1) Determine output current as a function of input voltage. Assume transistor is FAR

The op amp is given to be ideal. So we can immediately say:

Virtual short \( \Rightarrow V_1 = V_2 = V_{in} \)

\[ V_R = V_{in} \Rightarrow I_0 = \frac{V_R}{R} \Rightarrow I_0 \approx \frac{V_{in}}{R} \]

Actually \( I_C = \alpha I_E \)

\[ \Rightarrow I_0 = \frac{\alpha V_{in}}{R} \]

2) In the circuit below, determine the correct value of \( R_x \) so that the output voltage is zero when the input voltage is zero. Assume finite input bias current, but zero input offset current and voltage.

Want \( V_0 = 0 \) when \( V_{in} = 0 \)

Redraw the circuit with output & input shorted to zero.

Because of the high gain of the amplifier, we can assume a virtual short between input terminals: \( V_+ = V_- \)

\[ V_+ = I_{B1}(R_1 || R_2) \quad V_- = -I_{B2} R_x \]

Since \( V_+ = V_- \)

\[ I_{B1}(R_1 || R_2) = I_{B2} R_x \]

Given that \( I_{B1} = I_{B2} \) (offset current = 0)

\[ R_x = R_1 || R_2 \]
3)

(a) Find the DC operating currents.

(i) Find current by current-source model. Since $p = 200$, it is fairly safe to assume all $I_b's = 0$.

**KVL @ ①**:

$-I_{ref} \cdot 5.0k - I_{ref} \cdot 2.8k - 1.4 - I_{ref} \cdot 2.2k - (-6) = 0$

$-I_{ref} (-5k - 2.8k - 2.2k) = -6 + 1.4 = -4.6$

$I_{ref} (10k) = -4.6 \Rightarrow I_{ref} = 460 \mu A$

**KVL @ ②**:

$I_{ref} \cdot 2.2k + 1.4 + I_{ref} \cdot 2.8k - V_{beL} - 500 \cdot I_{ee} - 1k \cdot I_{ee} = 0$

$5k \cdot I_{ref} - V_{beL} + 1.4 = 1.5k I_{ee}$

$(5k \cdot 460 \mu A) + 1.4 - V_{beL} \frac{I_{ee}}{I_s} = I_{ee}$

$1.5k$

$2.47m - 17.33 \mu A \ln \left( \frac{I_{ee}}{5 \times 10^{-15}} \right) = I_{ee}$

by trial & error

1st guess: $I_{ee} = 2mA$

wow, I got it on the 1st try! all my EE experience has paid off!
3 cont'd)

(a) $I_{C1} = I_{C2}$

Assume $V_{B1} = V_{B2} = 0$.

$V_{E1} = V_{E2} = -7V$

$\frac{I_{C1}}{I_{C2}} = \frac{V_{E2}}{V_{E1}} = \frac{-7}{4.8k} = 1.1mA$

(b) Find $R_{01}$, $R_{02}$, $A = \frac{U_o}{U_{in}}$

This circuit is symmetric -> use half circuit analysis.

First find gain of diff. pair. and then the gain of CC output stage and multiply together.

**DM = 1/2 CHT w/o Q5 (C.C. buffer):**

$U_{x} = \frac{R_{x}}{R_{01} + R_{x} \frac{V_{in}}{2}}$

$R_{x} = R_{c}(c e w/o dog) = R_{\pi3} + \beta (\beta + 1) R_{e2} = 5.2k + (201)(50) = 15.2k \Omega$

$R_{0} = R_{o}(c c) = \frac{R_{\pi}}{\beta + 1} (R_{s} = 0) = \frac{4.72k}{201} = 23 \Omega$

$\Rightarrow U_{x} = \frac{4.8k || 15.2k}{4.8k || 15.2k + 23} \frac{U_{in}}{2} \Rightarrow U_{x} \approx \frac{U_{in}}{2}$
$$U'_d = -G_m U_x \left( P_{o2} \parallel 3k \right) \Rightarrow \frac{U'_d}{U_{id/2}} = -G_m \left( P_{o2} \parallel 3k \right)$$

$$P_{o2} = f_o (c.e. \omega / \deg) = f_0 \left( 1 + G_m R_e \right) \quad \text{[since } R_i \gg R_s + R_e \text{]}$$

$$G_m = \frac{f_i}{V_i} = \frac{1 mV}{26 mV} = 38.5 \text{ mV}$$

$$P_{o2} = \frac{120}{1 mV} \left( 1 + (38.5 mV) (50) \right) = 380 k\Omega$$

$$\Rightarrow P_{o2} \parallel 3k \approx 3k\Omega$$

$$G_m = \frac{G_m}{1 + G_m R_e} = \frac{38.5 mV}{1 + (38.5 mV) (50)} = 13.2 mV$$

$$\frac{U'_d}{U_{id/2}} = - \left( 13.2 mV \right) (3 k\Omega) = -39$$

$$A_{ce} = 1 \left( \frac{R_L}{R_L + R_{o2}} \right) \Rightarrow P_{o2} = \frac{R_{o2} + R_3}{\beta + 1} = \frac{R_{o2} (20 \Omega)}{1.18 mV}$$

$$= 375 \Omega$$

$$A_{ce} = 1 \left( \frac{2 k}{2 k + 37} \right) \approx 1$$

$$\Rightarrow \left[ \frac{U_d}{U_{id/2}} = \frac{U'_d}{U_{id/2}} = \left( -39 \right)^{1/2} = -19.5 mA \right]$$

$$R_{act} = \frac{R_{o2} \text{ (w/ out load)}}{R_{out}} \approx \frac{375 \Omega}{R_{out}}$$

$$R_{id} = \frac{U_{id}}{i_{b1}} \approx \left[ \frac{R_t + (\beta + 1) R_e}{2} \right]$$

$$R_e = 4.8 k \Omega \quad R_{i2} = 4.8 k \Omega \quad 15.2 k = 3.64 k \Omega$$

$$R_{id} = \left[ 4.7 k \Omega + (20 \Omega) 3.64 k \Omega \right] / 2$$

$$R_{id} = 73 k \Omega \times 2 = 1.47 M\Omega$$