University of California
Berkeley

College of Engineering
Department of Electrical Engineering
and Computer Science

Robert W. Brodersen
EECS140

Analog Circuit Design

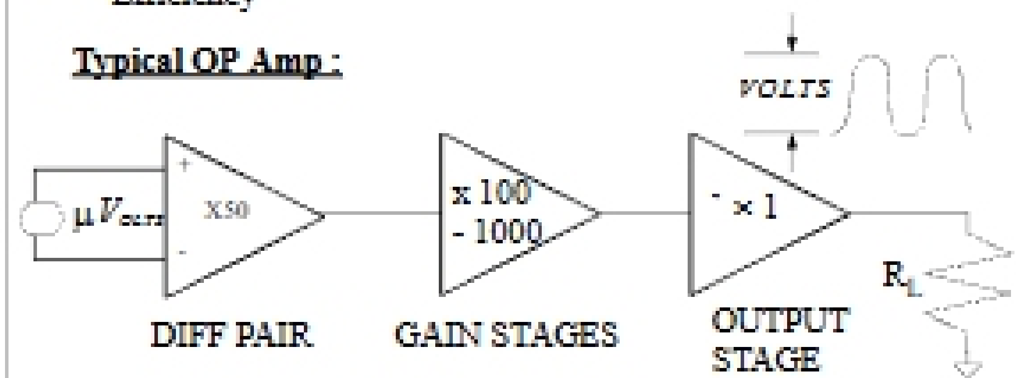
Lectures on OUTPUT STAGES

Output Stages

O-1

Large Signal Swing
Distortion
Power
Efficiency

Typical OP Amp :

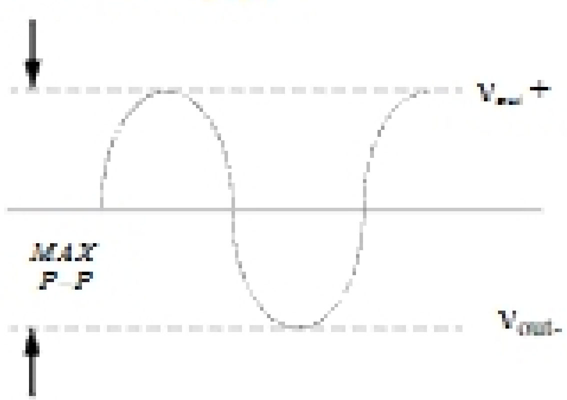


O-2

Power :

Total power from supplies = P_{SUPPLY}
Power into Load = P_{LOAD}

$$Efficiency = \frac{P_{LOAD}}{P_{SUPPLY}} (\%)$$

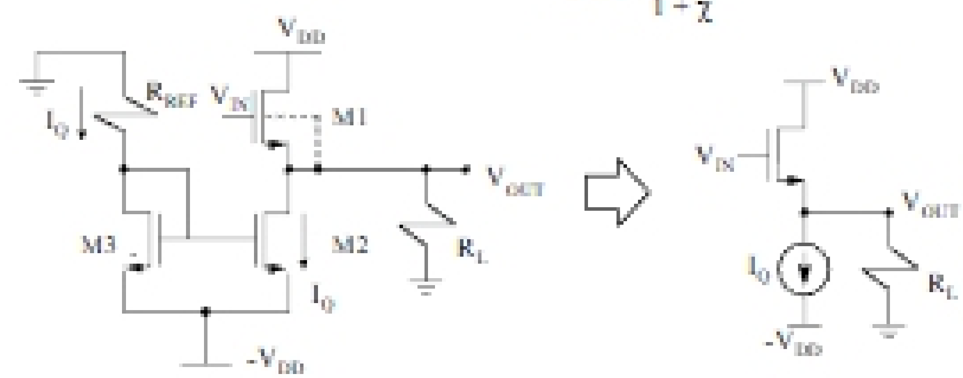


V_{out+} = desired plus swing
V_{out-} = desired neg. swing

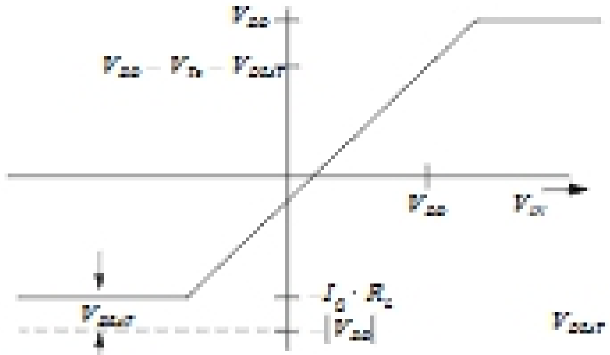
O-3

Typically output load is low impedance (but not always!)
If it is, a source follower is a possible output stage.

$$A_{vout} \approx \frac{1}{1+\chi}$$



O-4



$V_{DSAT} = V_{GS} - V_T$

$$V_{OUT,MAX} = V_{DD} - V_T - V_{DSAT}$$

$$V_{OUT,MIN} = \underbrace{V_{DSAT} + (-|V_{SS}|)}$$

are the absolute maximum swings in the positive and negative directions

V_{out+}, V_{out-} are the desired positive and negative swings
They typically should be equal for symmetric outputs

O-5

(1) $$I_Q = \frac{|V_{out-}|}{R_L}$$

(2) $$R_{SET} = \frac{V_{DD} - V_T - V_{DSAT}}{I_Q} \approx \frac{V_{DD} - V_T}{I_Q}$$

To set $\left(\frac{W}{L}\right)_2$ use Vout-

$$V_{DSAT} = (V_{SS} - |V_{OUT-}|)$$

(3) $$\left(\frac{W}{L}\right)_2 = \left(\frac{2 \cdot I_Q}{k'}\right) \cdot \frac{1}{(V_{SS} - |V_{OUT-}|)^2}$$

Find the W/L of M1:

$$I_{D1} = I_Q + I_L = I_Q + \frac{V_{OUT+}}{R_L}$$

O-6

$$\frac{k'}{2} \cdot \left(\frac{W}{L}\right)_1 \cdot (V_{DD} - V_{OUT+} - V_T)^2 = I_Q + \frac{V_{OUT+}}{R_L}$$

(4) $$\left(\frac{W}{L}\right)_1 = \frac{2 \cdot \left(I_Q + \frac{V_{OUT+}}{R_L}\right)}{k' \cdot (V_{DD} - V_{OUT+} - V_T)^2}$$

e.g. $R_L = 300\Omega$ $\quad |V_{OUT+}| = |V_{OUT-}| = 3V$

$$V_{DD} = 5V \quad I_Q = 10mA \quad R_{SET} = \frac{3 - 0.7}{10mA} = 230\Omega$$

$$\left(\frac{W}{L}\right)_2 = \frac{2 \times 10^{-2}}{90 \times 10^{-6}} \cdot \frac{1}{(5-3)^2} = 56$$

$$\left(\frac{W}{L}\right)_1 = \frac{2 \cdot (2 \times 10^{-2})}{90 \times 10^{-6} \cdot (5 - 3 - 0.7)^2} = 263$$

O-7

$$GAIN = \frac{g_m \cdot (R_L \| r_o)}{1 + g_m \cdot (R_L \| r_o)} \approx \frac{g_m \cdot R_L}{1 + g_m \cdot R_L}$$

$$R_{OUT} = \frac{1}{g_m} \| R_L$$

$$g_m = \left(2 \cdot k' \cdot \frac{W}{L} \cdot I_{D1}\right)^{\frac{1}{2}} = (2 \times 90 \times 10^{-6} \times 263 \times 10^{-2})^{\frac{1}{2}} = 22 \times 10^{-3}$$

$$\frac{1}{g_m} = 45\Omega$$

$$GAIN = \frac{R_L}{\frac{1}{g_m} + R_L} = \frac{300}{45 + 300} = 0.87$$

$$R_{OUT} = \frac{1}{g_m} \| R_L = 45 \| 300 \approx 40\Omega$$

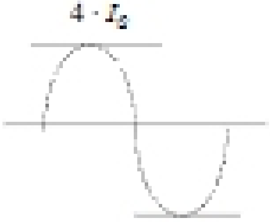
O-8

$$Power = \sum V_{SUPPLY} \cdot (CurrentOut)$$

$Power@V_{out} = 0V$ DC Power without any Signal

$$Power = (-I_{M1}) \cdot (-V_{SS}) + (-I_{M2}) \cdot (-V_{SS}) + (I_{M1}) \cdot V_{DD}$$

$$= 3 \cdot I_Q \cdot V_{DD} = 3 \cdot (10 \times 10^{-3}) \cdot 5 = 150mW$$



$$Average = 3 \cdot I_Q$$

$$Efficiency = \frac{\text{Power to Load}}{3 \cdot I_Q \cdot V_{DD}} (\%)$$

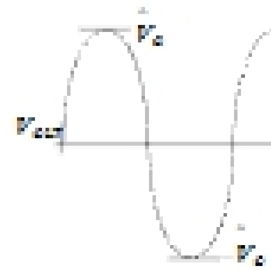
O-9

$$V_{ERROR} = V_{IN}|_{V_{out}=0V}$$

$$V_{IN} = V_{GS1} = V_{TN} + \underbrace{\left(\frac{2 \cdot I_{D1}}{K' \cdot \frac{W}{L}}\right)^{\frac{1}{2}}}_{\Delta V} = 0.7 + \left(\frac{2 \times 10 \times 10^{-3}}{90 \times 10^{-6} \times 263}\right) = 1.6V$$

$I_{D1} = I_Q$

Efficiency (Sine Wave)

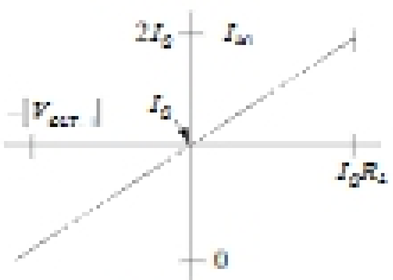


$$\hat{V}_o = PeakVoltage$$

$$P_L = \frac{1}{2} \cdot \hat{V}_o \cdot \hat{I}_o = \frac{1}{2} \cdot (I_Q \cdot R_L) \cdot I_Q = \frac{1}{2} \cdot I_Q^2 \cdot R_L$$

$$= \frac{1}{2} \cdot 10^{-4} \times 300 = 15mW$$

O-10



$$I_{M1} = I_Q + I_{RL} = I_Q + \frac{V_{OUT}}{R_L}$$

$$|V_{OUT-}| = |V_{OUT+}|$$

$$P_{SUPPLY} = \underbrace{\frac{1}{T_C} \cdot \int_0^{T_C} (I_{DD}(m1) \cdot V_{DD}) dt}_{I_Q \cdot V_{DD}} + 2 \cdot I_Q \cdot |V_{SS}|$$

$$= 3 \cdot I_Q \cdot V_{DD} = 150mW$$

$$Efficiency = \frac{P_{LOAD}}{TotalPower} = \frac{15mW}{150mW} = 10\%$$

$$= \left(\frac{\frac{1}{2} \cdot I_Q^2 \cdot R_L}{3 \cdot I_Q \cdot V_{DD}}\right) = \frac{1}{6} \cdot \left(\frac{I_Q \cdot R_L}{V_{DD}}\right) < 16\% \text{ MAX}$$

O-11