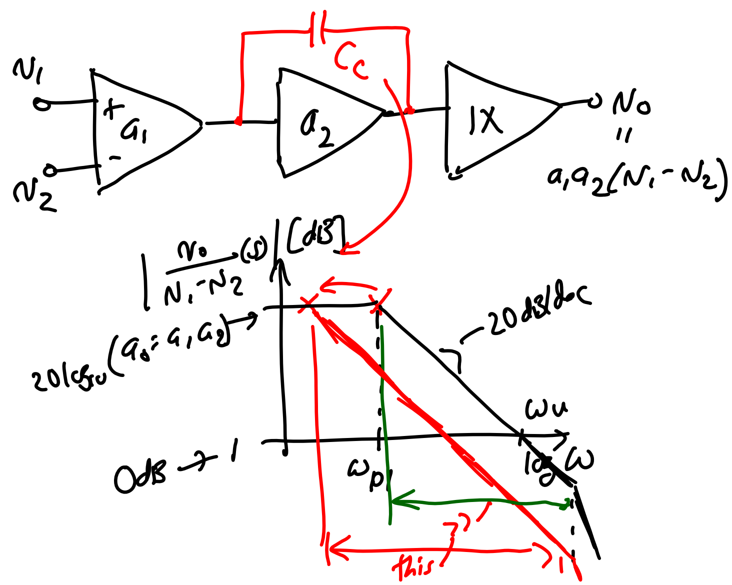
Lecture 19: Compensation

- **Announcements**:
  - HW#9 online
  - Lab#2 due this Friday
    - Grade depends heavily on the report
    - Make sure you spend enough effort on the report per your TA's requirements
  - Lab#3 update online (update for 240A folks)
  - No lecture next Tuesday; this lecture is 2 hours to compensate
  - Two lectures after next Tuesday also 2 hours
- **Lecture Topics**:
  - Compensation
- ------------------------------------
- **Last Time**:

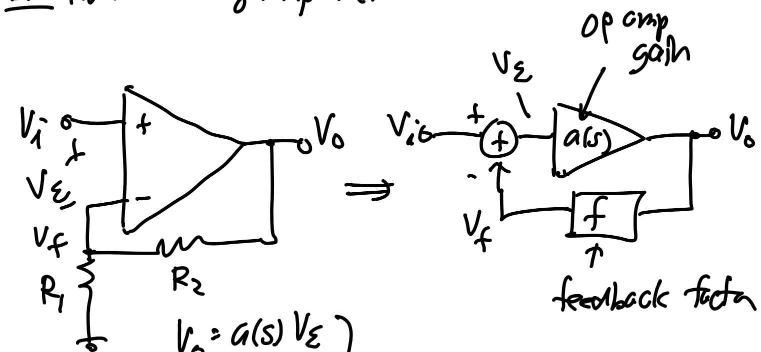
$\boxed{\text{Stability \& Compensation}}$



Where does instability come from? practical

⇒ any neg. FB becomes unstable under certain conditions → ∴ must compensate to suppress instability!

Ex. Non-Inverting Amplifier



$$\left.\begin{aligned} V_o &= a(s) V_\varepsilon \\ V_\varepsilon &= V_i - V_f \\ V_f &= f V_o \end{aligned}\right\} V_o = a(s)(V_i - f V_o)$$

$$A(s) = \frac{V_o}{V_i}(s) = \frac{a(s)}{1 + a(s)f} = \frac{a(s)}{1 + T(s)}$$

closed loop gain

Loop Transmission: $T(s) = a(s) f$ — fcn of freq.

@ dc: loop gain $= a_o f = T_o$

Instability occurs when $A(s) \to \infty$!

$$\Rightarrow A(s) = \frac{a(s)}{1 + a(s)f} \longrightarrow A(s) = \frac{a(s)}{1 - 1} = \frac{a(s)}{0} \to \infty$$

$a(s)f = -1$

will also go unstable if denominator is (−)

In General:

$\boxed{\text{If } |a(s)f| \geq 1 \text{ when } \measuredangle a(s)f = -180^\circ \Rightarrow \text{Instability}}$

This is a simplified form of the Nyquist Criterion.

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

For a single pole op amp: $a(s) = \dfrac{a_0}{1 - \frac{s}{p_1}} \equiv$ op amp transfer function

Thus: closed loop T.F.

$$A(s) = \frac{a(s)}{1+a(s)f} = \underbrace{\frac{a_0}{1+a_0 f}}_{A_o} \cdot \underbrace{\frac{1}{1 - \frac{s}{p_1(1+a_0 f)}}}_{\text{Freq. Shaping Term}}$$

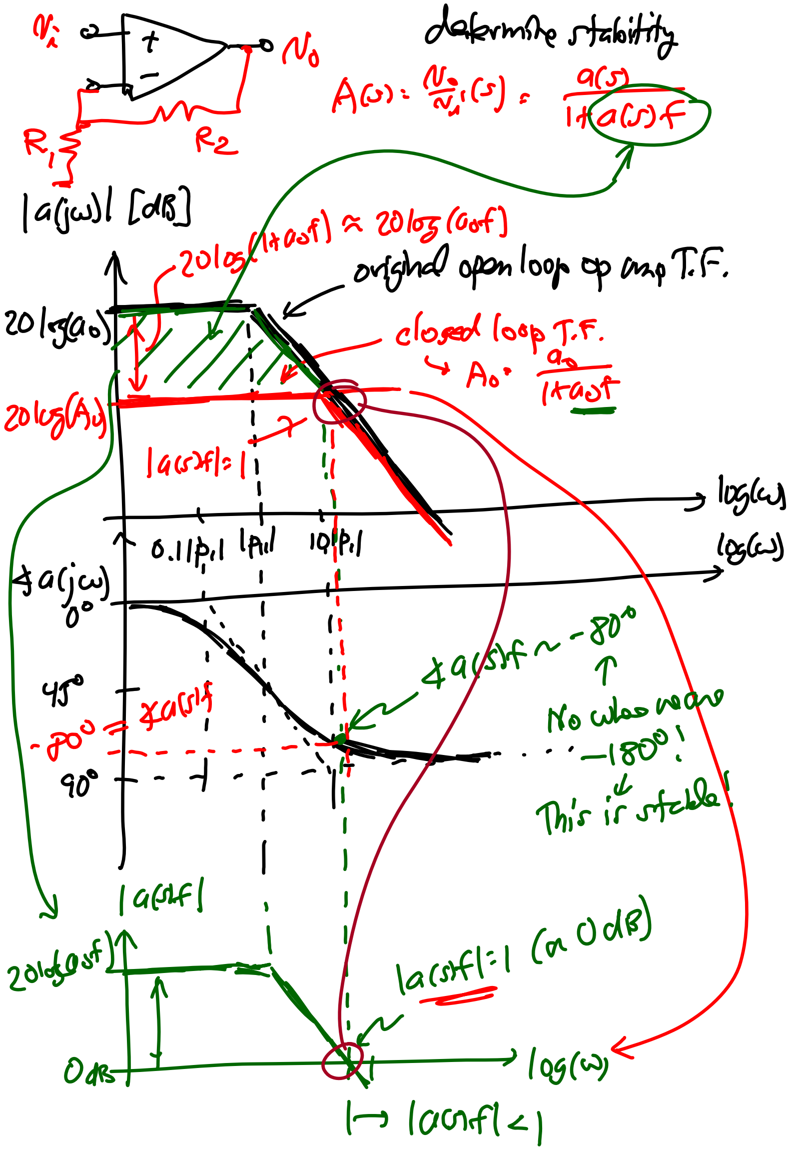
$p_1(1+a_0 f)$ ← BW increases

A_o: closed loop dc gain → $(1+a_0 f)$ smaller than a_0 $\approx \frac{1}{f}$

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

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

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

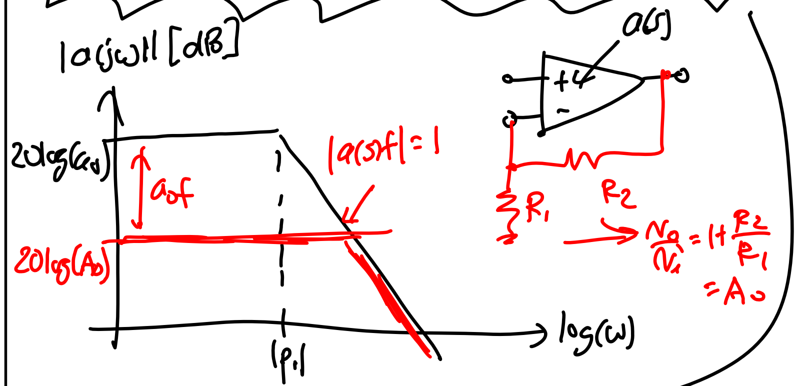


Remarks:

w/ f = const.

① For the case of a single-pole op amp, FB can never reach ∡a(s)f = −180°. (90° is the limit.)

② Thus, a single-pole op amp in FB w/ f = const., i.e., f ≠ function of s = jω, is always stable!



But in reality, op amp also has non-dominant poles! → there can get ∡a(s)f → 180°

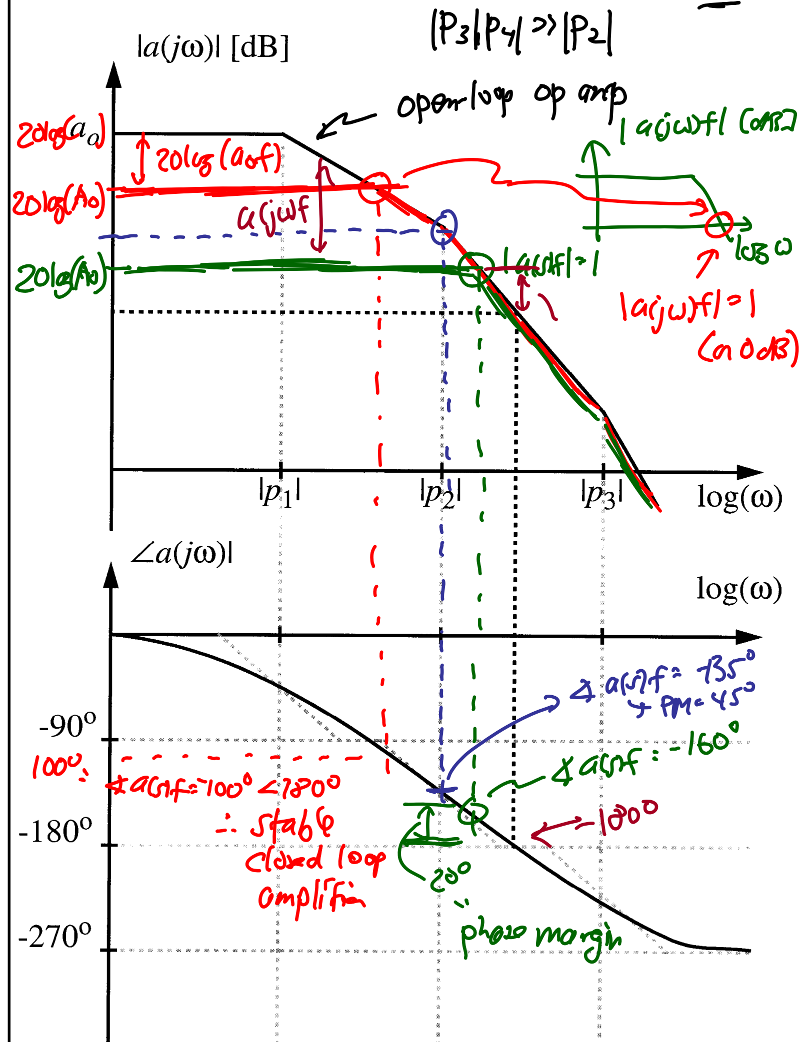
→ Can instigate instability!

Use again a Bode plot to investigate.

Stability of a FB Ckt. Using a mul·

Assume: dominant pole: p_1, non-dominant pole: p_2

$|p_3|, |p_4| >> |p_2|$



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

⇒ $A(s)$ has the same additional poles (f = const.)

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

$$A(s) \cong \frac{A_o}{\underbrace{\left(1-\frac{s}{|p_1|(1+a_o f)}\right)\left(1-\frac{s}{|p_2|}\right)}_{\text{But can also get peaking}}\left(1-\frac{s}{|p_3|}\right)}$$

Definitions:

Phase Margin: $180^\circ + (\measuredangle a(j\omega)f$ @ freq. where $|a(j\omega)f| = 1)$

$= 180^\circ - 160^\circ = 20^\circ$

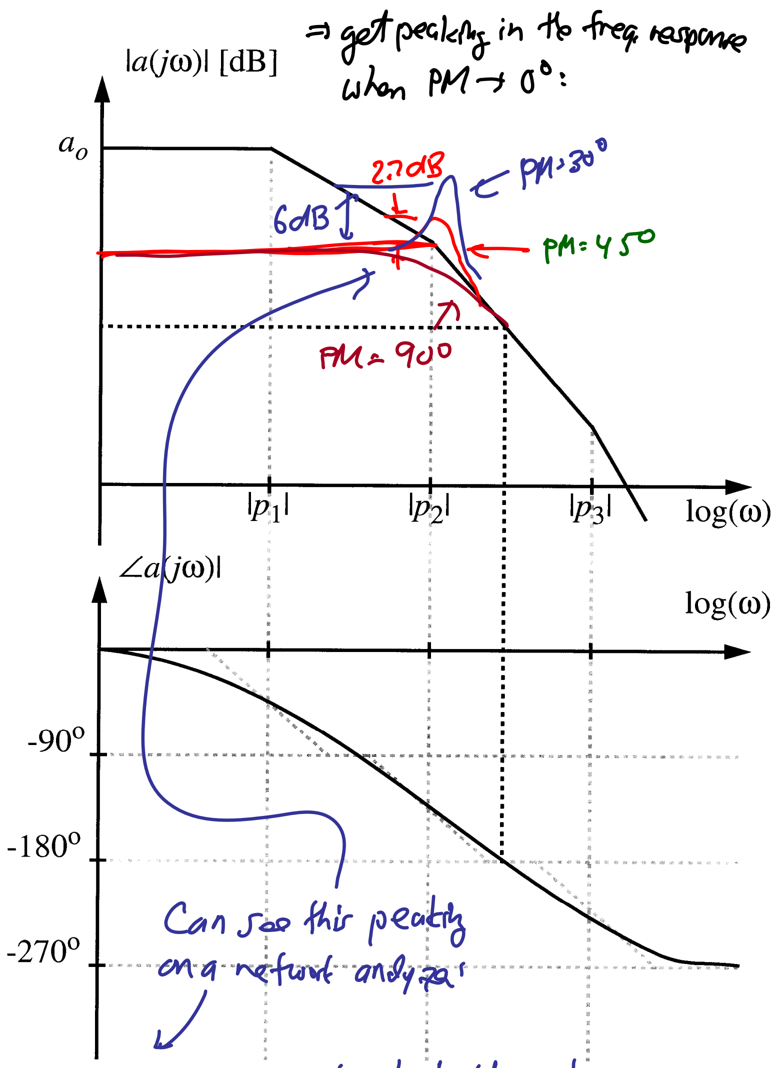
$= 180^\circ - 100^\circ = 80^\circ$

⇒ phase margin must be $> 0^\circ$ for stability

$\boxed{\text{For stability: Phase Margin} > 0^\circ}$

⇒ for design safety, design for $\boxed{\text{Phase Margin} \geq 45^\circ}$

⇒ even safer (for settling time): $\boxed{PM \geq 60^\circ}$

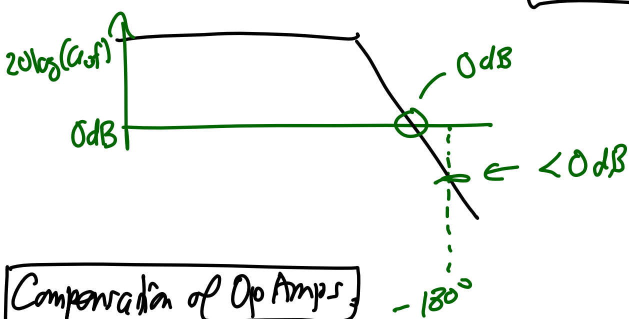


As the PM continues to shrink, the peak grows & when the peak gets sufficiently large, the ckt. will oscillate @ its freq. → instability!

Definition:

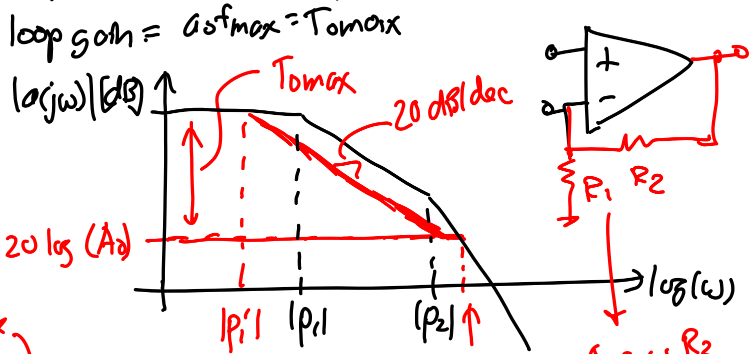
Gain Margin = $|a(j\omega)f|$ in dB @ freq. where $\measuredangle a(j\omega)f = -180°$

For stability: $\boxed{\text{Gain Margin} < 0\,dB}$



$\boxed{\text{Compensation of Op Amps:}}$

To compensate, need distance between p_1 & p_2 to be large enough to encompass the largest desired loop gain $= a_o f_{max} = T_{omax}$



$A_o = 1 + \frac{R_2}{R_1}$

smallest closed loop gain intended

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

for PM = 45°

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

$20\log\left(\frac{|p_2'|}{|p_1'|}\right) = 20\log(T_{omax})$ *

Two Ways to Compensate:

① Narrowbanding

② Pole Splitting

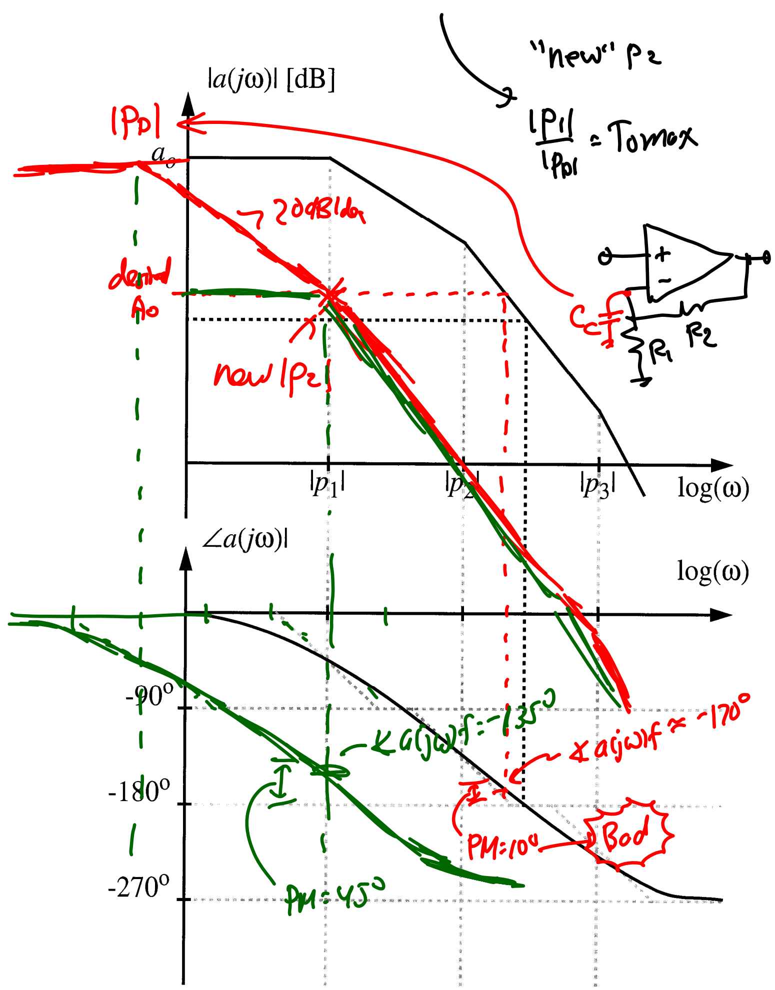
over

Narrowbanding

dominant ≡ "D"

→ introduce a pole p_D so that there is sufficient separation between p_D & p_1 ← which becomes the "new" p_2

$\frac{|p_1|}{|p_D|} = T_{omax}$



Remarks on Narrowbanding

1. Assumption: p_1, p_2, p_3 don't move when p_D is introduced (often not true, but the movement isn't that big)
2. Summarize: choose p_D such that $|T(j\omega)| = 0\text{dB} = 1$ @ p_1 (which becomes the "new 2nd most dominant pole")
   ↳ this gives PM=45° (for $|p_2| \gg |p_1|$ & $|p_3| \gg |p_2|$)
3. Why do this? Wouldn't it be much better to just move the original $|p_1|$ (i.e., pole-split)
   ↳ Do it when you have no other choice, e.g., when you have a packaged op amp & have access only to a few terminals, not the optimum compensation node.
4. $\boxed{|p_D| = \frac{|p_1|}{T_{omax}}}$ ← maximum expected/needed loop gain

Problem:

1. often, $|p_D| \ll |p_1|$ ∴ f_{-3dB} BW of the op amp will be very small
2. $\omega_{closed\ loop} = |p_1|$ which isn't that large

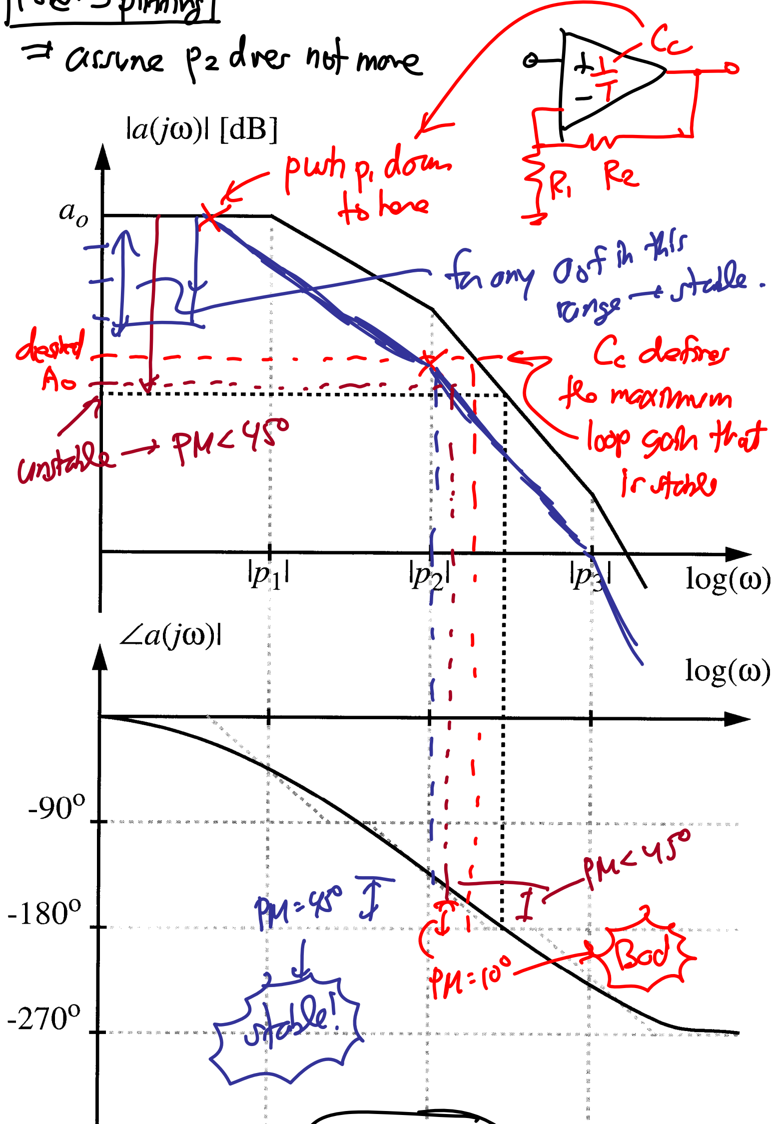
Solution: **Pole-Splitting**

→ move $|p_1|$ down & either keep $|p_2|$ still
↳ or move $|p_2|$ up simultaneously

↳ after doing this:
1. $\omega_{-3dB} = |p_1'|$
2. $\omega_{closed\ loop} = |p_2'|$

Pole-Splitting

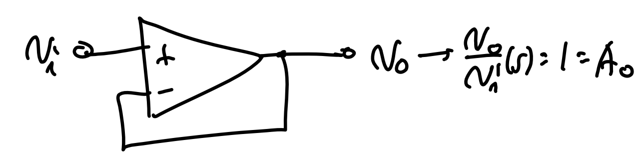
⇒ assume p_2 does not move



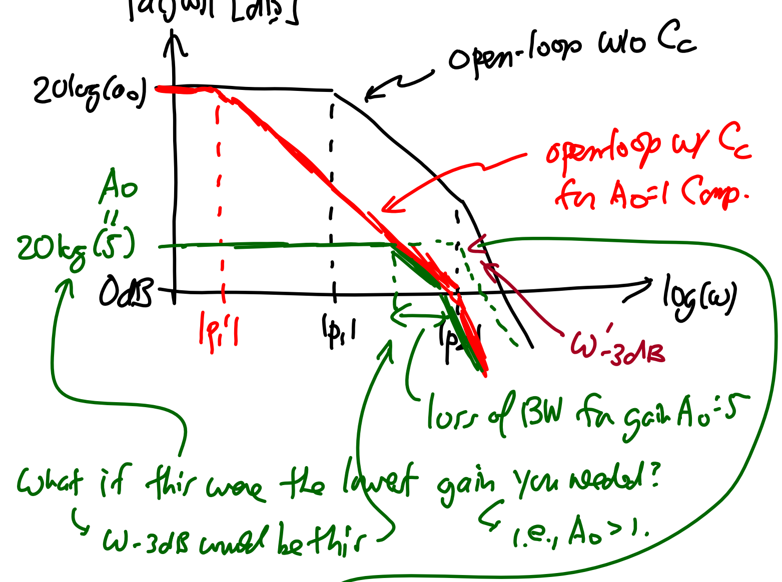
For pole-splitting: $\boxed{|p_1| = \dfrac{|p_2|}{T_{o\,max}}}$

Unity Gain Stable Op Amps

→ e.g., 741 op amp



monolithically compensated w/ an internal C_c to be stable when $A_o = 1$ (closed loop gain)



Could have done this if compensate for the needed $A_o = 5 \rightarrow \omega'_{-3dB} > \omega_{3dB}$

↑ Higher BW if compensate for A_o, rather than for unity gain.