Lecture 32: Multi-Transistor High Frequency

- Announcements:
- HW#10 online soon and due Friday Nov. 16 via Gradescope
- Lab#5 due Tuesday, Nov. 6, 5 p.m.
- Midterm coming up
  - Friday this week, Nov. 9, @ 5 p.m., in 277 Cory (just like last time)
  - Midterm Info Sheet online
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- Lecture Topics:
  - Multi-Transistor Example (Inspection Analysis)
    - —Input/Output Resistances
    - —Gain
    - —High Frequency
  - MOS Inspection Analysis
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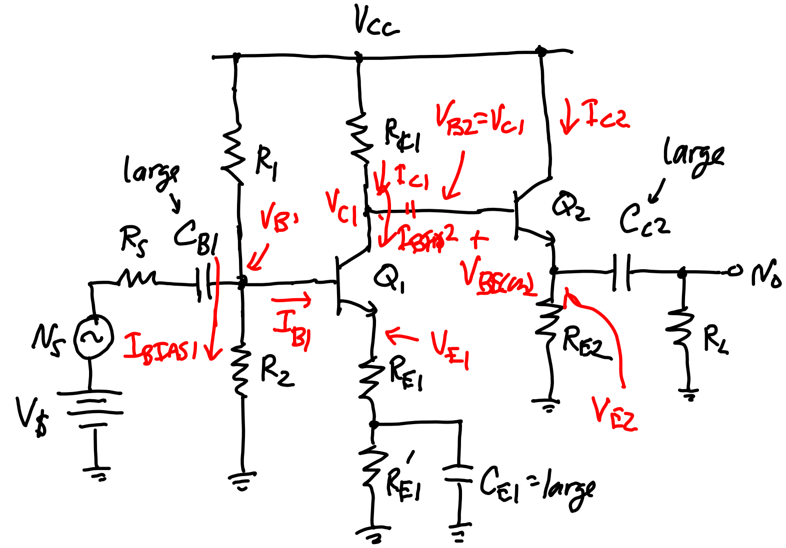
- Last Time:
- Got the gain of the amplifier
- Now, get the high frequency cut-off

Example. Multi-Transistor Amplifier Inspection Analysis

(C.E. w/ Degeneration, C.C. Cascade)



Find $R_i, R_o, a_v = \frac{v_o}{v_s}$, and f_H.

First, find the DC operating pt:

Good Design: $I_{BIAS1} > 10 I_{B1}$

$$V_{B1} = \frac{R_2}{R_1+R_2} V_{CC} \rightarrow V_{E1} = V_{B1} - \underbrace{V_{BE(on)}}_{0.7V}$$

$$I_{C1} \approx I_{E1} = \frac{V_{E1}}{R_{E1}+R'_{E1}} = \frac{V_{B1}-V_{BE(on)}}{R_{E1}+R'_{E1}}$$

$$V_{C1} = V_{CC} - I_{C1}R_{C1} = V_{B2} \rightarrow V_{E2} = V_{B2} - V_{BE(on)}$$

$$I_{C2} = I_{E2} = \frac{V_{E2}}{R_{E2}}$$

Remarks.

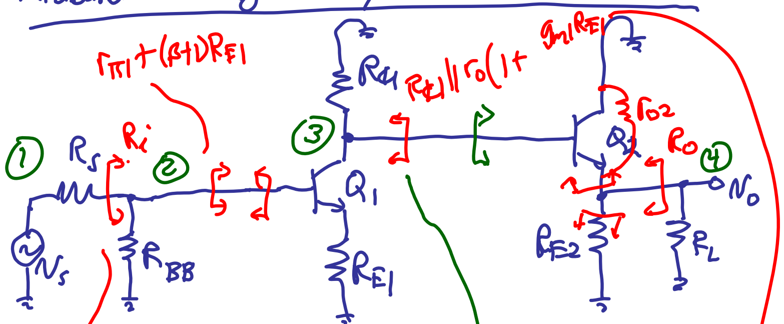
① Look for the $V_{BE(on)}$'s. → well-defined voltages.

② Currents usually be determined by $\frac{V_E}{R_E}$'s.

For Bias Stability:

$I_{BIAS1} > 10 I_{B1}$ also $I_{C1} - I_{BIAS2} \geq 10 I_{B2}$

Midband Small-Signal Analysis for Gain, R_i, and R_o:



$$R_i = R_{BB} \| (r_{\pi1} + (\beta_1+1)R_{E1})$$

$$R_o = R_{E2} \| r_{o2} \| \left\{ \frac{R_{C1} \| r_{o1}\left(1 + \frac{g_{m1}R_{E1}}{1 + \frac{R_S \| R_{BB}}{r_{\pi1}}}\right) + r_{\pi2}}{(\beta_2+1)} \right\}$$

bis

bis

$$R_o = R_{E2} \| \left(\frac{r_{\pi2} + R_{C1}}{\beta+1}\right)$$

Get gain $\frac{v_o}{v_s}$: (gain from ① to ④)

$$\frac{v_②}{v_①} = \frac{v_②}{v_s} = \frac{R_i}{R_s + R_i} = \frac{R_{BB} \| (r_{\pi1} + (\beta_1+1)R_{E1})}{R_s + R_{BB} \| (r_{\pi1} + (\beta+1)R_{E1})}$$

(voltage divider)

$$\frac{v_③}{v_②} = -G_{m1} R_{C1}$$

$$= -\frac{g_{m1}}{1 + g_{m1}R_{E1}} \Bigg\{ R_{C1} \,\Big\|\, \underbrace{r_{o1}\left(1 + \frac{g_{m1}R_{E1}}{1 + \frac{R_S \| R_{BB}}{r_{\pi1}}}\right)}_{\text{large}} \,\Big\|\, \underbrace{[r_{\pi2} + (\beta_2+1)(R_{E2} \| R_L \| r_{o2})]}_{\text{large}} \Bigg\}$$

$$\frac{v_③}{v_②} \approx -\frac{g_{m1}R_{C1}}{1 + g_{m1}R_{E1}}$$

$$\frac{v_④}{v_③} = \frac{R_{E2} \| R_L \| r_{o2}}{r_{e2} + R_{E2} \| R_L \| r_{o2}} \simeq 1$$

$r_{e2} = \frac{1}{g_{m2}}$

$$\therefore \frac{v_o}{v_s} = \frac{v_2}{v_1}\cdot\frac{v_3}{v_2}\cdot\frac{v_4}{v_3} = \frac{v_4}{v_1}$$

$$= \boxed{-\frac{R_{BB}\|(r_{\pi}+(\beta_1+1)R_{E1})}{R_s+R_{BB}\|(r_{\pi}+(\beta_1+1)R_{E1})}\;\frac{g_{m1}R_{C1}}{1+g_{m1}R_{E1}} = \frac{v_o}{v_s}}$$

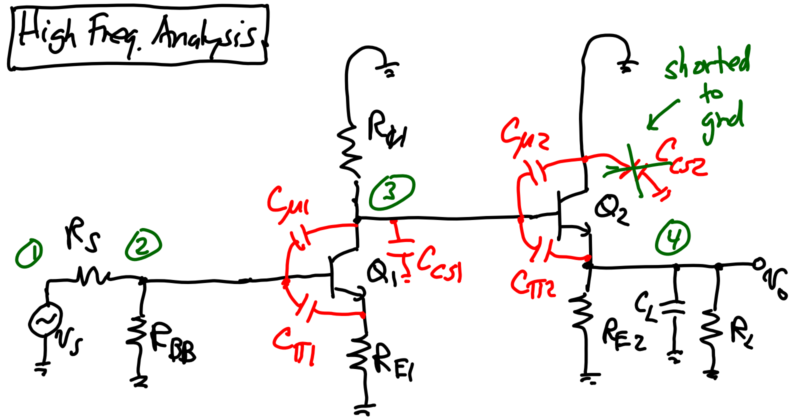
Procedure for Midband Gain Inspection Analysis:

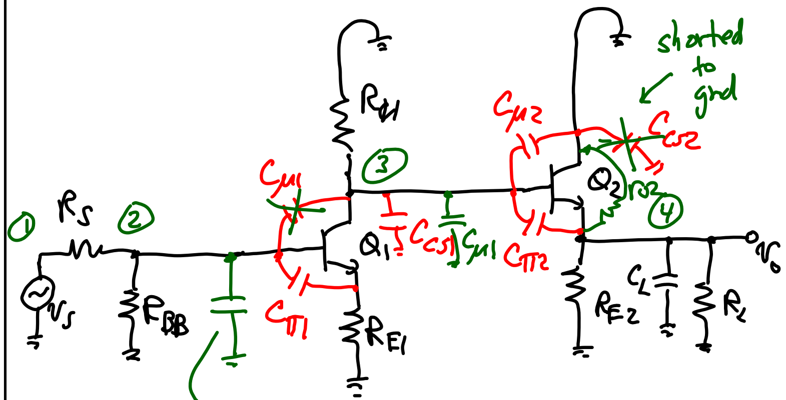
- Identify and label all signal path nodes
- Get stage gain from node to node
  - For each stage, be sure to account for loading by the next stage, specifically load resistance to ground
  - For transistor terminal-to-terminal gains, will likely need to determine output node resistance to ground
    - — including loading by the next stage, and
    - — even the influence of loading by the previous stage, e.g., when determining R_c
- Take the product of all node-to-node gains to get the total gain
- Can do all of this by inspection if
  - There is no feedback
  - You know all the terminal-to-terminal gain equations or can "see" or "derive" them quickly
  - You know all the equations for resistances looking into the transistor terminals (to ground) or can "see" or "derive" them quickly
  - "see" or "derive" quickly can often be done by following the currents

Procedure for High Frequency Inspection Analysis:

- Identify and label all signal path nodes
- Draw in the small transistor capacitors
- Use the Miller transform to turn the base-to-collector or gate-to-drain capacitor into shunt capacitors to ground
- For the base-to-emitter or gate-to-source capacitor you will need to know the equation for driving point resistance, i.e., resistance in parallel
- Get the time constant for each node by
  - Determining the total capacitance C_{node} from that node to ground
  - Determining the total resistance R_{node} from that node to ground
  - Time constant = $R_{node} * C_{node}$
- Handle each feedback capacitor separately using knowledge of its driving point R equation (or derive the equation from scratch using the hybrid-π model
- Add up all the time constants and take the reciprocal to get the ω_H

$\boxed{\text{High Freq. Analysis}}$





$$C_{\mu1}(1-a_{v1}) = C_{\mu1}(1+G_{m1}R_{③})$$

Using OCTC Analysis:

$$\omega_H = \frac{1}{C_{②}R_{②} + C_{③}R_{③} + C_{④}R_{④} + C_{\pi1}R_{\pi1} + C_{\pi2}R_{\pi2}}$$

total shunt C @ node ②

total shunt R @ node ②

haven't seen these yet → need to determine the $R_{\pi o}$'s

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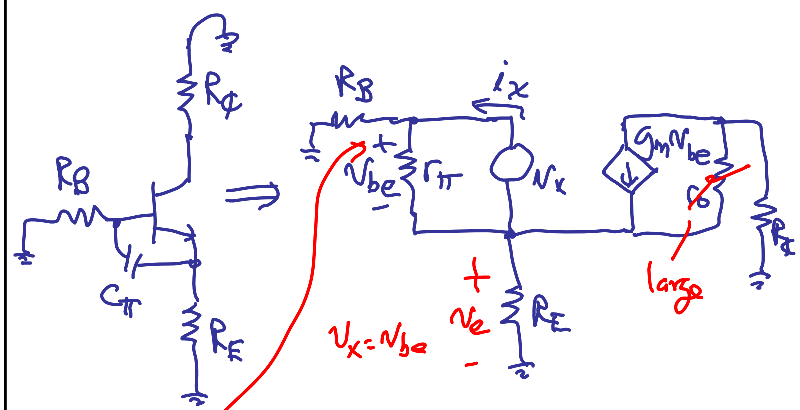
Do it for the general case:



KCL: $i_x = \frac{v_x}{r_\pi} + \frac{v_e + v_x}{R_B} = \frac{v_x}{r_\pi} + \frac{v_e}{R_B} + \frac{v_x}{R_B}$

$$v_e = R_E\left(\frac{v_x}{r_\pi} - i_x + g_m v_x\right)$$

$$i_x = \frac{v_x}{r_\pi} + \frac{v_x}{R_B} + \frac{R_E}{R_B}\left(\frac{v_x}{r_\pi} - i_x + g_m v_x\right)$$

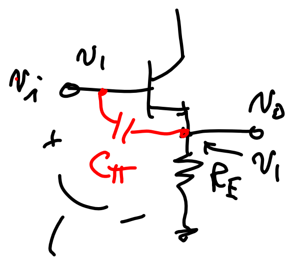
$$i_x\left(1 + \frac{R_E}{R_B}\right) = v_x\left(\frac{1}{r_\pi} + \frac{1}{R_B} + \frac{R_E}{r_\pi R_B} + \frac{g_m R_E}{R_B}\right)$$

$$R_{\pi o} = \frac{v_x}{i_x} = \frac{1}{\frac{\cancel{(R_E+R_B)}}{r_\pi \cancel{(R_E+R_B)}} + \frac{1+g_m R_E}{R_B+R_E}} = \boxed{r_\pi \,\|\, \frac{R_B+R_E}{1+g_m R_E} = R_{\pi o}}$$

$R_{\pi o} = r_\pi \| \frac{R_B \| R_E}{1+g_m R_E}$

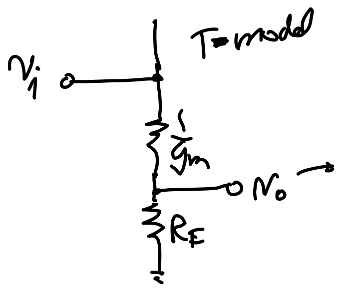
$R_E = $ large

$r_\pi \| \frac{1}{g_m} = $ small $\rightarrow$ often times can be neglected



$\frac{v_o}{v_i} \simeq \frac{R_E}{\frac{1}{g_m}+R_E} \approx 1$ (R_E: 1kΩ, $\frac{1}{g_m}$: 25Ω)

$v_i - v_i \approx 0 \rightarrow C_\pi$ is effectively not there!



T-model

$\frac{v_o}{v_i} = \frac{R_E}{\frac{1}{g_m}+R_E}$

Now, get the τ's to get ω_H:

$C_{②} = C_{\mu 1}(1+G_m R_{③})$

$= C_{\mu 1}\left(1+\frac{g_{m1}}{1+g_{m1}R_{E1}}\left\{R_{C1} \| \underbrace{r_{o1}\left(1+\frac{g_{m1}R_{E1}}{1+\frac{R_s \| R_B}{r_\pi}}\right)}_{\text{large}} \| \underbrace{\left(r_{\pi 2}+(\beta_2+1)(r_{o2}\|R_{E2}\|R_L)\right)}_{\text{large}}\right\}\right)$

$= C_{\mu 1}\left(1+\frac{g_{m1}R_{C1}}{1+g_{m1}R_{E1}}\right)$

$R_{②} = R_s \| R_{BB} \| \underbrace{(r_\pi+(\beta+1)R_{E1})}_{\text{large}} \simeq R_s \| R_{BB} \approx R_s$

$\boxed{\tau_{②} = C_{\mu 1}\left(1+\frac{g_{m1}R_{C1}}{1+g_{m1}R_{E1}}\right)R_s}$

$C_{③} = C_{cs1}+C_{\mu 1}+C_{\mu 2}$

$R_{③} = R_{C1} \| \underbrace{r_{o1}\left(1+\frac{g_{m1}R_{E1}}{1+\frac{R_s \| R_B}{r_\pi}}\right) \| (r_{\pi 2}+(\beta_2+1)(R_{E2}\|R_L\|r_{o2}))}_{\text{large}}$

$\simeq R_{C1}$

$\tau_{③} = (C_{cs1}+C_{\mu 1}+C_{\mu 2})R_{C1}$

$C_{④} = C_L$

$R_{④} = R_{E2} \| R_L \| r_{o2} \| \frac{r_{\pi 2}+R_{C1} \| \overbrace{r_{o1}\left(1+\frac{g_{m1}R_{E1}}{1+\frac{R_B \| R_s}{r_{\pi 1}}}\right)}^{\text{large}}}{\beta_2+1}$

$\simeq R_{E2} \| R_L \| \left(\frac{r_{\pi 2}+R_{C1}}{\beta_2+1}\right)$

$\boxed{\tau_{④} = C_L\left(R_{E2} \| R_L \| \frac{r_{\pi 2}+R_{C1}}{\beta_2+1}\right)}$