POWER AMPLIFIERS

- DELIVERS SIGNIFICANT POWER TO OUTPUT LOAD
- SHOULD HAVE LOW OUTPUT IMPEDANCE
- USUALLY REQUIRES LOW THD (TOTAL HARMONIC DISTORTION)

$$THD = \frac{\text{RMS OF HARMONICS}}{\text{RMS OF FUNDAMENTAL}}$$

- SHOULD BE <u>EFFICIENT</u>

$$\eta \equiv \frac{\text{LOAD POWER } (P_L)}{\text{SUPPLY POWER } (P_S)}$$

100% EFFICIENT ALL SUPPLY P_S GOES TO LOAD

50% EFFICIENT HALF OF P_S GOES TO LOAD

- USUALLY THERMAL DISSIPATION OF HEAT IN POWER TRANSISTORS IS IMPORTANT CONSIDERATION.

- CLASS A OUTPUT STAGE

  ⇒ OUTPUT TRANSISTOR ALWAYS CONDUCTING (100% CONDUCTING)

  ⇒ GOOD LINEARITY
  POOR EFFICIENCY

- CLASS B

  ⇒ OUTPUT TRANSISTOR CONDUCTS ONLY WHEN $v_o > 0$ (50% CONDUCTING)
  (A DIFFERENT OUTPUT TRANSISTOR CONDUCTS WHEN $v_o < 0$)

  ⇒ POORER LINEARITY
  BETTER EFFICIENCY

- CLASS AB

  ⇒ SOME OVERLAP WHEN BOTH TRANSISTORS CONDUCTING
  (>50% CONDUCTING)

  ⇒ BETTER LINEARITY
  EFFICIENCY BETTER THAN <u>A</u>
  SLIGHTLY WORSE THAN <u>B</u>

OTHER CLASSES (NOT COVERED)

- CLASS C $< 50\%$ CONDUCTING

  ⇒ INTO TUNED OUTPUT STAGE (RF AMP)

- CLASS D HIGHLY EFFICIENT

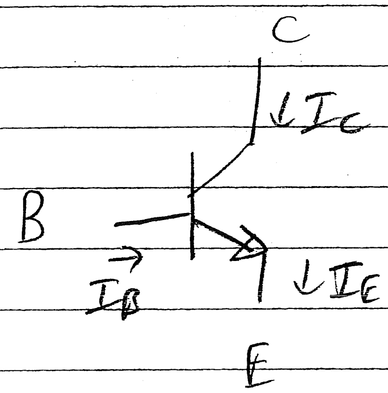
  USES PULSE-WIDTH MODULATION
  OR PULSE DENSITY MODULATION

  TRANSISTOR EITHER OFF OR ON (USED AS A SWITCH)

  REQUIRES FILTER TO REMOVE HIGH FREQUENCY PULSE FREQ + HARMONICS

  CLOCK FRQ

RECALL FOR BJT



$$I_E = I_C + I_B$$

ACTIVE

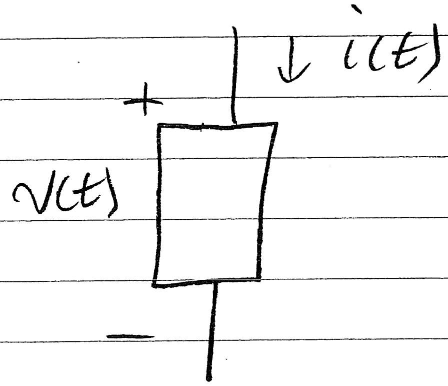
$$I_C = I_S e^{\frac{V_{BE}}{V_T}} \qquad \alpha = \frac{\beta}{\beta + 1}$$

$$I_C = \beta I_B$$

$$g_m = \frac{I_C}{V_T} \qquad r_e = \frac{\alpha}{g_m} = \frac{V_T}{I_E}$$

SATURATION $\quad V_{CE\,SAT} \approx 0.2\ V$

POWER DISSIPATION OF A CIRCUIT ELEMENT



INSTANTANEOUS POWER DISSPATED

$$p(t) = v(t)\, i(t)$$

AVERAGE POWER DISSIPATED

$$P_D = \frac{1}{T}\int_0^T p(t)\, dt \quad \text{AS } T \to \infty$$

$$P_D = \frac{1}{T}\int_0^T v(t)\, i(t)\, dt$$

RESISTOR

IF CIRCUIT IS A RESISTOR $i(t) = \frac{v(t)}{R}$

$$P_R = \frac{1}{T}\int_0^T v(t)\, \frac{v(t)}{R}\, dt$$

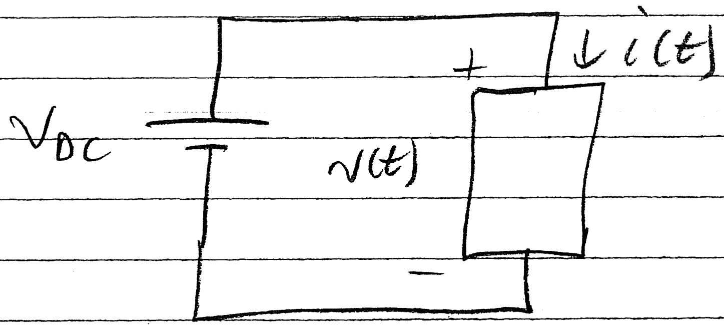
$$= \frac{1}{R}\left[\frac{1}{T}\int_0^T v^2(t)\, dt\right] \leftarrow \text{MEAN SQUARED VOLTAGE}$$

$$= \frac{(V_{RMS})^2}{R}$$

IF $v(t) = \hat{V}_0 \sin(\omega t)$

$$V_{RMS} = \frac{\hat{V}_0}{\sqrt{2}}$$

IF $v(t) = V_{DC}$



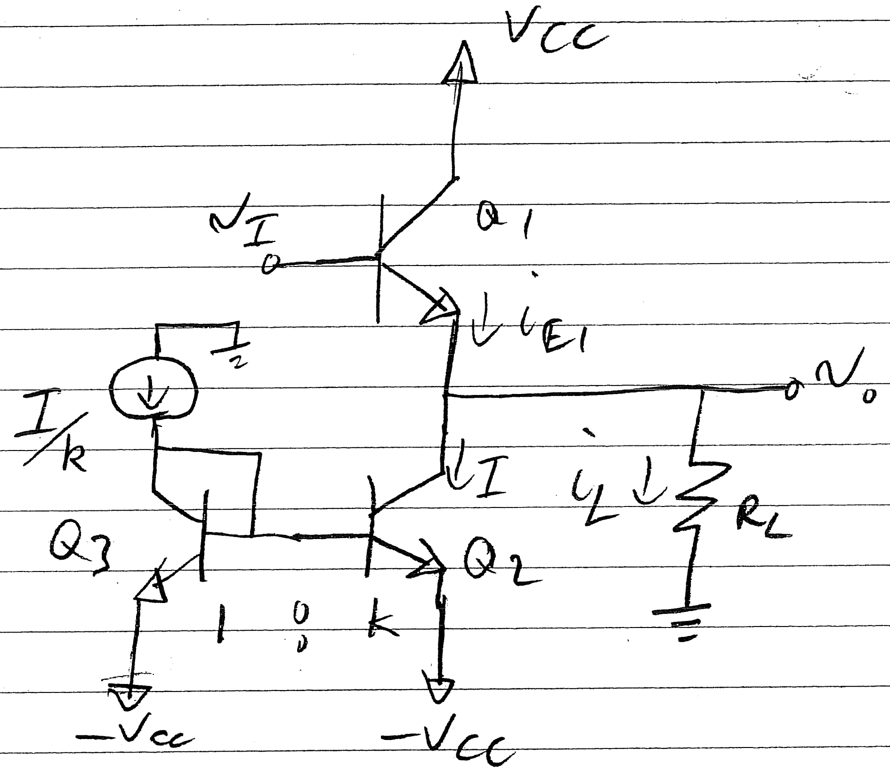
$$P_D = \frac{1}{T}\int_0^T v(t)\, i(t)\, dt$$

$$= \frac{1}{T}\int_0^T V_{DC}\, i(t)\, dt$$

$$= V_{DC}\left[\frac{1}{T}\int_0^T i(t)\, dt\right]$$

$$P_D = V_{DC}\, I_{AVERAGE} \qquad I_{AVERAGE} = \frac{1}{T}\int_0^T i(t)\, dt$$

CLASS A



$A_{BE_2} = k \times A_{BE_3}$ $\quad A_{BE} \Rightarrow$ AREA OF BASE EMITTER

Q_3 IS TO BIAS Q_2

ASSUME $k \gg 1$ SO CAN IGNORE I/k CURRENT

PA5

$$v_O = v_I - v_{BE1}$$

$$v_{O\,MAX} = V_{CC} - V_{CE1\,SAT}$$ MAX v_O

$$v_{O\,MIN} = -IR_L$$ MIN v_O

OR

$$v_{O\,MIN} = -V_{CC} + V_{CE2\,SAT}$$

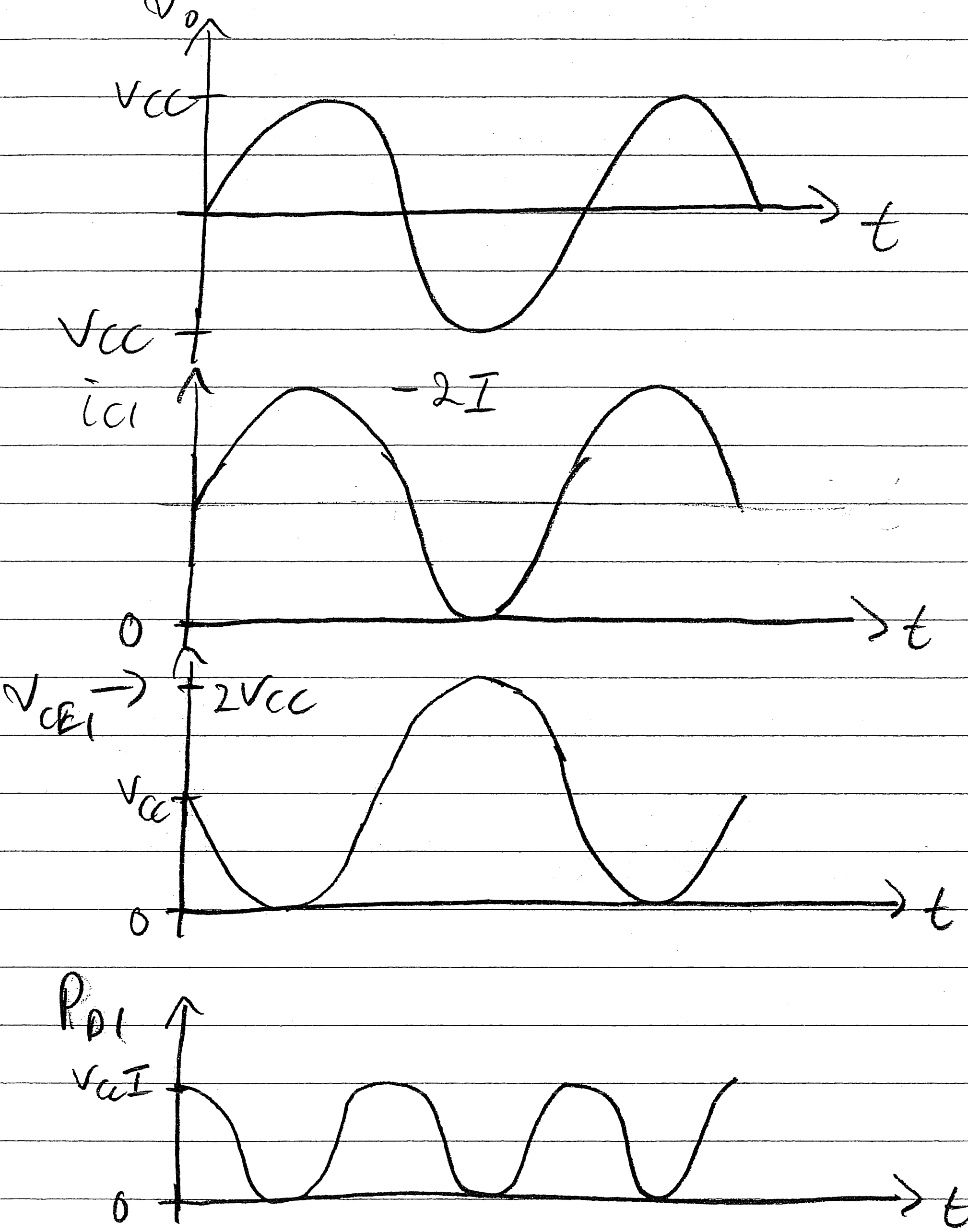
$$\text{IF} \quad I \geq \left| \frac{-V_{CC} + V_{CE2\,SAT}}{R_L} \right|$$

SIGNAL WAVEFORMS

ASSUME $V_{CE\,SAT} = 0$ $\quad V_{BE} = 0$

$$I = \frac{V_{CC}}{R_L}$$

$$v_I = V_{CC} \sin(\omega t)$$



POWER DISSIPATED BY Q_1

$$P_{D_1} \equiv v_{CE_1} i_{C_1}$$

INSTANTANEOUS POWER DISSIPATION IN Q_1

EFFICIENCY

$$\eta \equiv \frac{P_L}{P_L}$$

ASSUME $v_o = \hat{V}_o \sin(\omega t)$

$$P_L = \frac{\left(\hat{V}_o/\sqrt{2}\right)^2}{R_L} = \frac{1}{2}\frac{\hat{V}_o^2}{R_L}$$

$$P_S = P_{S+} + P_{S-} = V_{CC} I + (-V_{CC})(-I)$$

$$P_S = 2V_{CC} I$$

$$\eta = \frac{P_L}{P_S} = \frac{1}{4}\left(\frac{\hat{V}_o}{IR_L}\right)\left(\frac{\hat{V}_o}{V_{CC}}\right)$$

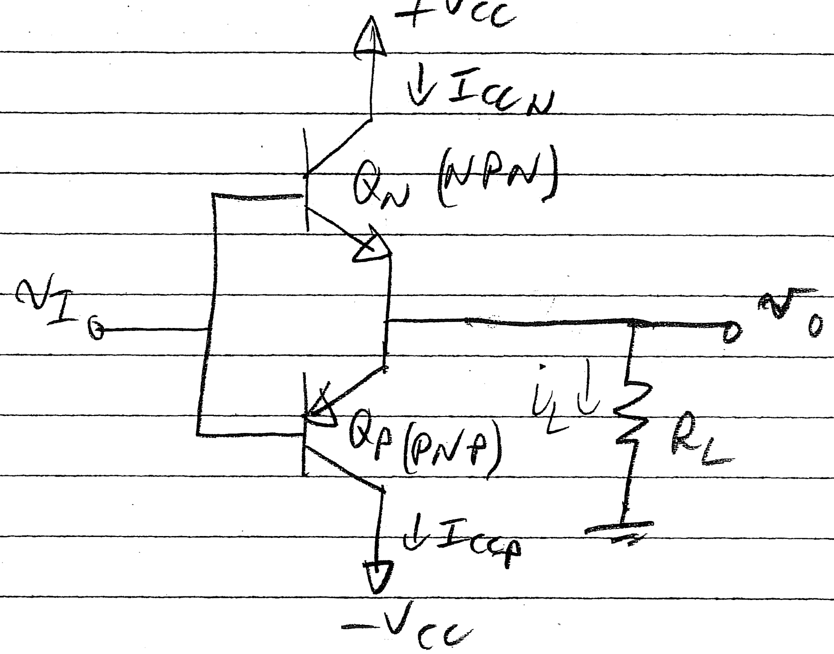
SINCE $\hat{V}_o \leq V_{CC}$ & $\hat{V}_o \leq IR$

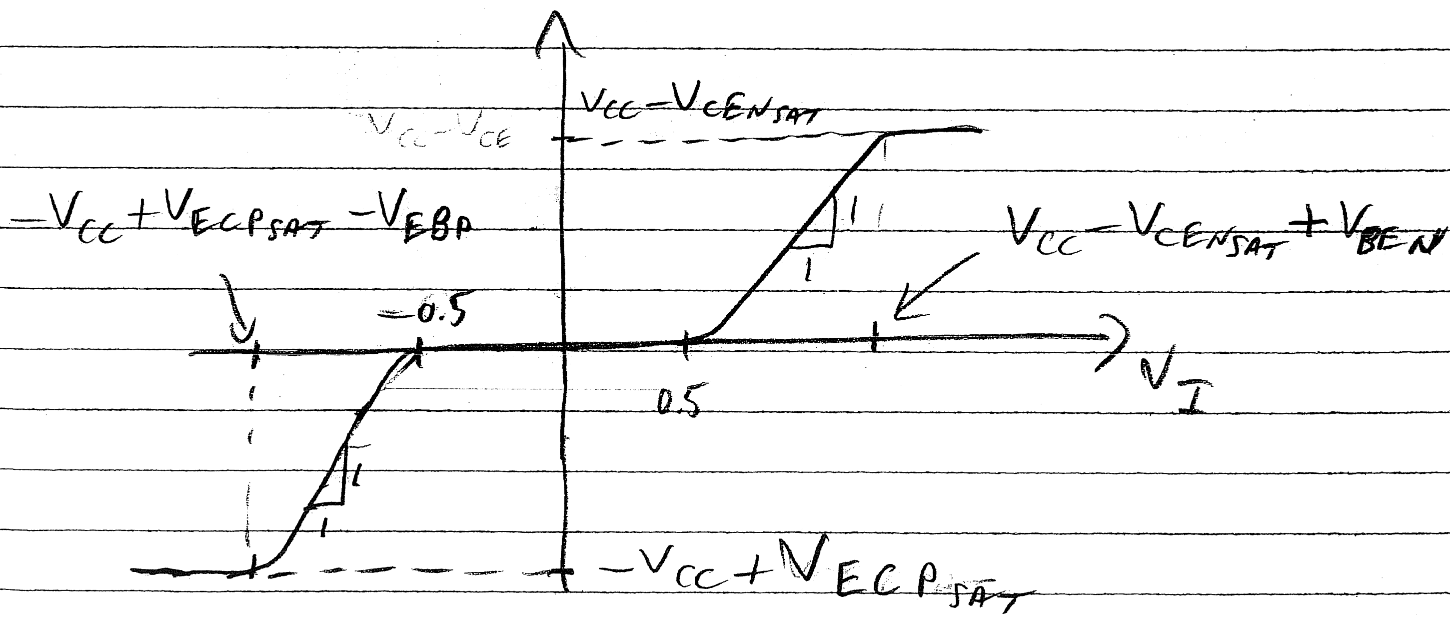
MAX η OCCURS WHEN $\hat{V}_o = V_{CC} = IR_L$

$$\eta_{MAX} = \frac{1}{4} = \underline{\underline{25\%}}$$

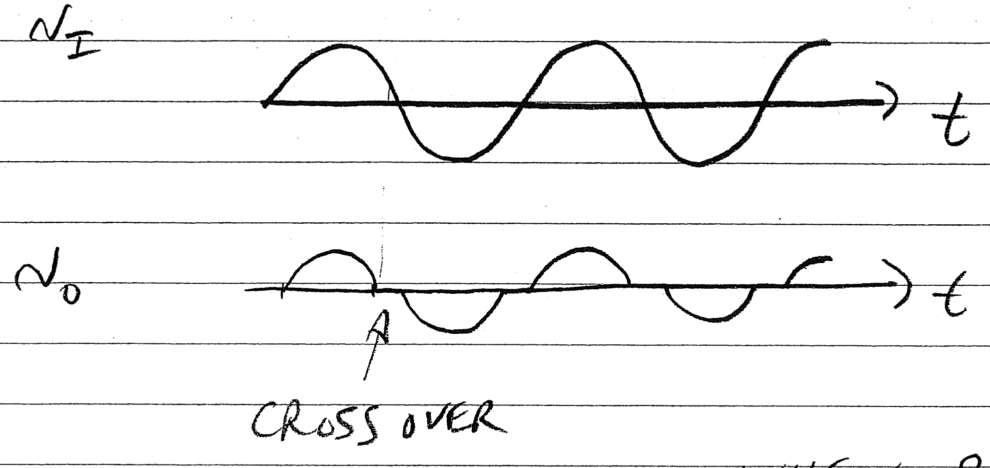
POOR EFFICIENCY

CLASS B





NOT TO SCALE



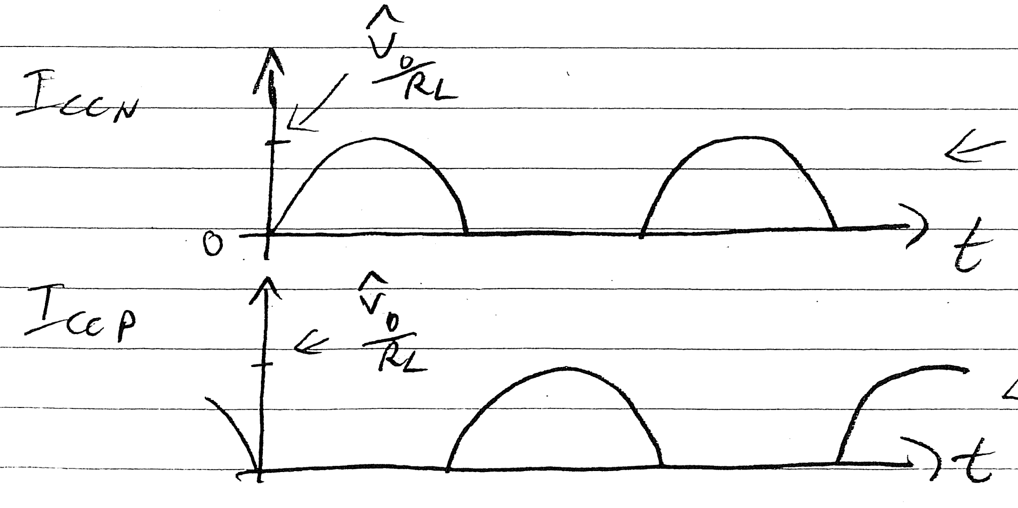
CROSSOVER DISTORTION WHEN BOTH Q_N & Q_P OFF

POWER EFFICIENCY

IGNORING CROSSOVER DISTORTION & V_{BEN} & $V_{EBP} \approx 0$, $V_{CESAT} \approx 0$

$$v_O = \hat{V}_O \sin(\omega t)$$

$$P_L = \frac{1}{2} \frac{\hat{V}_O^2}{R_L} \quad \text{FROM BEFORE}$$



$\leftarrow I_{CCN\_AVERAGE} = \frac{\hat{V}_O}{\pi R_L}$

$\leftarrow I_{CCP\_AVERAGE} = \frac{\hat{V}_O}{\pi R_L}$

$$P_{S+} = P_{S-} = \frac{1}{\pi} \frac{\hat{V}_o}{R_L} V_{CC}$$

$$P_S = P_{S+} + P_{S-} = \frac{2}{\pi} \frac{\hat{V}_o}{R_L} V_{CC}$$

EFFICIENCY

$$\eta = \frac{P_L}{P_S} = \frac{\pi}{4} \frac{\hat{V}_o}{V_{CC}}$$

MAXIMUM EFFICIENCY WHEN $\hat{V}_o = V_{CC}$

$$\eta_{MAX} = \frac{\pi}{4} = 78.5\%$$

& $P_{LMAX} = \frac{1}{2} \frac{V_{CC}^2}{R_L}$ WHEN $\hat{V}_o = V_{CC}$

(POWER DISSIPATED IN LOAD)

POWER DISSIPATION OF OUTPUT STAGE, P_D

$$P_D = P_S - P_L$$

$$P_D = \frac{2}{\pi}\frac{\hat{V}_o}{R_L}V_{CC} - \frac{1}{2}\frac{\hat{V}_o^2}{R_L} \quad (1)$$

$\frac{1}{2}$ POWER DISSIPATED IN Q_N

& $\frac{1}{2}$ POWER DISSIPATED IN Q_P

TO FIND WORST CASE $P_{D_{MAX}}$

USED TO DETERMINE HOW MUCH HEAT NEEDS TO BE DISSIPATED IN Q_N & Q_P

DIFFERENTIATE P_D WITH RESPECT TO $\hat{V}_o$ & SET TO ZERO

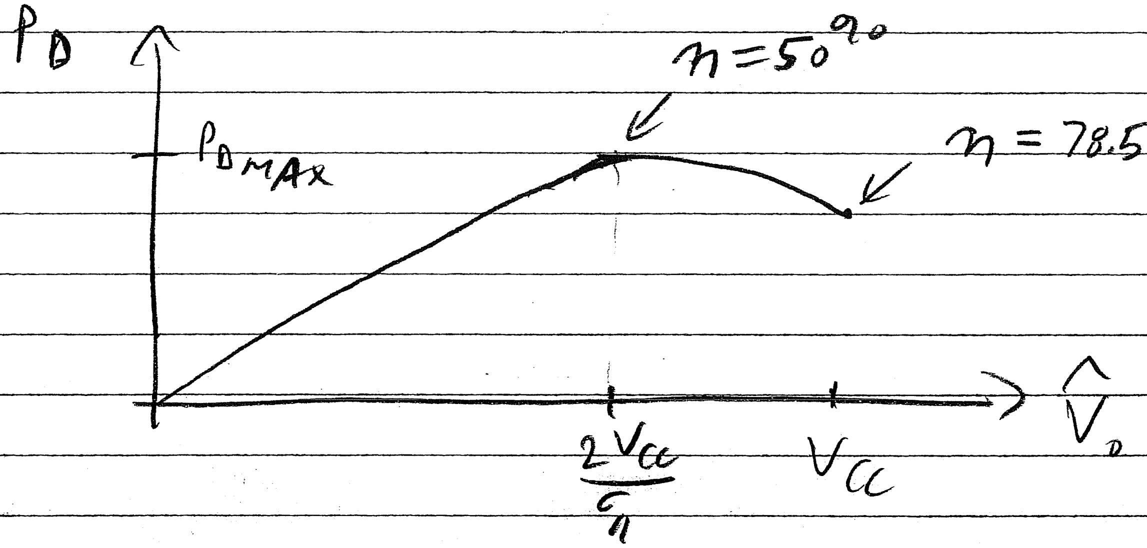
$$\frac{\partial P_D}{\partial \hat{V}_o} = \frac{2}{\pi}\frac{V_{CC}}{R_L} - \frac{\hat{V}_o}{2R_L} = 0$$

$$\hat{V}_o = \frac{2}{\pi}V_{CC} \quad \text{PUT INTO } (1)$$

$$\Rightarrow P_{D_{MAX}} = \frac{2V_{CC}^2}{\pi^2 R_L}$$

SO $P_{DN\,MAX} = P_{DP\,MAX} = \dfrac{V_{CC}^2}{\pi^2 R_L}$

& $\eta = 50\%$ FOR $\hat{V}_0 = \frac{2}{\pi} V_{CC}$



EX DELIVER 20W INTO $R_L = 8\,\Omega$

$V_{CC} = 5V + V_{0\,PEAK}$

FIND
- I_{CC_PEAK}
- P_{S+}, P_{S-}
- η
- $P_{DN\,MAX}$, $P_{DP\,MAX}$

$P_L = \frac{1}{2}\frac{\hat{V}_0^2}{R_L}$

$20W = \frac{1}{2}\frac{\hat{V}_0^2}{(8)} \Rightarrow \hat{V}_0 = 17.9V$

$V_{CC} = 17.9 + 5 = 23\,V$

$I_{CC\_PEAK} = \frac{\hat{V}_0}{R_L} = \frac{17.9}{8} = 2.24\,A$

PEAK TRANSISTOR CURRENTS AS WELL

$P_{S+} = P_{S-} = \frac{1}{\pi} 2.24 \times 23 = 16.4\,W$

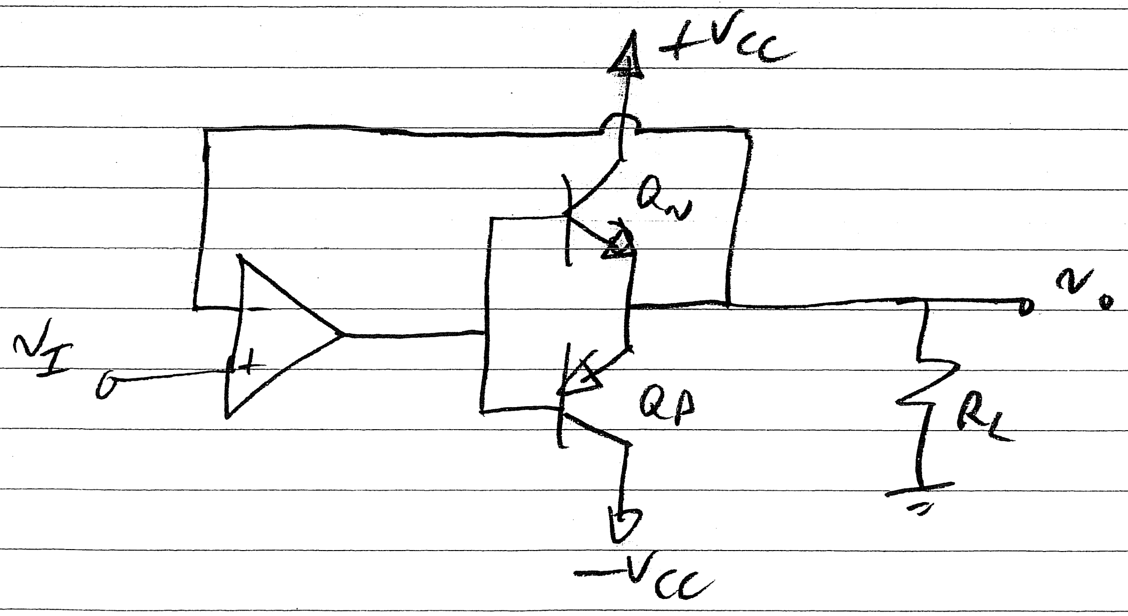
$P_S = 32.8\,W \qquad P_L = 20\,W$

$\eta = \frac{20}{32.8} = 61\%$

$P_{DN\,MAX} = P_{DP\,MAX} = \frac{V_{CC}^2}{\pi^2 R_L} = 6.7\,W$

WHEN $\hat{V}_o = \frac{2}{\pi} V_{CC} = 14.64\,V$

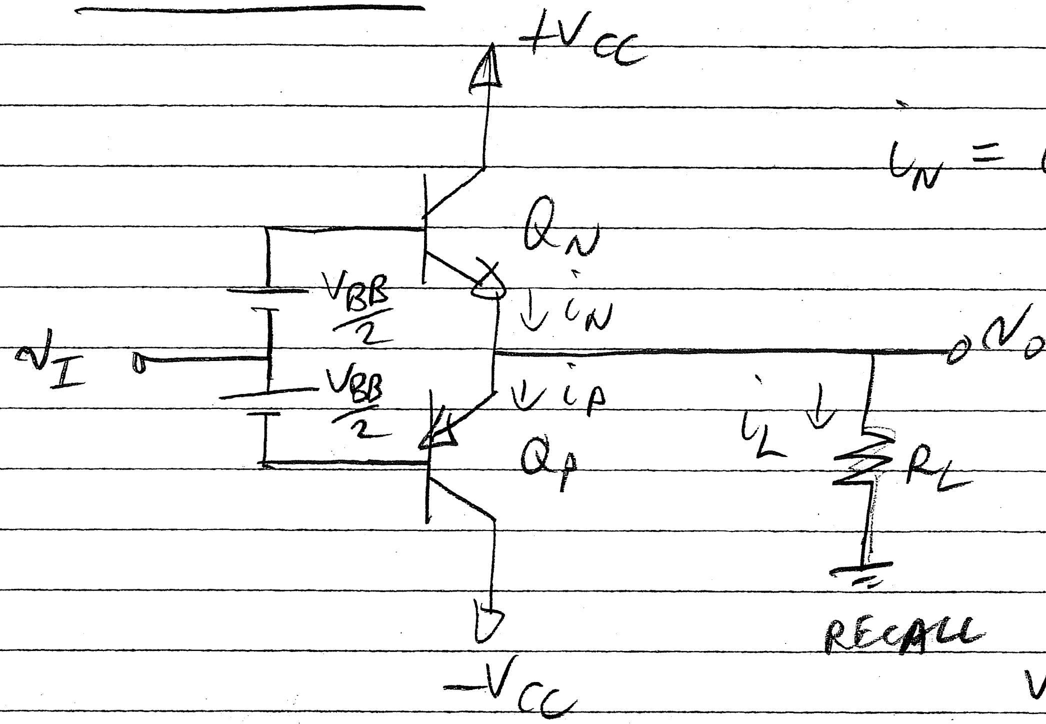
ONE WAY TO REDUCE CROSSOVER DISTORTION



SLEW-RATE IN OPAMP MAY LIMIT PERFORMANCE

BETTER TO LEAVE TRANSISTORS BOTH ON WHEN $v_o \approx 0$

CLASS AB



$i_N = i_P + i_L$

RECALL

$i_N = I_S e^{V_{BE}/V_T}$

$V_{BE} = V_T \ln \frac{i_N}{I_S}$

FOR $v_I = v_O = 0$ & ASSUMING MATCHED DEVICES

$$i_N = i_P = I_Q = I_S e^{V_{BB}/2V_T} \quad (1)$$

V_{BB} SELECTED TO DETERMINE QUIESCENT CURRENT I_Q

BOTH TRANSISTORS ON WITH $I_C = I_Q$ WHEN $v_O = 0$

AS $v_I > 0$

$$v_O = v_I + \frac{V_{BB}}{2} - V_{BEN}$$

SINCE $i_N = i_P + i_L$ (2) AS $i_N \uparrow$

$V_{BEN} \uparrow$

WHICH MEANS

$V_{EBP} \downarrow$

SINCE $v_{BEN} + V_{EBP} = V_{BB}$ FROM (1)

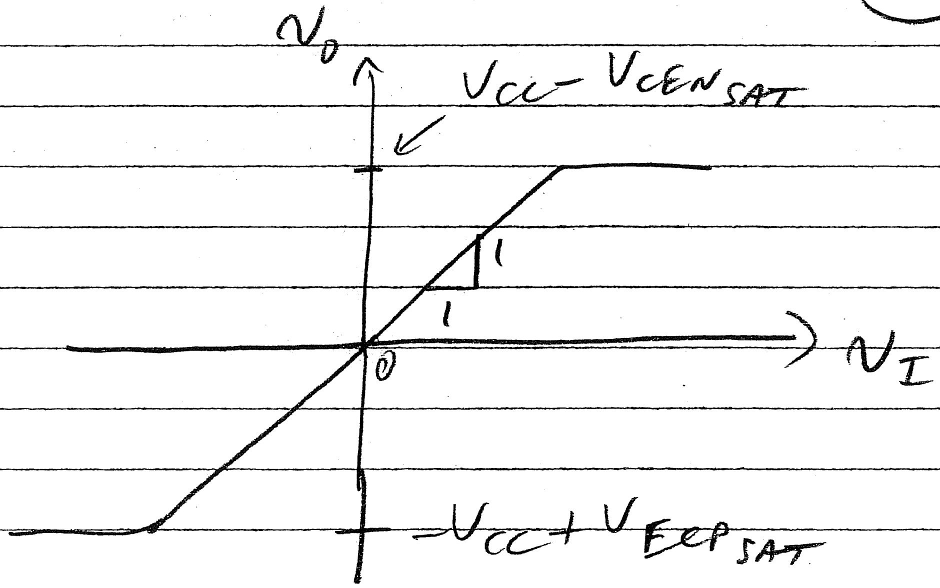
$$V_T \ln \frac{i_N}{I_S} + V_T \ln \frac{i_P}{I_S} = 2V_T \ln \frac{I_Q}{I_S}$$

$$i_N i_P = I_Q^2 \quad (3)$$

COMBINE (2) & (3)

$$i_N^2 - i_L i_N - I_Q^2 = 0 \quad (4)$$

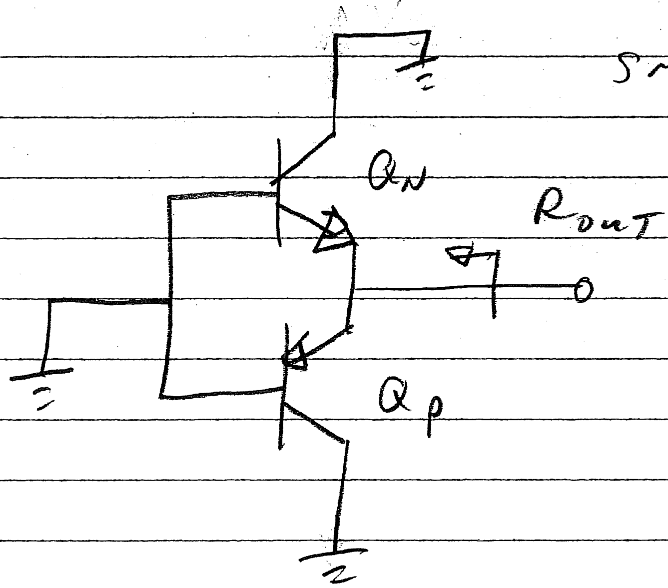
TO FIND i_N FOR A GIVEN i_L



POWER RELATIONS ALMOST SAME AS CLASS B

JUST ADD I_Q TO RESULTS IN CLASS B
(USUALLY I_Q SMALL SO IT DOES NOT CHANGE RESULTS MUCH)

OUTPUT RESISTANCE



SMALL-SIGNAL MODEL

RECALL $r_e = \frac{V_T}{I_E}$

$V_T = \frac{kT}{q} \hat{=} 25\,mV$

$$R_{OUT} = r_{eN} \parallel r_{eP}$$

$r_{eN} = \frac{V_T}{i_N}$ $\qquad$ $r_{eP} = \frac{V_T}{i_P}$

$$R_{OUT} = \frac{V_T}{i_P + i_N}$$

LARGEST R_{OUT} WHEN $i_P = i_N = I_Q$

AS $v_o > 0$ $\quad$ $\left.\begin{array}{l} i_N > I_Q \\ i_P < I_Q \end{array}\right\}$ R_{OUT} DECREASES

SIMILAR FOR $v_o < 0$

EXAMPLE CLASS AB

$V_{CC} = 15\,V \qquad I_Q = 2\,mA \qquad R_L = 100\,\Omega$

Q_N & Q_P HAVE $I_S = 10^{-13}\,A$

1) FIND V_{BB}

2) FOR VARIOUS v_O VALUES

FIND i_L, i_N, i_P, v_I

ALSO FIND R_{OUT} & $\frac{v_o}{v_i} = \frac{R_L}{R_L + R_{OUT}}$

(SMALL-SIGNAL GAIN)

$V_T = 25\,mV$

1) ① ⇒ $V_{BB} = 2 V_T \ln\left(\frac{I_Q}{I_S}\right)$

$= 2(25e{-3}) \ln\left(\frac{2e{-3}}{1e{-13}}\right)$

$V_{BB} = 1.186\,V$

2) TO FIND VALUES FOR v_O

1. ASSUME VALUE FOR v_O
2. $i_L = v_O / R_L$
3. $i_N^2 - i_L i_N - I_Q^2 = 0 \Rightarrow$ FIND i_N

   $i_N = i_L + i_P$
4. $v_{BEN} = V_T \ln\left(\frac{i_N}{I_S}\right)$
5. $v_I = v_O + v_{BEN} - V_{BB}/2$

$\frac{R_L}{R_L + R_{OUT}}$ ↓

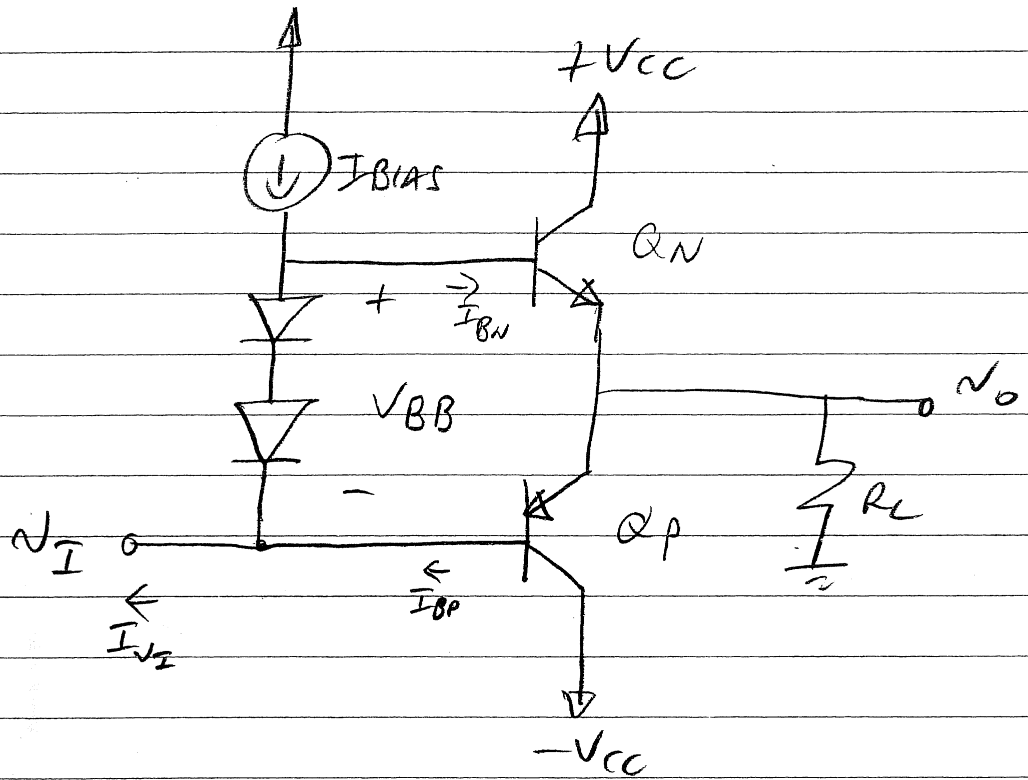
v_O	i_L	i_N	i_P	v_I	$\frac{v_O}{v_I}$	R_{OUT}	$\frac{v_O}{v_i}$
+10	100	100.04	0.04	10.1	0.99	0.25	1.00
+5	50	50.08	0.08	5.08	0.98	0.5	1.00
+0.5	5	5.7	0.7	0.526	0.95	4.03	0.96
0	0	2	2	0	—	6.25	0.94

SIMILAR FOR $v_O < 0$

i_L, i_N, i_P IN UNITS OF mA

BIASING CLASS AB CIRCUIT.

USING DIODES



v_I MUST SOURCE CURRENT OF

$$I_{v_I} = I_{BIAS} - I_{BN} + I_{BP}$$

IF $\beta_N = \beta_P \Rightarrow I_{BN} = I_{BP}$ WHEN $v_o = 0$

OTHERWISE $I_{BN} \neq I_{BP}$

$A_{BE} = n A_D$ AREA BASE EMITTER $= n \times$ AREA DIODE

SO THAT $I_Q = n I_{BIAS}$

TYPICALLY $I_Q \approx 0.1 I_{C\,PEAK}$

BUT $I_{BN} = \frac{I_C}{\beta}$ & $\beta \approx 20 \rightarrow 40$ (SINCE POWER DEVICES)

& $I_{BIAS} > I_{BN}$ SO DIODE AREA

NOT MUCH SMALLER THAN BE AREA

$\Rightarrow n \lesssim 1$

DISADVANTAGE OF USING DIODES

ONE ADVANTAGE IS THERMAL STABILIZATION OF I_Q

RECALL RISE IN TEMP $\Rightarrow$ DECREASE IN V_{BE}

$\approx -2\,mV/^\circ C$ IF I_C FIXED

IF V_{BB} CONSTANT $\Rightarrow I_C$ INCREASES

$I_C \uparrow \Rightarrow P_D \uparrow \Rightarrow$ TEMP $\uparrow \Rightarrow I_C \uparrow$

ECT. THERMAL RUNAWAY IF GAIN GREATER THAN 1

IF DIODES USED & PLACED IN

THERMAL CONTACT WITH Q_N & Q_P

THEN AS

TEMP RISES => V_{BB} LOWERS

AND I_Q ROUGHLY CONSTANT.

Ex

CLASS AB WITH DIODES

$A_D = \frac{A_{BE}}{3}$ $V_{CC} = 15\ V$

$(n = 3)$ $R_L = 100\ \Omega$

$v_o = 10 \sin(\omega t)$

Q_N, Q_P HAS $I_S = 10^{-13}\ A$ & $\beta = 50$

FIND I_{BIAS} SUCH THAT $I_{D\_MIN} = 1\ mA$

FIND I_Q, & P_{DQ} (QUIESCENT POWER DISSIPATION)

FIND V_{BB} FOR $v_o = 0, +10V, -10\ V$

SOLN

$I_{CN\_MAX} = \frac{10}{100} = 100\ mA$

$I_{B\_MAX} = \frac{I_{CN\_MAX}}{\beta} = 2\ mA$

SO $I_{BIAS} = I_{B\_MAX} + I_{D\_MIN} = 3\ mA$

$\Rightarrow I_Q = n\ I_{BIAS} = 9\ mA$

$P_{DQ} = 2 \times V_{CC} \times I_Q = 270\ mW$

FOR $v_o = 0$ $\quad I_E = 9\,mA$

$$I_B = \frac{I_E}{\beta+1} = \frac{9}{51} = 0.18\,mA$$

SO $I_D = I_{BIAS} - I_{BN} = 2.82\,mA$

$$I_{S(DIODE)} = \frac{1}{3}\times 10^{-13}\,A \Rightarrow V_{BB} = 2V_T \ln \frac{2.82\,mA}{I_{S(DIODE)}}$$

$$V_{BB} = 1.26\,V$$

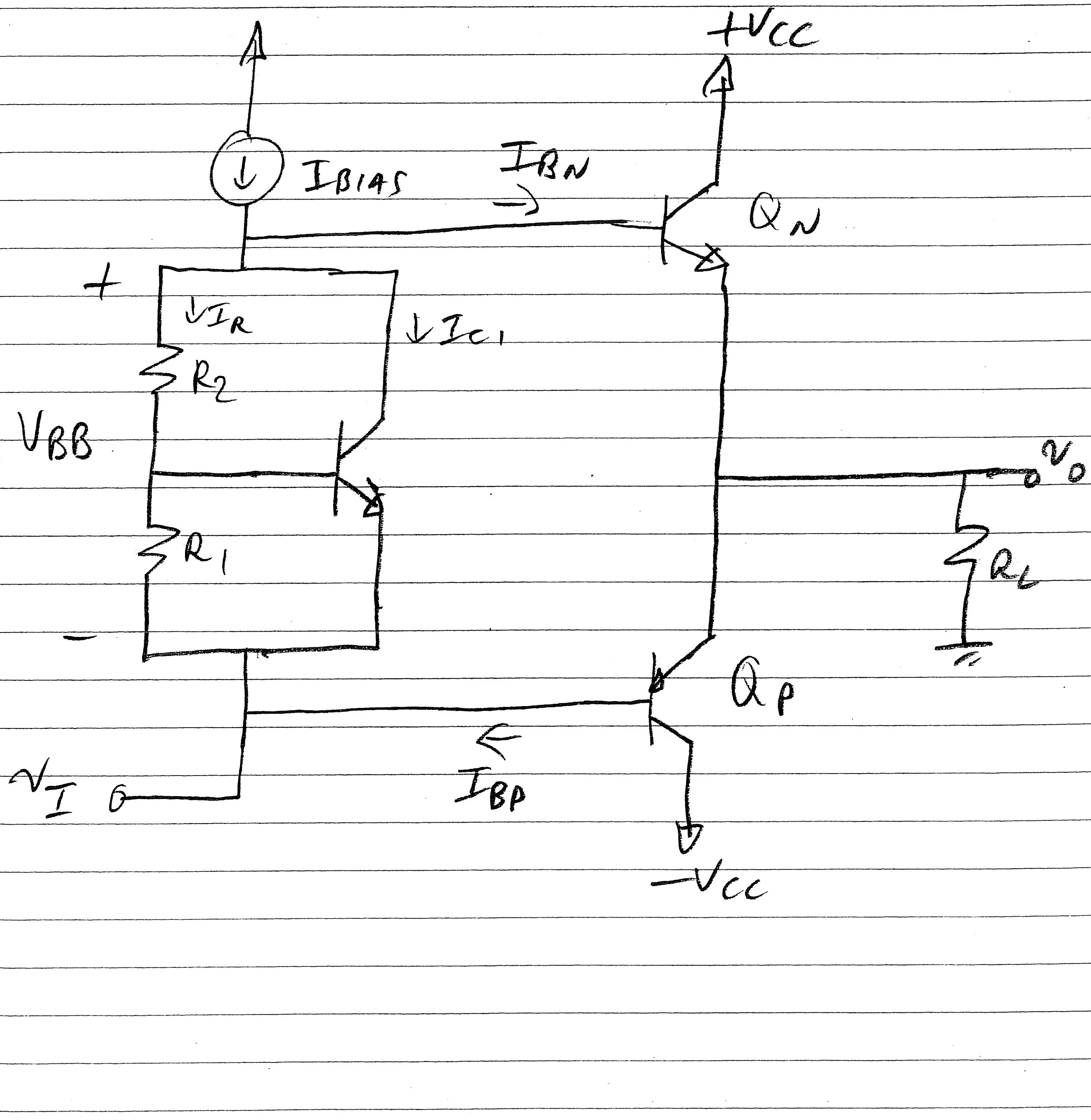
$v_o = +10V$ $\quad I_D = 1\,mA$

$$V_{BB} = 2V_T \ln \frac{1\,mA}{I_{S(DIODE)}} = 1.21\,V$$

$v_o = -10V$ $\quad I_{QN} \simeq 0 \Rightarrow I_D = 3\,mA$

$$V_{BB} = 2V_T \ln \frac{3\,mA}{I_{S(DIODE)}} \simeq 1.26\,V$$

V_{BE} MULTIPLIER



ASSUME $I_{B1} \approx 0$

$$I_R = \frac{V_{BE1}}{R_1}$$

$$V_{BB} = I_R (R_1 + R_2) =$$

$$V_{BB} = V_{BE} \left(1 + \frac{R_2}{R_1}\right)$$

$I_{C1} = I_{BIAS} - I_{BN} - I_R$ & $V_{BE1} = V_T \ln\left(\frac{I_{C1}}{I_{S1}}\right)$

IN DISCRETE DESIGN => ADJUST R_2, R_1 TO OBTAIN DESIRED I_Q (USUALLY THROUGH POTENTIOMETER)

NOTE AS I_{BN} CHANGES => I_{C1} CHANGES

=> V_{BE1} SLIGHTLY CHANGES

SO I_R REMAINS ABOUT SAME

ΔI_{BN} => RESULTS IN ΔI_{C1} CHANGE BUT $I_R \approx$ CONSTANT &

$V_{BB} \simeq$ CONSTANT.

REPEAT EXAMPLE WITH VBE MULTIPLIER WHERE $I_{S1} = 10^{-14}$ A ($\frac{1}{10}$ SIZE OF Q_N + Q_P)

DESIGN FOR $I_Q = 2$ mA

$I_{BN\text{-}MAX} = 2$ mA $\Rightarrow$ $I_{BIAS} = 1$ mA $+ I_{BN\text{-}MAX}$

$I_{BIAS} = 3$ mA

I_Q DESIGN $\quad I_{BN} = \frac{I_Q}{\beta + 1} \simeq 0.04$ mA

$$I_R + I_{C1} = I_{BIAS} - I_{BN} \cong 3 \text{ mA}$$

NEED TO DECIDE I_R + I_{C1} BREAKDOWN

WHEN $I_{BN\text{-}MAX} = 2$ mA $\Rightarrow$ $I_R + I_{C1} = 1$ mA (MIN VALUE)

GIVE EACH 0.5 mA IN THIS CASE + I_R WILL NOT VARY MUCH SO FOR $V_O = 0$ CASE

$$I_R = 0.5 \text{ mA} \qquad I_{C1} = 2.5 \text{ mA}$$

SINCE $I_Q = 2$ mA $\quad V_{BB} = 2V_T \ln\left(\frac{2\text{ mA}}{10^{-13}}\right)$

$$= 1.19 \text{ V}$$

(PA28)

$$I_R = \frac{V_{BB}}{R_1+R_2} \Rightarrow 0.5 = \frac{1.19}{R_1+R_2}$$

$$\Rightarrow R_1+R_2 = 2.38\,k\Omega$$

$$V_{BE_1} = V_T \ln \frac{2.5\,mA}{10^{-14}A} = 0.656\,V$$

$$I_R = \frac{V_{BE1}}{R_1} \Rightarrow R_1 = \frac{0.66}{0.5\,mA} = 1.31\,k\Omega$$

$$R_2 = 2.38 - 1.32 = 1.07\,k\Omega$$

$v_o = +10V$

$$I_{C1} = 0.5\,mA \Rightarrow V_{BE_1} = V_T \ln\left(\frac{0.5\,mA}{10^{-14}}\right)$$

$$= 0.616\,V$$

$$I_R = 0.47\,mA \simeq 0.5\,mA$$

$$V_{BB} = V_{BE1}\left(1+\frac{R_2}{R_1}\right) = V_{BE_1}(1.817)$$

$$= 1.12\,V$$

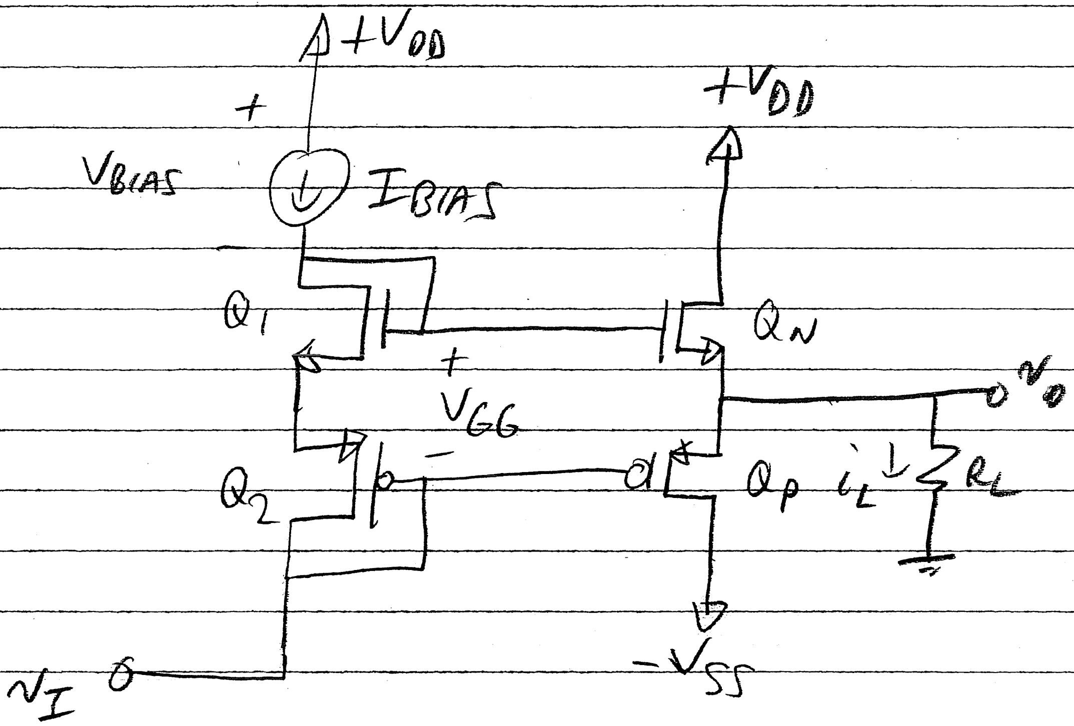
$v_o = -10\,V$

$$I_{C1} = 2.5\,mA \Rightarrow V_{BE_1} = 0.656\,V$$

$$V_{BB} = V_{BE_1}\left(1+\frac{R_2}{R_1}\right) = 1.19\,V$$

CMOS CLASS AB OUTPUT STAGES

CLASSICAL - BASED ON BJT



$I_{D1} = I_{D2} = I_{BIAS}$ INDEPENDENT OF I_{DN} & I_{DP}

V_{GG} CONSTANT

I_Q

$$I_{D1} = \frac{\mu_N C_{ox}}{2}\left(\frac{W}{L}\right)_1 \left(V_{GS1} - V_{tN}\right)^2 \quad (1)$$

$$I_{D2} = \frac{\mu_p C_{ox}}{2}\left(\frac{W}{L}\right)_2 \left(V_{SG2} - |V_{tp}|\right)^2 \quad (2)$$

$$V_{GG} = V_{GS1} + V_{SG2} = V_{tN} + |V_{tp}| + \sqrt{2 I_{BIAS}}\left(\frac{1}{\sqrt{\mu_N C_{ox}\left(\frac{W}{L}\right)_1}} + \frac{1}{\sqrt{\mu_p C_{ox}\left(\frac{W}{L}\right)_2}}\right)$$

SIMILAR $V_{GG} = V_{GS_N} + V_{SG_P}$

CAN SHOW

$$I_Q = I_{BIAS}\left[\frac{\frac{1}{\sqrt{\mu_N C_{ox}\left(\frac{W}{L}\right)_1}} + \frac{1}{\sqrt{\mu_p C_{ox}\left(\frac{W}{L}\right)_2}}}{\frac{1}{\sqrt{\mu_N C_{ox}\left(\frac{W}{L}\right)_N}} + \frac{1}{\sqrt{\mu_p C_{ox}\left(\frac{W}{L}\right)_P}}}\right]^2$$

IF Q_1 & Q_2 MATCHED $\mu_p C_{ox}\left(\frac{W}{L}\right)_2 = \mu_N C_{ox}\left(\frac{W}{L}\right)_1$

& Q_N & Q_P MATCHED

THEN

$$I_Q = I_{BIAS} \frac{(W/L)_N}{(W/L)_1}$$

PROBLEM WITH ABOVE CMOS OUTPUT STAGE IS SMALL OUTPUT SIGNAL RANGE

$$v_O = V_{DD} - V_{BIAS} - V_{GSN}$$

$$v_{O\_MAX} = V_{DD} - V_{OV}|_{BIAS} - (V_{tN} + V_{OVN})$$

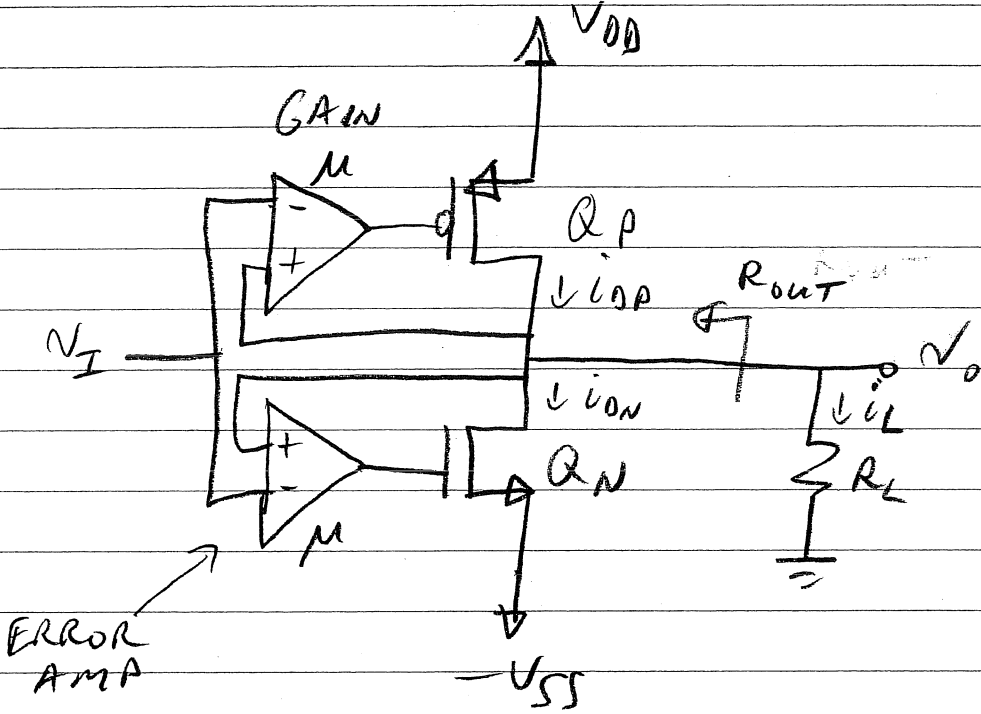
V_{OVN} CAN BE LARGE WHEN $i_L = i_{LMAX}$

SIMILAR

$$v_{O-MIN} = -V_{SS} + V_{OV}|_I + |V_{tp}| + |V_{OVp}|$$

$V_{OV}|_I$ IS OVERDRIVE VOLTAGE DUE TO INPUT.

CMOS PUSH-PULL OUTPUT STAGE



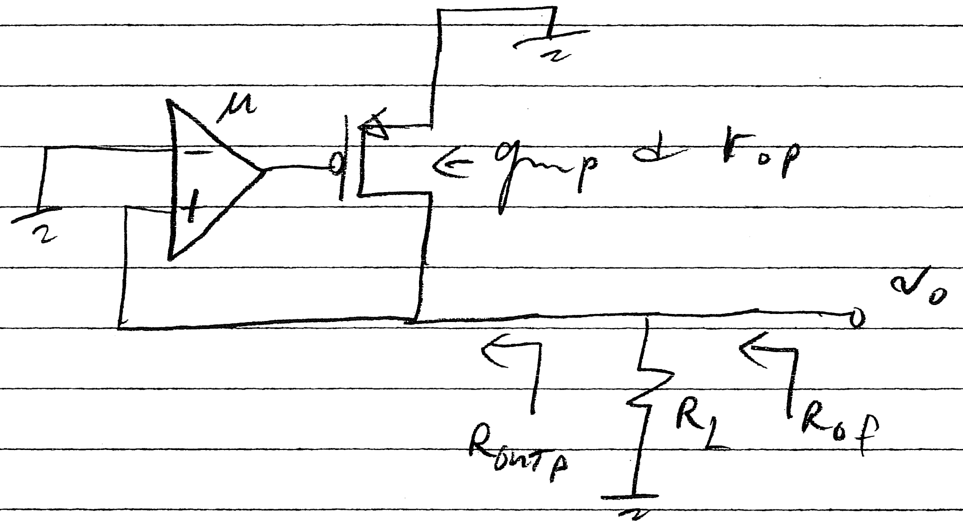
IF NO ERROR AMPLIFIERS ⇒ OUTPUT RESISTANCE WOULD BE HIGH

ERROR AMPS ⇒ FEEDBACK TO REDUCE OUTPUT RESISTANCE

ALSO $v_O \approx v_I$ DUE TO FEEDBACK

OUTPUT RESISTANCE

TOP HALF (SMALL-SIGNAL)



$$R_{of} = R_{po}\left[\frac{1+L_s}{1+L_o}\right] \qquad L_s = 0$$

$$L_o = \mu g_{mp}(r_{op} \| R_L)$$

$$R_{po} = r_{op} \| R_L$$

$$R_{of} = \frac{r_{op} \| R_L}{1+\mu g_{mp}(r_{op} \| R_L)} = R_{outp} \| R_L$$

$$R_{outp} = \left(\frac{1}{R_{of}} - \frac{1}{R_L}\right)^{-1}$$

$$R_{outp} = r_{op} \| \frac{1}{\mu g_{mp}} \simeq \frac{1}{\mu g_{mp}}$$

SIMILARLY $R_{OUT_N} \cong \frac{1}{\mu \, g_{mn}}$

COMBINING

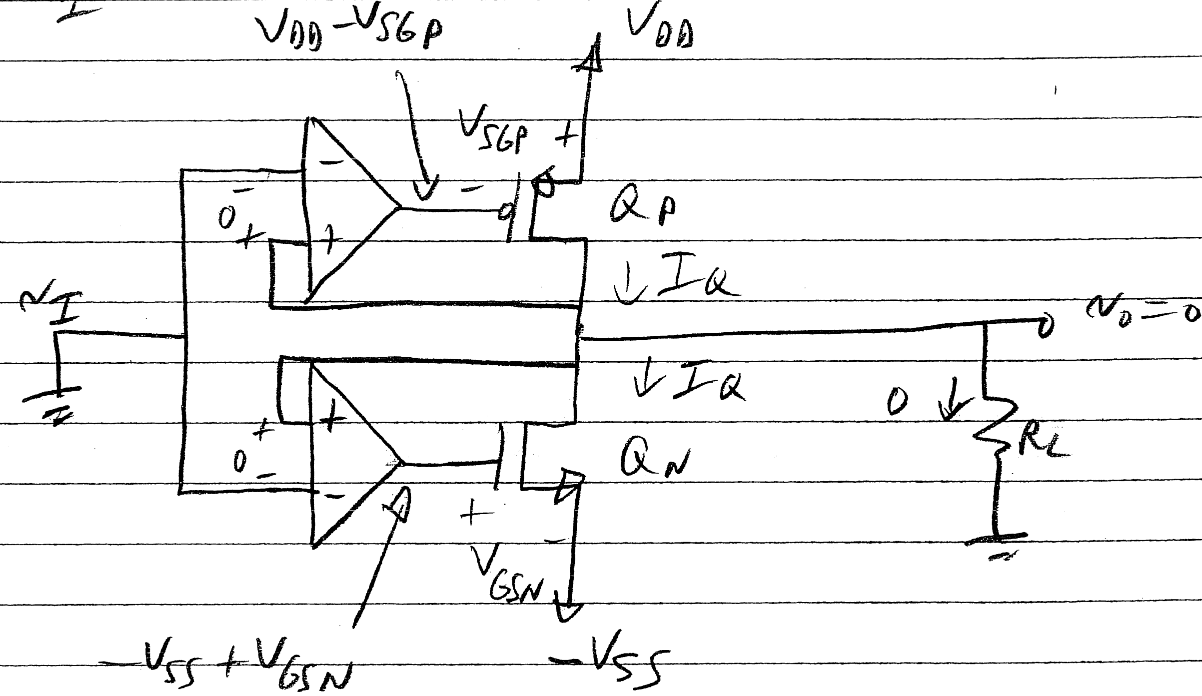
$$R_{OUT} \cong \frac{1}{\mu (g_{mp} + g_{mn})}$$

LARGE SIGNAL v_O / v_I RELATIONSHIP

ASSUME $k \equiv \mu_n C_{ox} \left(\frac{W}{L}\right)_N = \mu_p C_{ox} \left(\frac{W}{L}\right)_P$

MATCHED DEVICES Q_N & Q_P

WHEN $v_I = 0$



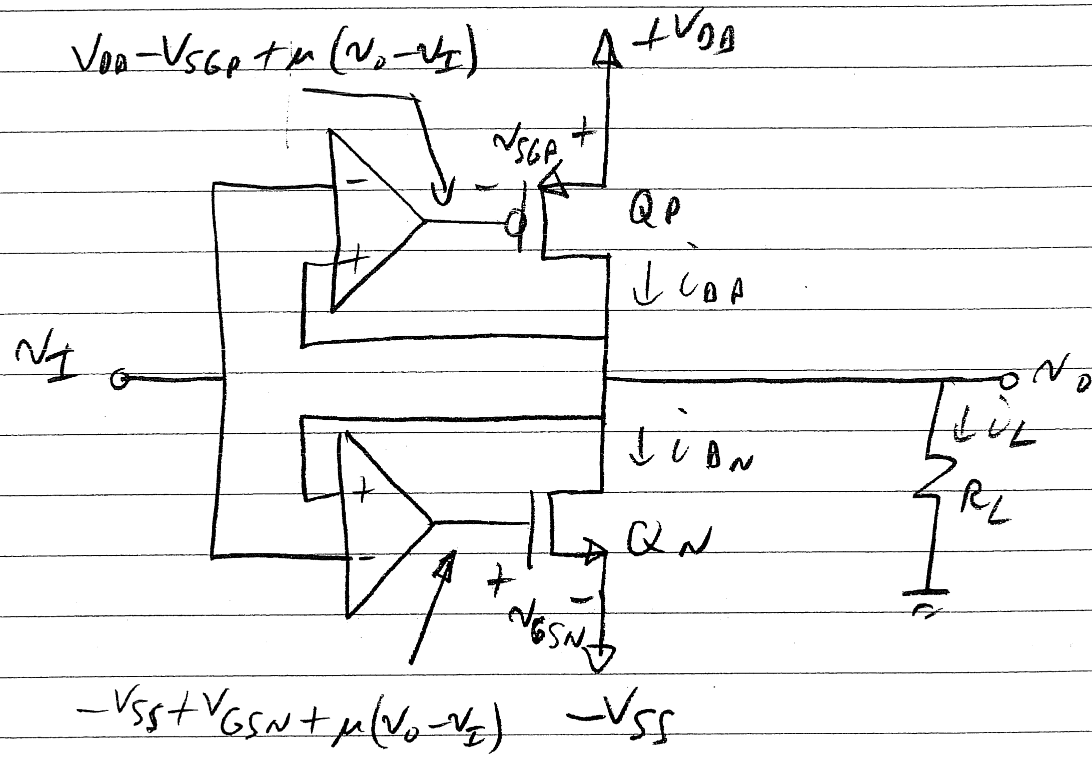
$$V_{SGP} = V_{ov} + |V_{tp}| \Rightarrow V_{ov} = V_{SGP} - |V_{tp}| \quad (1)$$

$$i_{DP} = I_Q = \frac{1}{2} k \left(V_{SGP} - |V_{tp}|\right)^2 = i_N$$

$$I_Q = \frac{1}{2} k V_{ov}^2 \quad (2)$$

FOR $v_I \neq 0$

OUTPUT OF ERROR AMP IS
ORIGINAL $v_I = 0$ VALUE + $\mu(v_O - v_I)$



$$v_{SGP} = V_{DD} - (V_{DD} - V_{SGP} + \mu(v_O - v_I))$$

$$v_{SGP} = V_{SGP} - \mu(v_O - v_I)$$

$$v_{SGP} = |V_{tp}| + V_{OV} - \mu(v_O - v_I) \quad \text{FROM } ①$$

$$i_{DP} = \frac{1}{2}k\left(v_{SGP} - |V_{tp}|\right)^2$$

$$= \frac{1}{2}k\left(V_{OV} - \mu(v_O - v_I)\right)^2$$

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$$i_{DP} = \frac{1}{2} k V_{OV}^2 \left(1 - \mu \frac{v_O - v_I}{V_{OV}}\right)^2$$

$$i_{DP} = I_Q \left(1 - \mu \left(\frac{v_O - v_I}{V_{OV}}\right)\right)^2 \quad \text{FROM } (2)$$

SIMILAR $\quad i_{DN} = I_Q \left(1 + \mu \left(\frac{v_O - v_I}{V_{OV}}\right)\right)^2$

$$i_L = i_{DP} - i_{DN} \quad \text{(NOTE SQUARE TERMS CANCEL)}$$

$$i_L = -4 I_Q \mu \frac{(v_O - v_I)}{V_{OV}} \quad (3)$$

$$i_L = \frac{v_O}{R_L} \quad (4)$$

PUT (4) → (3) & SOLVE FOR v_O

$$v_O = \frac{v_I}{1 + \dfrac{V_{OV}}{4 \mu I_Q R_L}}$$

FOR $\dfrac{V_{OV}}{4 \mu I_Q R_L} \ll 1 \Rightarrow v_O \simeq v_I \left(1 - \dfrac{V_{OV}}{4 \mu I_Q R_L}\right)$

GAIN ERROR IS $v_O - v_I = -\dfrac{V_{OV}}{4\mu I_Q R_L}$

& SINCE $g_m \equiv g_{mN} = g_{mP} = \dfrac{2I_Q}{V_{OV}}$

$$\text{GAIN ERROR} = -\frac{1}{2\mu g_m R_L}$$

SO LARGE μ REDUCES GAIN ERROR & OUTPUT RESISTANCE

HOWEVER LARGE μ MAKE I_Q HIGHLY VARIABLE DUE TO MISMATCH & OFFSETS

TYPICAL $\mu \approx 5 \rightarrow 10$

EXAMPLE $V_{DD} = -V_{SS} = 2.5\,V$ $V_{tn} = -V_{tp} = 0.5\,V$

$\mu_N C_{ox} = 2.5\,\mu_P C_{ox} = 250\,\mu A/V^2$

LET $\mu = 10$ & $I_Q = 1\,mA$
AND $R_L = 100\,\Omega$, V_{OV} BETWEEN $0.1 \rightarrow 0.2\,V$

FIND Q_N, Q_P SIZES & QUIESCENT OPERATING POINTS

TO MINIMIZE GAIN ERROR & OUTPUT RESISTANCE

$\Rightarrow$ MAXIMIZE $g_m = \dfrac{2 I_Q}{V_{OV}}$

SO CHOOSE $V_{OV} = 0.1\,V$

$$g_m = \frac{2(1\,mA)}{0.1\,V} = 20\,mA/V$$

$$I_Q = \frac{1}{2} k (V_{OV})^2 = \frac{1}{2} \mu_N C_{ox} \left(\frac{W}{L}\right)_N (V_{OV})^2$$

$$1\,mA = \frac{1}{2}(250e-6)\left(\frac{W}{L}\right)_N (0.1)^2$$

$$\left(\frac{W}{L}\right)_N = \underline{\underline{800}}$$

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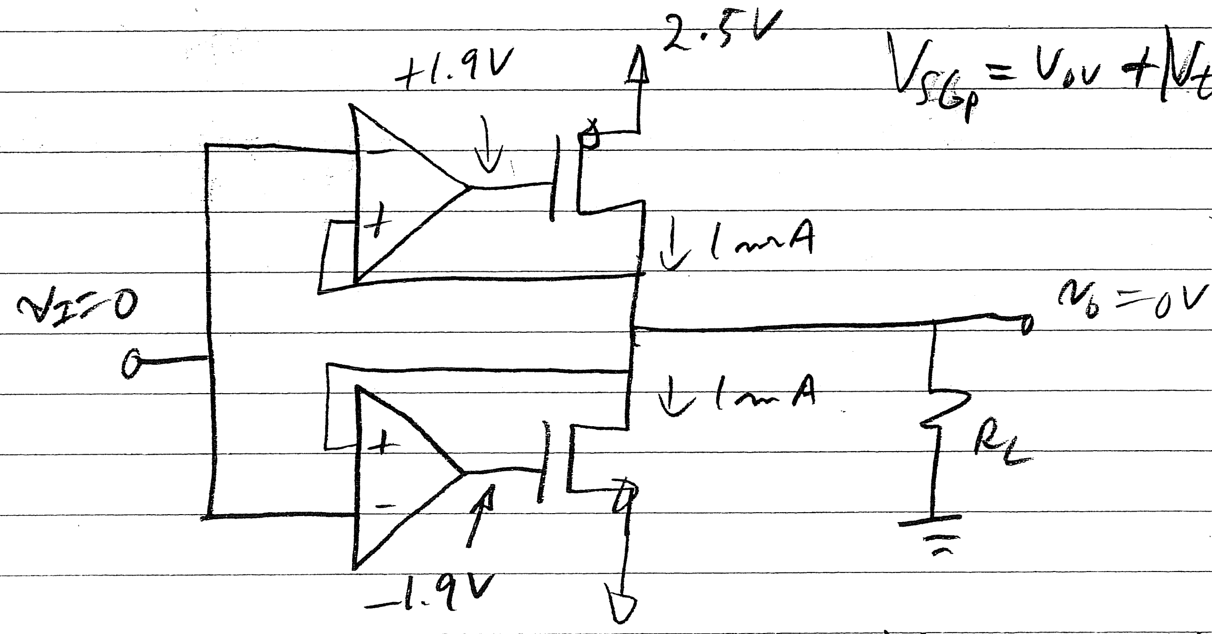
SIMILAR FOR $(W/L)_p$

$$1\,mA = \frac{1}{2}\left(\frac{250e\text{-}6}{2.5}\right)\left(\frac{W}{L}\right)_p (0.1)^2$$

$$\left(\frac{W}{L}\right)_p = \underline{\underline{2000}}$$

$$R_{OUT} = \frac{1}{\mu(g_{mp}+g_{mn})} = \frac{1}{(10)(20e\text{-}3+20e\text{-}3)}$$

$$= 2.5\,\Omega$$



$V_{SG_p} = V_{ov} + |V_{tp}| = 0.6V$

$V_{GS} = V_{ov} + V_{tN} = 0.6V$