualize this via a Bode plot.

## Stability of a FB ckt. Using a Multi-Pole Op Amp




For the more general case where $a(s)$ has multiple poles

⇒ $A(s)$ has the same additional poles

⇒ i.e., @ freqs. $> |p_1|(1+a_o f)$, the $A(s)$ curve just follows the $a(s)$ curve

$$A(s) \cong \frac{A_o}{\left(1 - \frac{s}{p_1(1+a_o f)}\right)\left(1 - \frac{s}{p_2}\right)\left(1 - \frac{s}{p_3}\right)}$$

makes sense, because @ freqs. $> |p_1|(1+a_o f)$, the loop transmission $|T(j\omega)| < 1$ → ∴ there isn't really much FB anymore...

**Definition.**

Phase Margin $= 180° + (\angle T(j\omega)$ @ the freq. where $|T(j\omega)| = 1)$

⇒ Phase Margin must be $> 0°$ for stability

**For Stability: Phase Margin $> 0°$**

⇒ For safety, though, usually design for

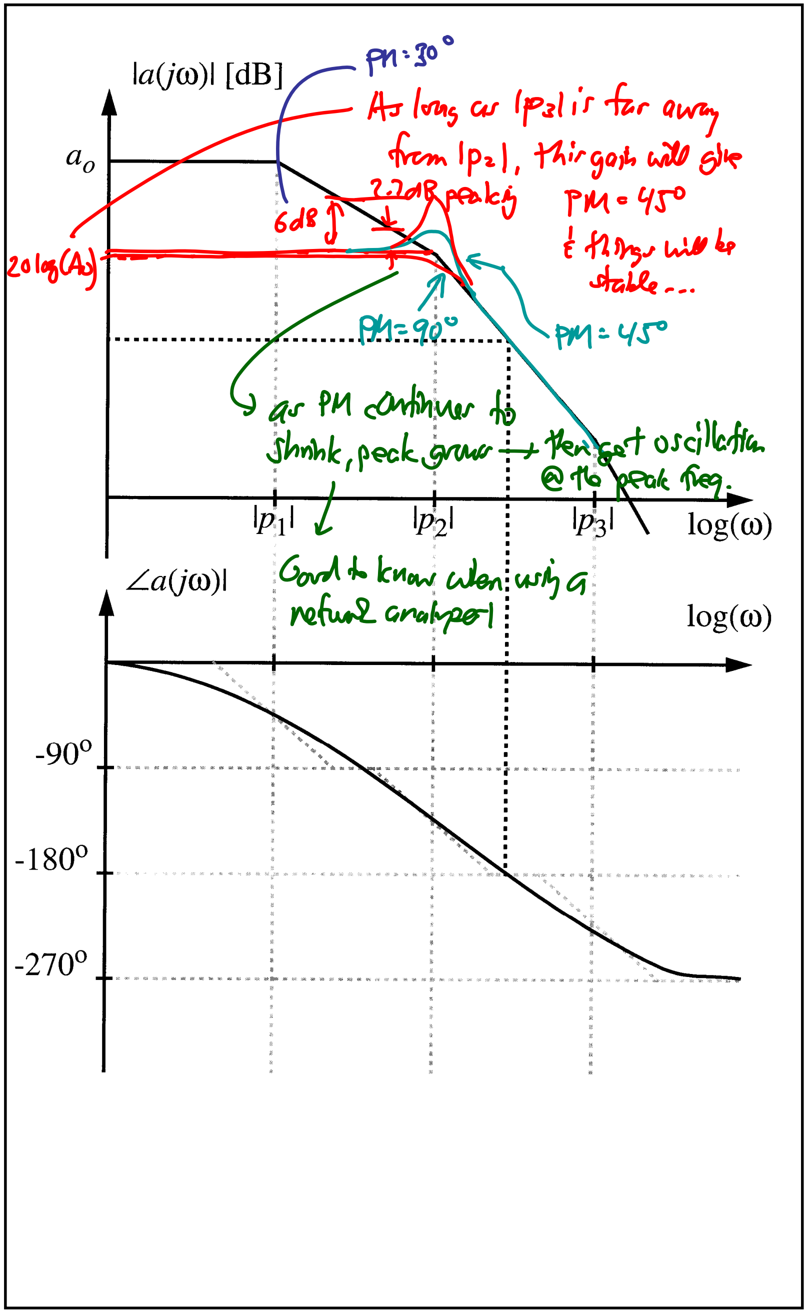
**Phase Margin $\geq 45°$**

↑ Design Criterion (for practical design)

**Definition.**

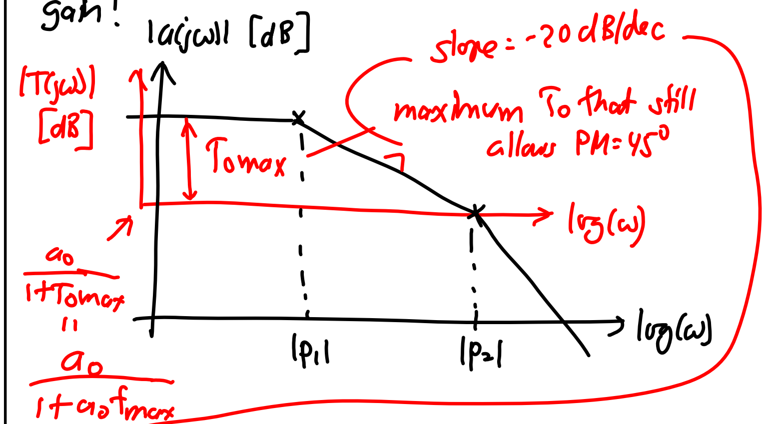
Gain Margin ≡ $|T(j\omega)|$ in dB @ freq. where $\angle T(j\omega) = -180°$

For stability: **Gain Margin $< 0$dB**




## Compensation of Op Amps

To compensate, need the distance between $p_1$ & $p_2$ to be large enough to encompass the largest desired loop gain!




$20(\log|p_2| - \log|p_1|) = 20\log(T_{omax})$

$\frac{|p_2|}{|p_1|} = T_{omax} \rightarrow |p_2| = |p_1| T_{omax}$

largest desired (expected) loop gain

provided $|p_3| \gg |p_2|$

Need for stability w/ PM=45° @ all desired closed loop gains

Two Ways to Compensate:

1. Narrowbanding
2. Pole-Splitting

Basically, there is a minimum separation between $p_1$ & $p_2$ that insures stability.

**Narrowbanding**

⇒ introduce a pole $p_D$ (dominant pole) so that there is sufficient separation between $p_D$ & $p_1$