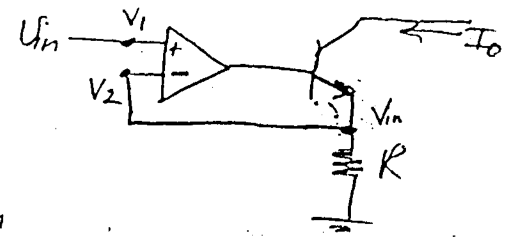
1) determine output current as a function of input voltage. assume transistor is FAR

the op amp is given to be ideal. so we can immediately say:



virtual short $\Rightarrow V_1 = V_2 = U_{in}$

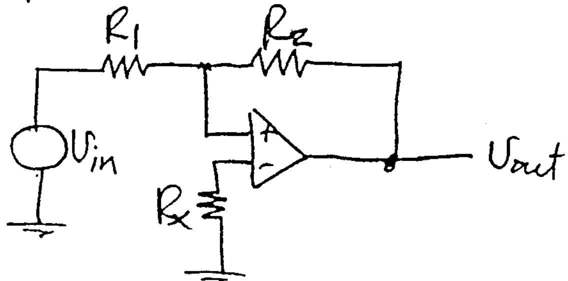
$\Rightarrow V_R = V_{in} \Rightarrow I_o = \frac{V_R}{R} \Rightarrow$ $\boxed{I_o \cong \frac{V_{in}}{R}}$

actually $I_C = \alpha I_E$

$\Rightarrow$ $\boxed{I_o = \frac{\alpha V_{in}}{R}}$

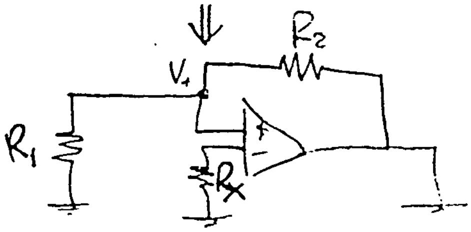
2) In the circuit below, determine the correct value of R_x so that the output voltage is zero when the input voltage is zero. Assume finite input bias current, but zero input offset current and voltage.

want $U_o = 0$ when $U_{in} = 0$

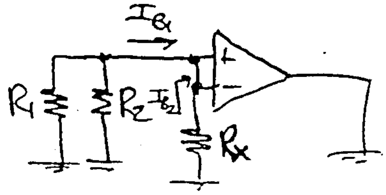


redraw the circuit with output & input shorted to zero.

⇓



R_2 & R_1 go between V_+ & ground $\Rightarrow$



because of the high gain of the amplifier, we can assume a virtual short between input terminals: $V_+ = V_-$

$V_+ = -I_{B1}(R_1 \| R_2)$, $V_- = -I_{B2} R_x$

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

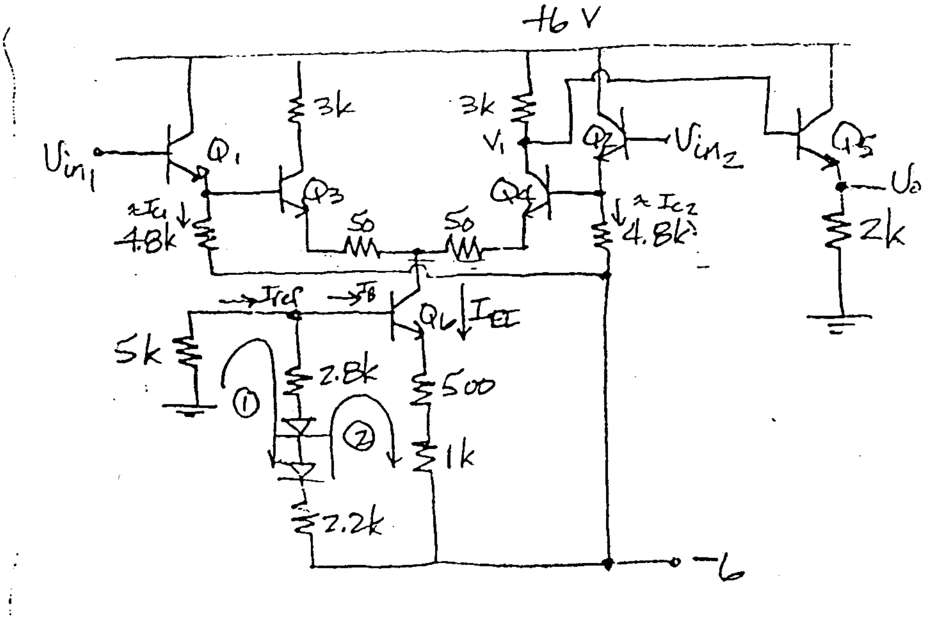
given that $I_{B1} = I_{B2}$ (offset current = 0) $\Longrightarrow$ $\boxed{R_x = R_1 \| R_2}$

3)

(a) find the DC operating currents.

(1) find current of current source

since $\beta = 200$, it is fairly safe to assume all I_B's $= 0$.



KVL @ ①:

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

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

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

KVL @ ②:

$$I_{ref}\cdot 22k + 1.4 + I_{ref}\, 2.8k - V_{BE6} - 500\cdot I_{EE} - 1k\cdot I_{EE} = 0$$

$$5k\cdot I_{ref} - V_{BE6} + 1.4 = 1.5k\, I_{EE}$$

$$\frac{(5k)(460\mu) + 1.4 - V_T \ln\frac{I_{EE}}{I_S}}{1.5k} = I_{EE}$$

$$2.47m - 17.33\mu \ln\left(\frac{I_{EE}}{5\times10^{-15}}\right) = I_{EE}$$

by trial & error

1st guess: $\underline{I_{EE} = 2mA}$

wow, I got it on the 1st try! All my EE experience has paid off!

(2) current through collectors of diff pair

$$\underline{I_{C3}} = \underline{I_{C4}} \approx \frac{I_{EE}}{2} = \underline{1\ mA} \quad \text{(matched transistors)}$$

(3) current through collector of Q5

V_B of $Q_5 = V_{cc} - I_{c4} R_c = 6 - (1mA)(3k\Omega) = 3V$

$V_{E5} = 3.0V - 0.7V = 2.3V$

$$I_{E5} = \frac{2.3V}{2k\Omega} \Rightarrow I_{E5} = 1.15\ mA$$

3 cont'd)

(4) I_{C_1} & I_{C_2}

assume $V_{B_1} = V_{B2} = 0$.

$V_{E_1} = V_{E_2} = -.7V$

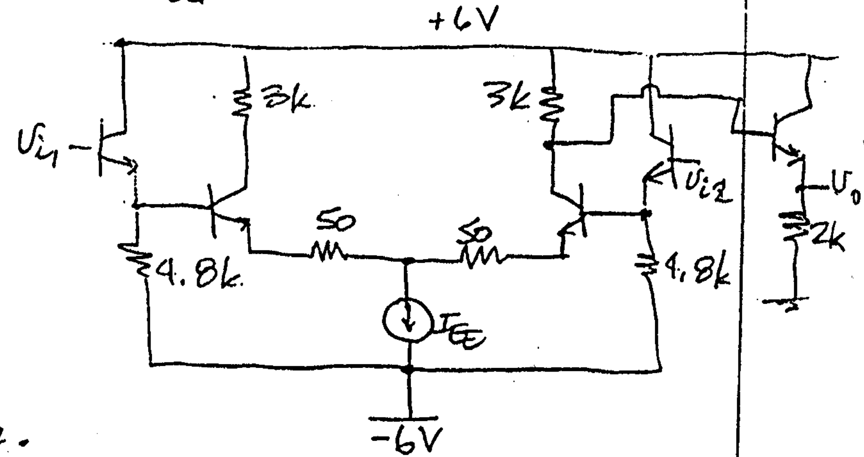
$I_{C_1} = I_{C_2} \simeq \frac{6-.7}{4.8k} = 1.1mA$

(b) find R_{id}, R_o; $A = \frac{v_o}{v_{id}}$

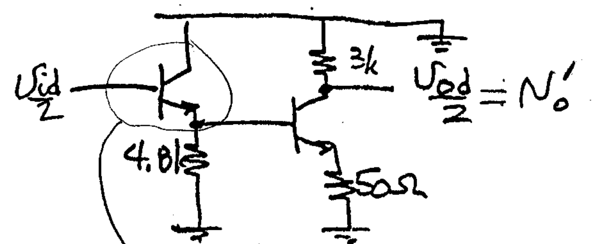
new circuit →

this circuit is ≈ symmetric ⇒ use half circuit analysis

1st find gain of diff pair and then the gain of CC output stage and multiply together.



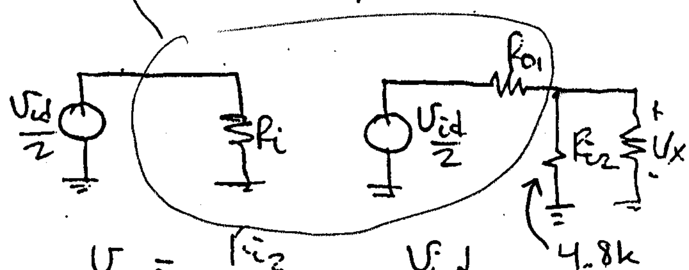
DM ½ ckt w/o Q5 (C.C. buffer):



CC, CE w/ deg

R_i of CC_3 is very large

⇒ $R_i \| 3k \approx 3k$



$v_x = \frac{R_{i2}}{R_{o1} + R_{i2}} \cdot \frac{v_{id}}{2}$

$R_{i2} = R_i(\text{CE w/ deg}) = r_{\pi_3} + (\beta+1)R_{E_3} = 5.2k + (201)(50)$

$R_{i2} = 15.2k\Omega$

$R_{o1} = R_o(cc) = \frac{r_\pi}{\beta+1} \quad (R_S = 0) = \frac{4.72k}{201} = 23\Omega$

$\Rightarrow v_x = \frac{4.8k \| 15.2k}{4.8k \| 15.2k + 23} \cdot \frac{v_{id}}{2} \quad \Rightarrow v_x \cong \frac{v_{id}}{2}$

3 cont'd)

$$v_o' = -G_m v_x (R_{o2} \| 3k) \Rightarrow \frac{v_o'}{v_{id}/2} = -G_m (R_{o2} \| 3k)$$

$$R_{o2} = r_o(\text{CE w/ deg}) \cong r_o(1 + g_m R_E) \quad \left[\text{ignore } R_S \text{ \& } R_E \text{ since } r_\pi \gg R_S + R_E\right]$$

$$g_{m3} = \frac{I_{C3}}{V_T} = \frac{1\,mA}{26\,mV} = 38.5\,m\mho$$

$$\Rightarrow R_{o2} = \frac{130}{1\,mA}\left(1 + (38.5m)(50)\right) = 380\,k\Omega$$

$$\Rightarrow R_{o2} \| 3k \approx 3\,k\Omega$$

$$G_m = \frac{g_m}{1 + g_m R_E} = \frac{38.5m}{1 + (38.5m)(50)} = 13.2\,m\mho$$

$$\frac{v_o'}{v_{id}/2} = -(13.2\,m\mho)(3\,k\Omega) = \underline{-39}$$

$$A_{cc} = 1 \cdot \left(\frac{R_L}{R_L + R_{o3}}\right) \Rightarrow R_{o3} = \frac{r_{\pi 3} + R_{S3}}{\beta + 1} = \frac{\left(\frac{200(26m)}{1.15m}\right) + 3k}{201}$$

$$= 37\,\Omega$$

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

$$\Rightarrow \boxed{\frac{v_o}{v_{id}} \cong \frac{1}{2}\frac{v_o'}{v_{id}/2} = (-39)\frac{1}{2} = -19.5 = A}$$

$$R_{out} = R_{o3}(\text{w/out load}) \cong \boxed{37\,\Omega = R_{out}}$$

$$R_{id} = \frac{v_{id}}{i_{b1}} \cong \left[r_\pi + (\beta+1)R_E\right] \times 2$$

$$R_E = 4.8k \| R_{i2} = 4.8k \| 15.2k = 3.64\,k\Omega$$

$$R_{id} = \left[4.7\,k\Omega + (201)3.64\,k\Omega\right] \times 2$$

$$R_{id} = 736\,k\Omega \times 2 = \boxed{1.47\,M\Omega}$$