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Lecture 40

- Last time:
  - Bias and output swing for BiCMOS voltage amp
  - Start open-circuit time constant analysis (back to Chapter 10)
- Today :
  - Applications of open-circuit time constant analysis: CE amplifier and cascode amplifier

Frequency Response of Multistage Amplifiers

We need a *systematic technique* rather than a bunch of qualitative results (e.g., CS suffers from Miller effect, CD and CG are wideband stages …)

Disappointing news: our analytical technique is capable of estimating only the dominant (lowest) pole … for a restricted class of amplifiers.

ω_1

DETAILED f RESPONSE …

SPICE

The Special Case.

RELEVANT $\omega_3 << \omega_T$.

The transfer function can have *no zeroes* and must have a *dominant* pole $\omega_1 << \omega_2, \omega_3, \ldots, \omega_n$ (COMMON)

V_{out}/V_{in}

$$H(j\omega) = \frac{H_o}{\left(1 + j\omega b_1 + (j\omega)^2 b_2 + (j\omega)^3 b_3 + \ldots\right)}$$

Factor denominator: (SYMBOLIC ONLY)

$$H(j\omega) = \frac{H_o}{(1 + j\omega/\omega_1)(1 + j\omega/\omega_2)\ldots(1 + j\omega/\omega_n)}$$

Approximating the Transfer Function

Multiply out denominator:

$$H(j\omega) = \frac{H_o}{(1 + j\omega/\omega_1)(1 + j\omega/\omega_2)\ldots(1 + j\omega/\omega_n)} \approx$$

$$\frac{H_o}{1 + j\omega\left(\frac{1}{\omega_1} + \frac{1}{\omega_2} + \ldots + \frac{1}{\omega_n}\right) + \ldots}$$

Since $\omega_1 \ll \omega_2, \omega_3, \ldots, \omega_n \rightarrow$

$$b_1 = \frac{1}{\omega_1} + \frac{1}{\omega_2} + \ldots + \frac{1}{\omega_n} \approx \frac{1}{\omega_1}$$

WHAT THE "DOMINANT POLE" MEANS!

How to Find b_1?

See P. R. Gray and R. G. Meyer, *Analysis and Design of Analog Integrated Circuits* (EE 140) for derivation.

Result: b_1 is the sum of *open-circuit time constants* τ_i which can be found by considering each capacitor C_i in the amplifier separately and finding its Thévenin resistance R_{Ti} →

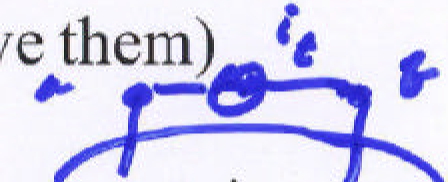
$$\tau_i = R_{Ti} C_i$$

$$\omega_1 \approx \frac{1}{b_1}.$$

$$b_1 = \sum_{i=1}^{n} R_{Ti} C_i \longrightarrow \boxed{\omega_1 \approx \frac{1}{\sum_{i=1}^{n} R_{Ti} C_i}}$$

Finding the Thévenin Resistance

1. Open-circuit all capacitors (i.e.; remove them)



2. For capacitor C_i, find the resistance R_{Ti} across its terminals with all independent sources removed (voltages shorted, currents opened) … might need to apply a test voltage and find the current in some cases.

ω_1 $R_{Ti} = v_t / i_t$.

Insight for design: the bandwidth of the amplifier will be limited by the capacitor that contributes the largest $\tau_i = R_{Ti}\, C_i \rightarrow$ not necessarily the largest C_i

$$\omega_1 = \frac{1}{\sum_{i=1}^{n} R_{Ti} C_i} \approx \frac{1}{(R_{Tj} C_j)}$$

BIGGEST.

"TECHNIQUE"

Systematic Approach

1. Construct *two-port* small-signal models for each stage

CHECK TO SEE WHETHER EVERYTHING IS INCLUDED.

2. Add the capacitors for each device across the appropriate nodes in the two-port models. Make sure how the gate, drain, and source (or base, collector, and emitter) terminals of each device fit onto the two-port models!

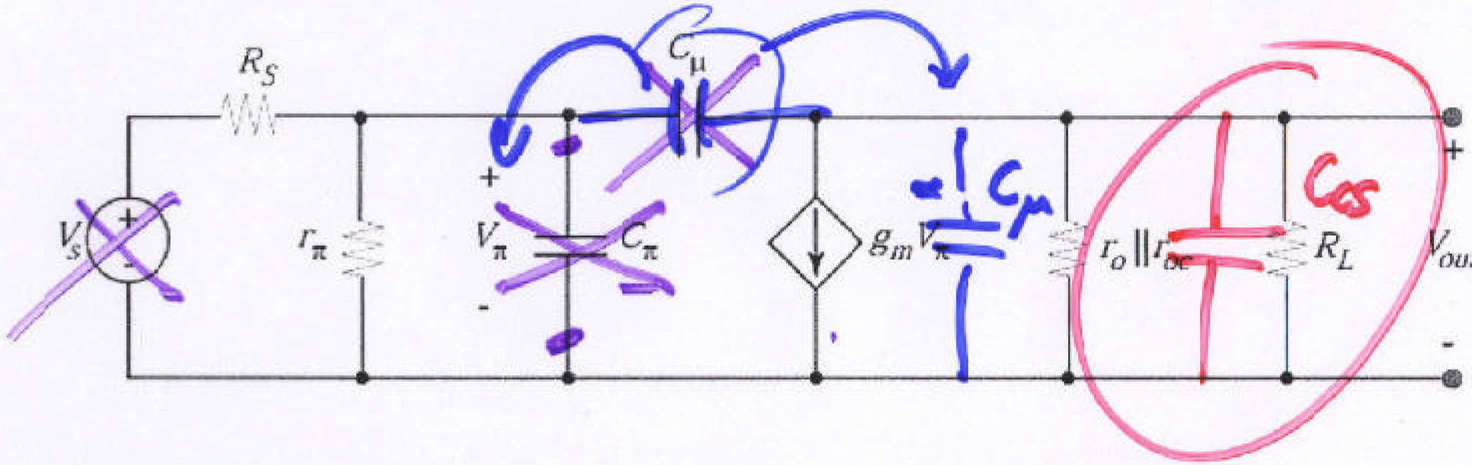
WATCH OUT!

3. (Optional) Use Miller's Theorem to transform capacitors across amplifiers into effective capacitances to ground (note that we ignore the "output Miller" in this course)

A GOOD IDEA!

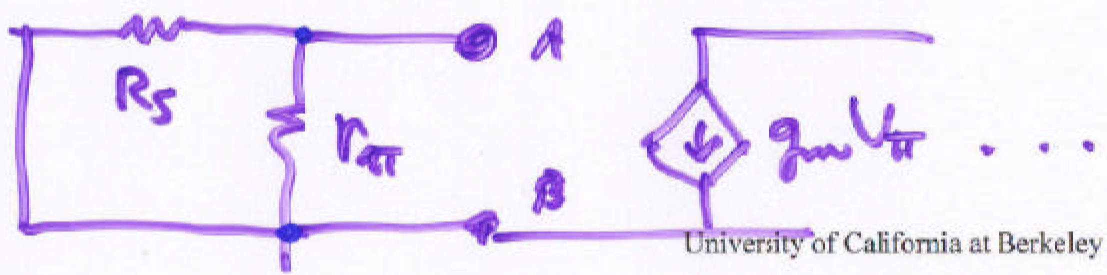
APPLYING O.C.T.C.

Common-Emitter Voltage Amplifier



Time constant for base-emitter capacitance C_π:

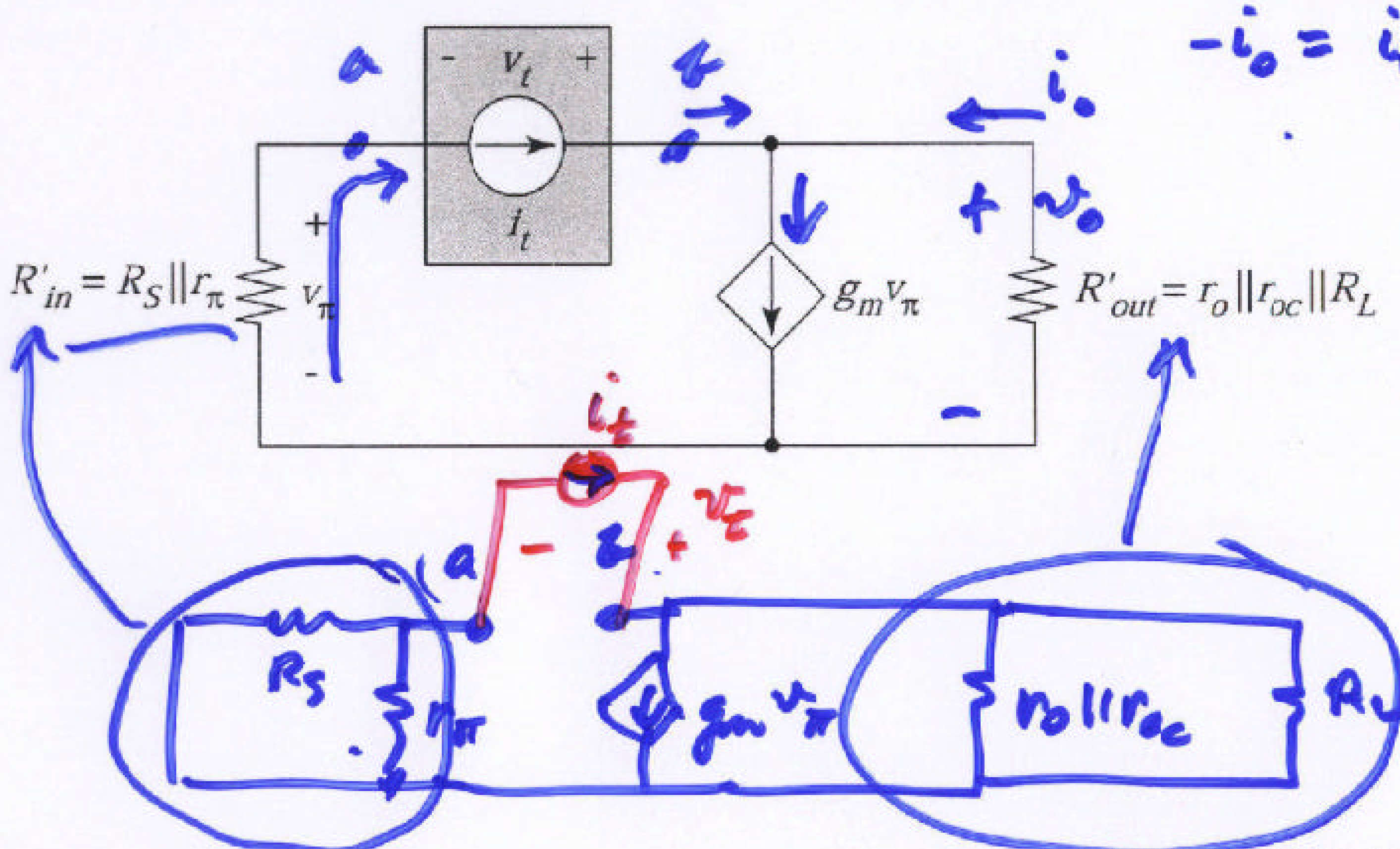
$$\tau_\pi = R_{T\pi} C_\pi = (R_S \| r_\pi) C_\pi$$



Base-Collector Time Constant

Must apply a test source (can't see $R_{T\mu}$ by inspection):

$-i_o = i_t - g_m v_\pi$



Solving for $R_{T\mu}$

- Find v_π: $v_\pi = -i_t(R_S \| r_\pi) = -i_t R'_{in}$
- Find v_o: $v_o = -i_o R'_{out} = (i_t - g_m v_\pi) R'_{out} = i_t(1 + g_m R'_{in}) R'_{out}$
- Find v_t: $v_t = v_o - v_\pi = i_t(1 + g_m R'_{in}) R'_{out} - (-i_t R'_{in})$

$v_t = i_t \left[R_{out}' + g_m R_{in}' R_{out}' + R_{in}' \right]$

Solve for Thèvenin resistance:

$$R_{T\mu} = \frac{v_t}{i_t} = R_{in}' + R_{out}' + g_m R_{in}' R_{out}'$$

Dominant Pole of CE Amplifier

Estimate dominant pole as inverse of sum of OCTCs:

$R_S \| r_\pi$ $\quad r_o \| r_{oc} \| R_L$

- $$\omega_1 \approx \frac{1}{\tau_{C_\pi} + \tau_{C_\mu}} = \left(R'_{in} C_\pi + [R'_{in} + R'_{out} + g_m R'_{in} R'_{out}] C_\mu\right)^{-1}$$

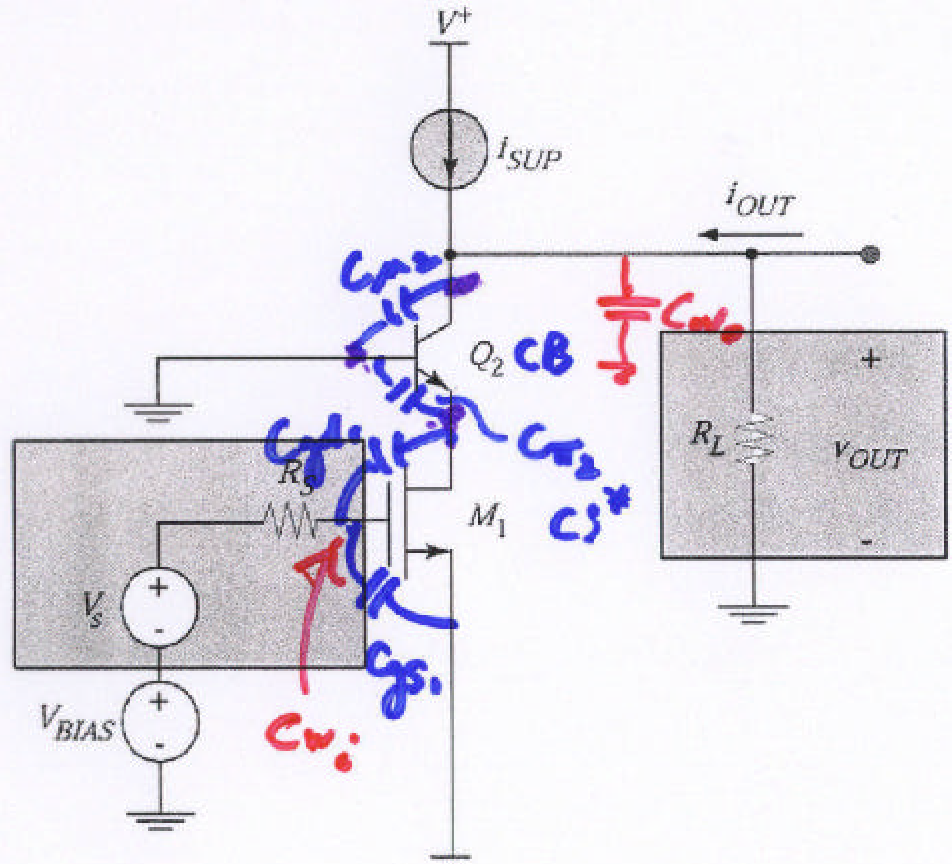
Identical to the "exact" analysis in Chapter 10

Why bother with the OCTC technique … add effect of C_{cs}

$$\frac{-g_m\left(\frac{r_\pi}{R_S + r_\pi}\right)(r_o \| r_{oc} \| R_L)(1 + j\omega/\omega_z)}{\boxed{(1 + j\omega/\omega_1)}(1 + j\omega/\omega_2)}$$

RIGHT!!

Multistage Amplifier Frequency Response



CS*-CB cascode

C_{gs1}

$C_{dg1} = C_{gd1}$

C_{db1}

~~C_{sb1}~~ → shorted

C_{gb1} ... omit.

$C_{\pi 2}$

$C_{\mu 2}$

C_{cs2}

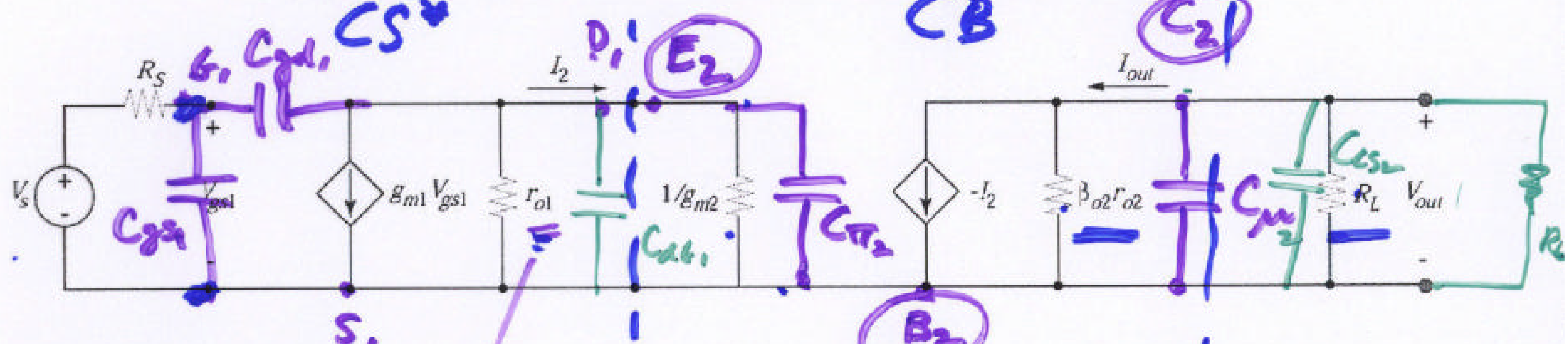
CURRENT SUPPLY...

C_{gd}'s

C_{db}'s

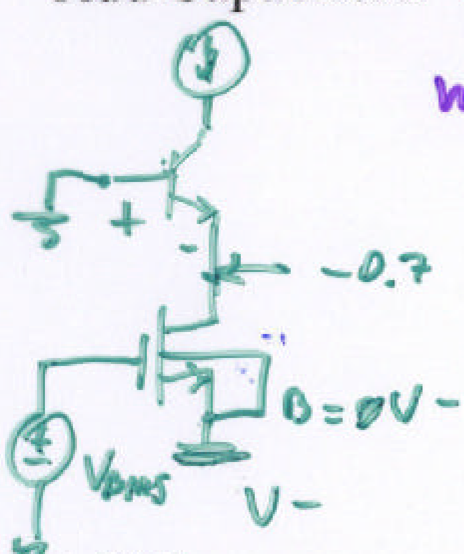
C_{wi}, C_{wo}

Cascode Two-Port Model



Add Capacitors: C_{gs1}, C_{gd1}, $C_{\pi 2}$, $C_{\mu 2}$ … what about C_{db1}, C_{cs2}?

no r_{oc}!



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Finding the Thèvenin Resistances

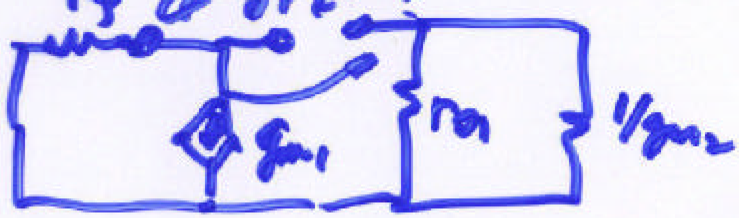
- C_{gs1}: $R_{TC_{gs1}} = R_S$

- C_{gd1}: $R_{TC_{gd1}} = R'_{in} + R'_{out} + g_{m1} R'_{in} R'_{out} = R_S + \frac{1}{g_{m2}} + g_{m1}\left(R_S \frac{1}{g_{m2}}\right)$

  $r_{o1} \| 1/g_{m2}$

  (+ C_{db1})

  R_S of g_1 C_{gd1}:



TYPO!

- $C_{\pi 2}$: $R_{TC_{\pi 2}} = r_{o1} \| 1/g_{m2} \cong 1/g_{m2}$

  (+ C_{db1})

- $C_{\mu 2}$: $R_{TC_{\mu 2}} = \beta_o r_{o2} \| R_L$

  (+ C_{cs2})

Dominant Pole

$R_L \ll \beta_o r_{o2} \| r_{oc2}$

Applying the theorem:

$$\omega_1^{-1} \approx \underbrace{R_S C_{gs1}}_{\tau_{gs}} + \underbrace{R_S\left(1 + g_{m1}/g_{m2}\right)C_{gd1}}_{\tau_{gd}} + \underbrace{(1/g_{m2})C_{\pi 2}}_{\tau_{\pi 2}} + \underbrace{R_L C_{\mu 2}}_{\tau_{\mu 2}}$$

Find approximate voltage transfer function:

- $$A_{vo} = \left.\frac{v_{out}}{v_s}\right|_{R_S, R_L} = -g_{m1}\left(\cancel{\frac{r_{o1}}{r_{o1} + 1/g_{m2}}}\right)\left(\beta_o r_{o2} \| r_{oc2} \| R_L\right) \simeq -g_{m1} R_L$$

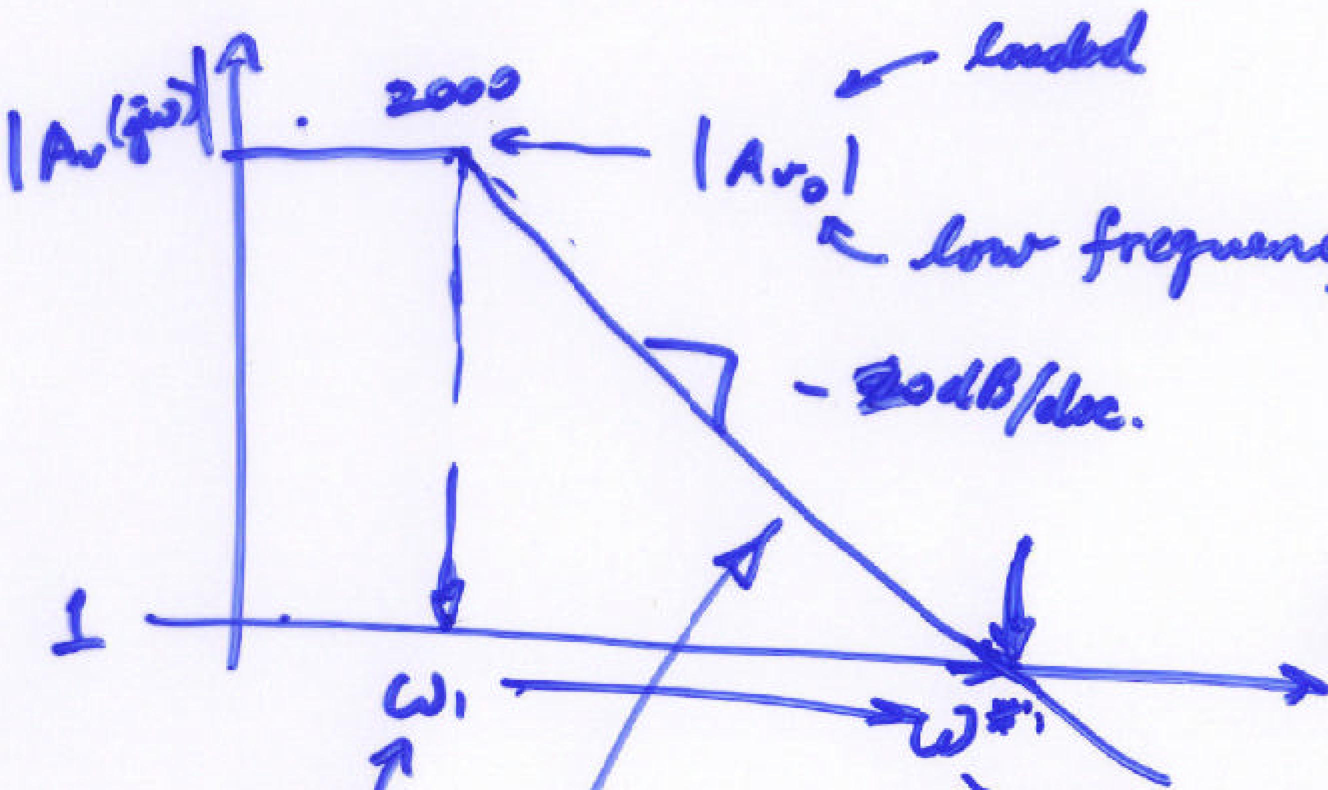
≈ 1

$R_L \ll r_{oc2}, \beta_o r_{o2}$

$$A_v(j\omega) \cong \frac{A_{vo}}{1 + j\omega/\omega_1}$$

$\leftarrow$ no capacitor

OCTC



$$= 1000 \times 2000 = 2\ \text{Mrads}^{-1}$$

$$\omega^* = |A_{vo}|\omega_1$$

$$|A_v(j\omega)| \approx \frac{|A_{vo}| \cdot \omega_1}{\omega} = \frac{|A_{vo}|}{(\omega/\omega_1)} = 1$$

$$\hookrightarrow \frac{|A_{vo}|}{\sqrt{1+(\omega/\omega_1)^2}} \approx \frac{|A_{vo}|}{(\omega/\omega_1)}, \quad \omega \gg \omega_1$$

ω^*