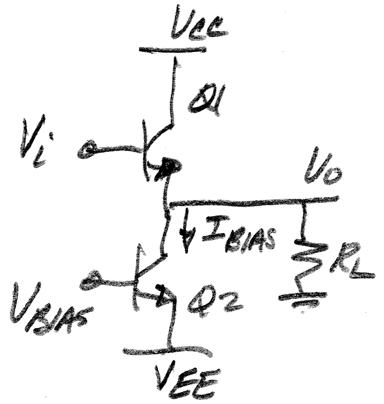
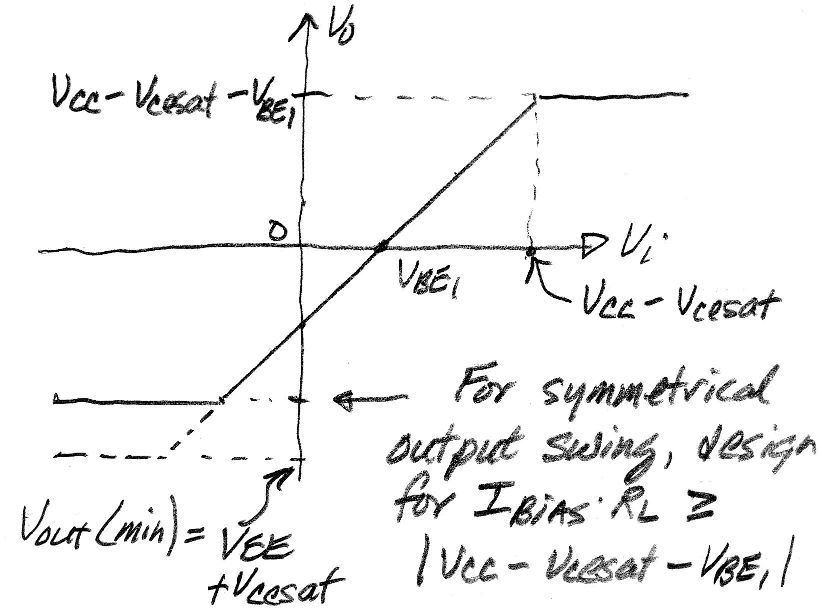
Output stages:

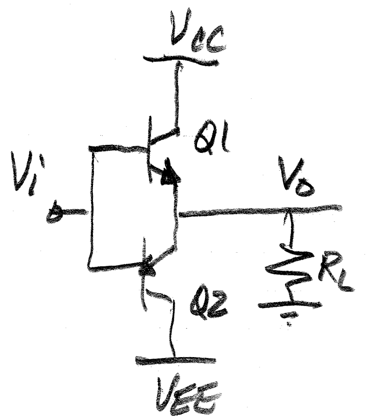
(A) Class-A (e.g., emitter follower):

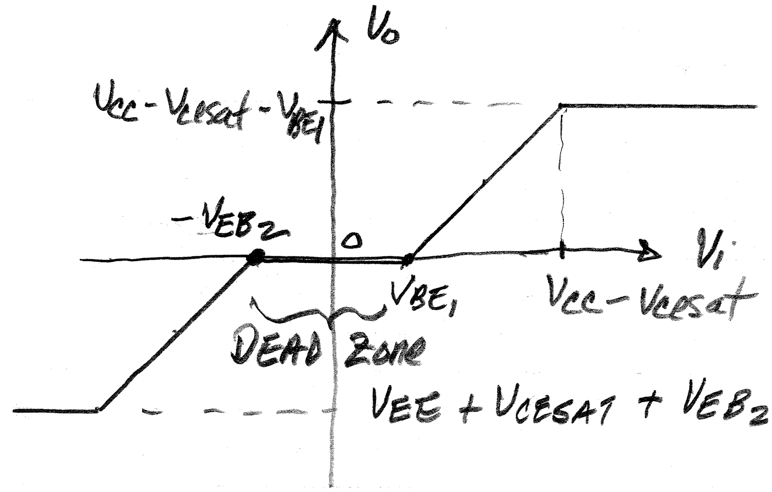




- Advantage: High linearity
- Disadvantages: Poor output swing for low supplies
  Poor efficiency – $\eta = \frac{P_{LOAD}}{P_{supply}} \leq 25\%$

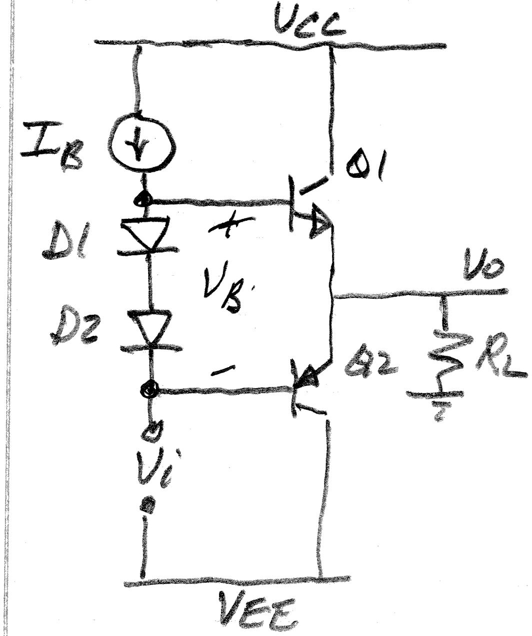
(B) Class-B (e.g., complementary emitter followers):



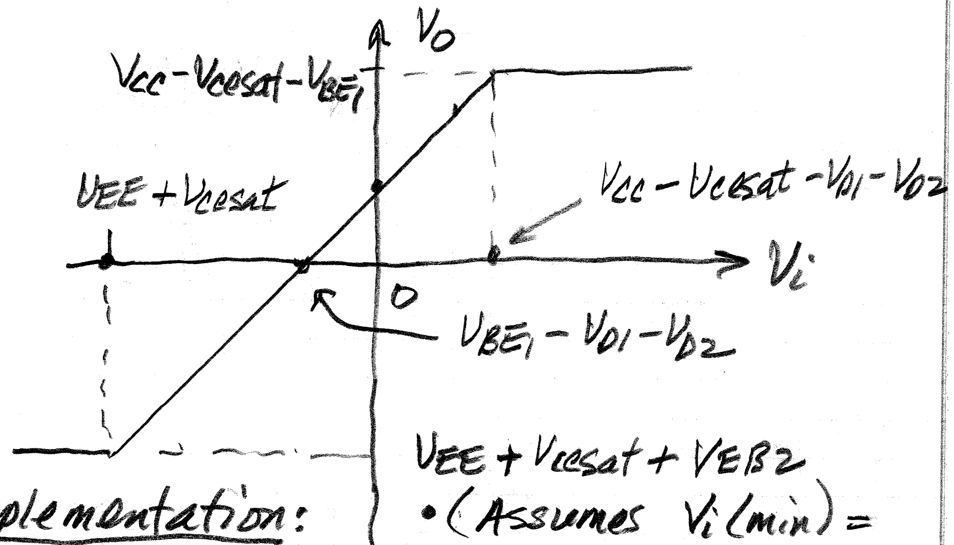


- Advantage: Excellent power efficiency –
  $$\eta = \frac{P_{LOAD}}{P_{supply}} \leq \frac{\pi}{4}\,\% = 78.5\,\%$$
- Disadvantage: Severe crossover distortion.

(c) Class-AB (e.g., 741 opamp output stage):

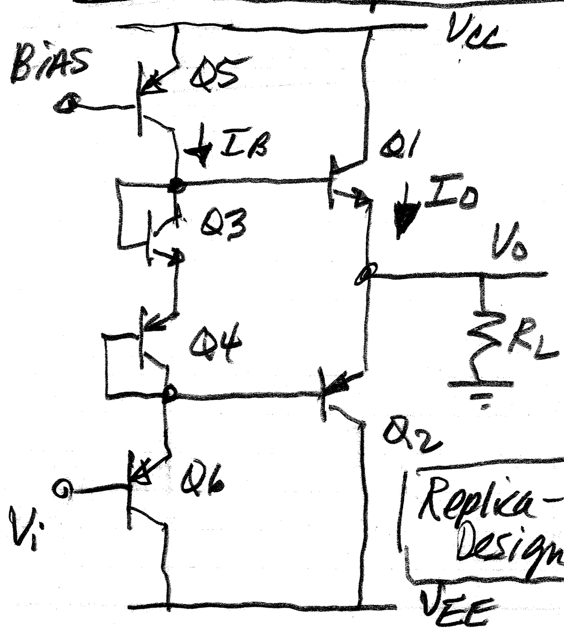


With $\beta_{npn} = \beta_{pnp} = \infty$, D1 and D2 are biased with constant I_B. Thus, they generate a constant voltage, $V_B \simeq 1.4V$, which is applied to Q_1 and Q_2. That is, $V_{D1} + V_{D2} = V_{BE_1} + V_{EB2}$. Ideally, Q_1 and Q_2 are biased on with a small current to eliminate crossover distortion:



• (Assumes $V_i(min) = V_{EE} + V_{cesat}$)

• Practical Implementation:



Replica-based Design

KVL: (β's very large)

$$V_{BE1} + V_{EB2} - V_{BE3} - V_{EB4} = 0$$

Assume: $A_{EB_1} = n A_{EB_3}$ and $A_{EB3} = n A_{EB4}$

$$V_T \ln \frac{I_O}{I_{S1}} + V_T \ln \frac{I_O}{I_{S2}} - V_T \ln \frac{I_B}{I_{S3}} - V_T \ln \frac{I_B}{I_{S4}} = 0$$

$$\therefore \boxed{I_O = n I_B}$$

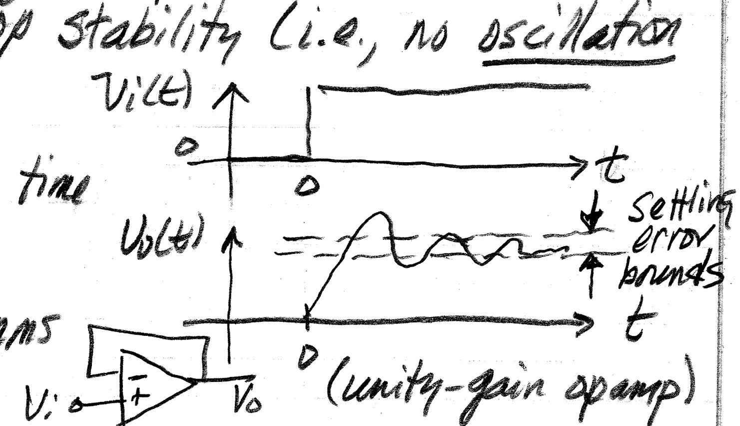
- **Stability and frequency Compensation in opamps:**

In general, opamps are used in negative feedback loops

- Feedback sets DC bias level at output ∴ no large coupling or bypass capacitors needed.
- FB increases bandwidth (with reduced gain)
- FB increases linearity of input stage (e.g., emitter degeneration is a type of negative FB (i.e., series negative feedback)
- Gain determined by (passive) FB network and is usually based on resistor or capacitor ratios that are much more accurate than absolute opamp gain values
- FB can improve temperature stability
- FB sets R_i and R_o

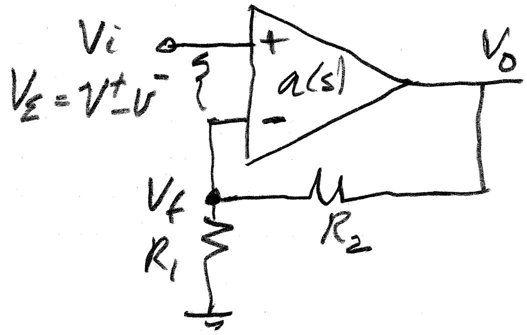
Input	Output	R_i	R_o	Type of Amp
Shunt FB	Shunt	Low	Low	$I \to V$; transresistance
Shunt	Series	Low	High	$I \to I$; current
Series	Shunt	High	Low	$V \to V$; Voltage
Series	series	High	High	$V \to I$; transconductance

- **Motivations for frequency compensation:**
  - Absolute closed-loop stability (i.e., no oscillation with $V_{in}=0$
  - Control of settling time in high-accuracy sampled-data systems (e.g., SC A/D, etc.)



Problem: Any FB loop can become unstable under certain conditions — must frequency compensate to guarantee stability in given, or worst-case operating condition.

Example: Non-inverting amplifier



$a(s) \equiv$ open-loop opamp gain

$V_f = \dfrac{R_1}{R_1+R_2} V_o = f V_o \equiv$ feedback voltage

$V_\varepsilon = V^+ - V^- = V_i - f V_o \equiv$ error voltage

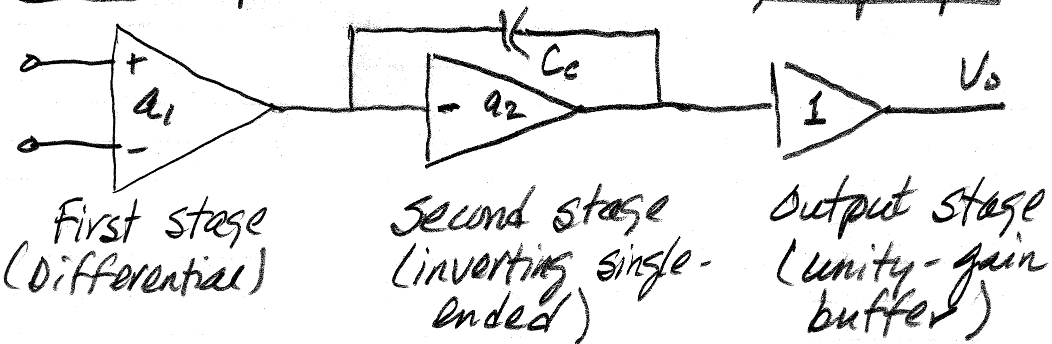
$V_o = a(s) V_\varepsilon$

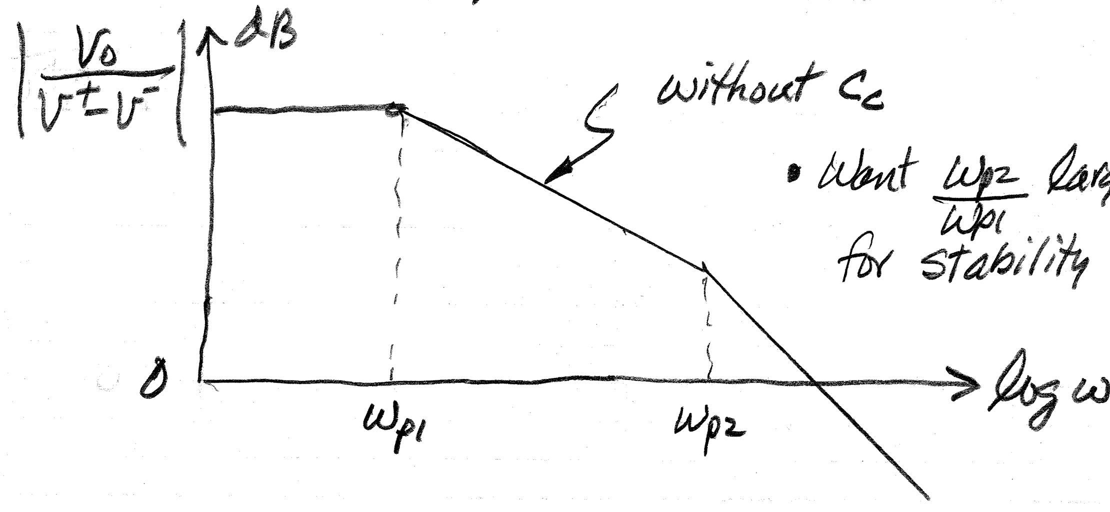
$= a(s)\left[V_i - f V_o\right]$

$\therefore\ A(s) \equiv$ closed-loop voltage gain $= \dfrac{V_o}{V_i}(s) = \dfrac{a(s)}{1+a(s)f}$

$= \dfrac{a(s)}{1+T(s)}$ where $T(s) \equiv$ loop transmission and $T_o \equiv$ loop gain at a specific frequency

- Miller compensation in two-stage opamps





- Want $\dfrac{\omega_{p2}}{\omega_{p1}}$ large for stability

- Instability occurs when $A(s) \rightarrow \infty$

$$\therefore A(s) = \frac{a(s)}{1+a(s)f} = \frac{a(s)}{1+T(s)} \rightarrow \frac{a(s)}{1-1} = \infty$$

$\therefore$ Loop transmission $\equiv \boxed{a(s)f = -1}$

- Also unstable if denominator is negative

__In general:__ $\boxed{\text{If } |a(s)f| \geq 1 \text{ when } \angle a(s)f = -180^\circ \text{ The amplifier is unstable.}}$

- This is a simplified version of __Nyquist__ __Stability Criterion__.
- __Stability of Feedback Circuit using a single stage opamp__

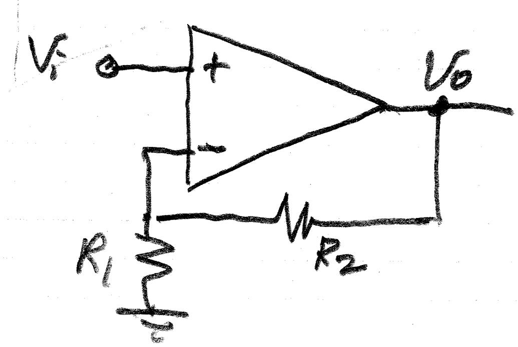
$$a(s) = \frac{a_o}{1-s/p_1} \equiv \text{opamp transfer function}$$

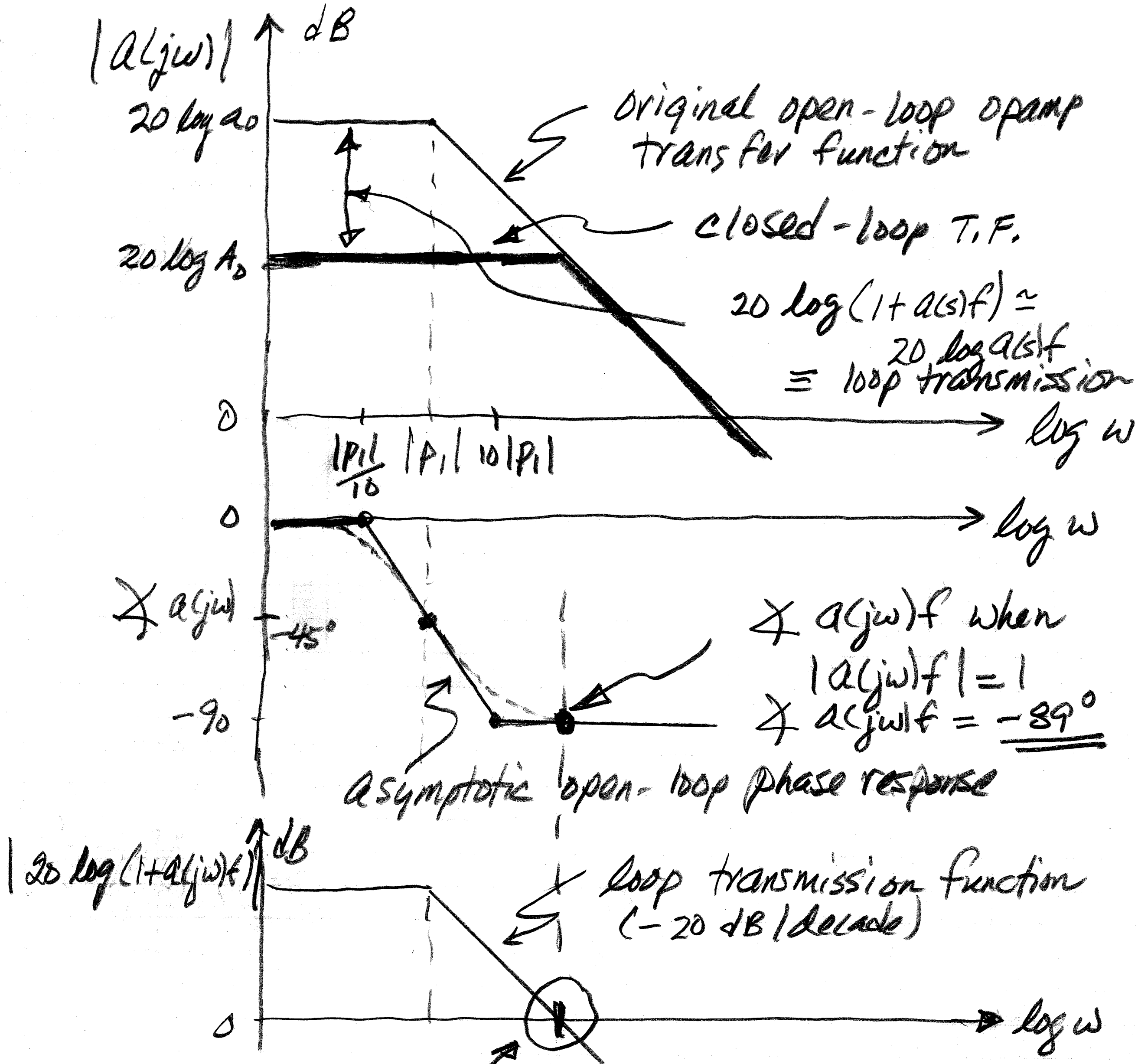
Thus, $$A(s) = \frac{a(s)}{1+a(s)f} = \underbrace{\frac{a_o}{1+a_of}}_{\substack{A_0 \equiv \text{closed-loop DC gain} \\ \text{if } a_of \gg 1 \\ A_0 \simeq \frac{1}{f}}} \frac{1}{1-\underbrace{\frac{s}{p_1(1+a_of)}}_{\substack{\text{BW increases} \\ \text{by } (1+a_of)}}}$$

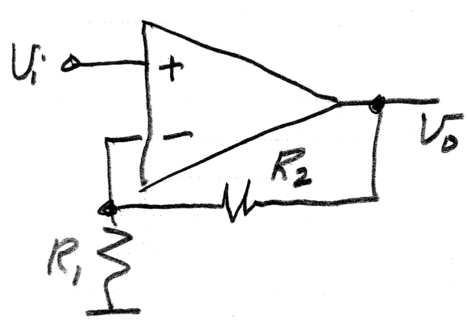
$T_0 = a_of$ = loop gain at DC

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

- __Bode Plot__: Use to find $\underbrace{\angle a(s)f \text{ when } |a(s)f| = 1}_{\text{This determines degree of stability}}$







$$f = \frac{R_1}{R_1 + R_2}$$

<u>Note:</u> phase shift for loop transmission is same as that for open-loop opamp ⇐ $\measuredangle(1+a(j\omega)f)$
$|a(j\omega)f| = 1$ at this freq.

- For a single-pole opamp, $\measuredangle\, a(j\omega)f$ can never reach $-180°$ (which converts negative FB to positive FB) so <u>always</u> stable with f = constant.

- <u>Real opamp has multiple poles:</u>

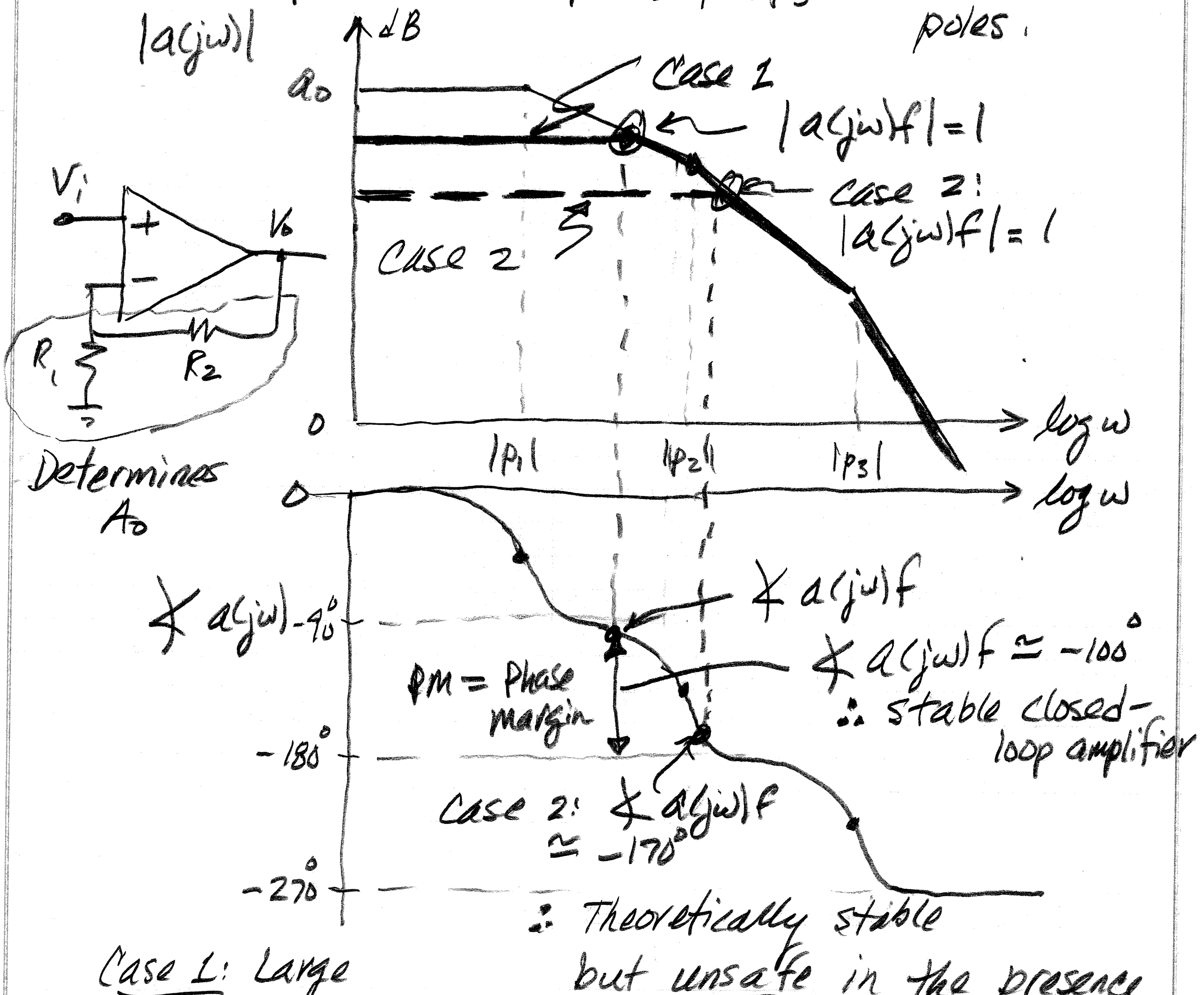
(i) Two-pole opamp — $\angle a(j\omega)f \rightarrow -180^\circ$ at $f \rightarrow \infty$

Theoretically, always stable but very, very marginal.

(ii) With three or more poles, $\angle a(j\omega)f = -180^\circ$ at some frequency and $< -180^\circ$ beyond that frequency.

- <u>Stability of Feedback circuit using three-stage opamp</u>

Assume p_1 = dominant pole; p_2, p_3 = non-dominant poles.



∴ Theoretically stable but <u>unsafe</u> in the presence of PVT variations and possible load variations.

<u>Case 1</u>: Large closed-loop gain

<u>Case 2</u>: Smaller closed-loop gain

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

(i) $A(s)$ has the same additional poles (f = constant)

(ii) at frequencies $> |p_1|(1+a_0 f)$, the $A(s)$ curve just follows the $a(s)$ curve:

$$A(s) \cong \frac{A_0}{\left(1-\frac{s}{|p_1|(1+a_0 f)}\right)\left(1-\frac{s}{|p_2|}\right)\left(1-\frac{s}{|p_3|}\right)}$$

where $|p_1|(1+a_0 f) < |p_2|$ as for case 1.

- Beyond this frequency, there is <u>peaking</u> in the closed-loop gain T.F. magnitude response

<u>Definitions</u>:

PM $\equiv$ phase margin $= 180° + (\measuredangle a(j\omega)f$ @ frequency where $|a(j\omega)|f = 1)$

$= 90°$ (very stable – one-pole exponential behavior)

$= 10°$ (stable but not practical – too dangerous)

$\simeq 60°$ desired for minimum settling time step response.

GM $\equiv$ gain margin $= |a(j\omega)f|$ @ frequency where $\measuredangle a(j\omega)f = -180°$. $|a(j\omega)f|$ should be less than 0 dB.

A good design value is GM ≈ -12 dB.