University of California
Berkeley

College of Engineering
Department of Electrical Engineering
and Computer Science

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EECS140

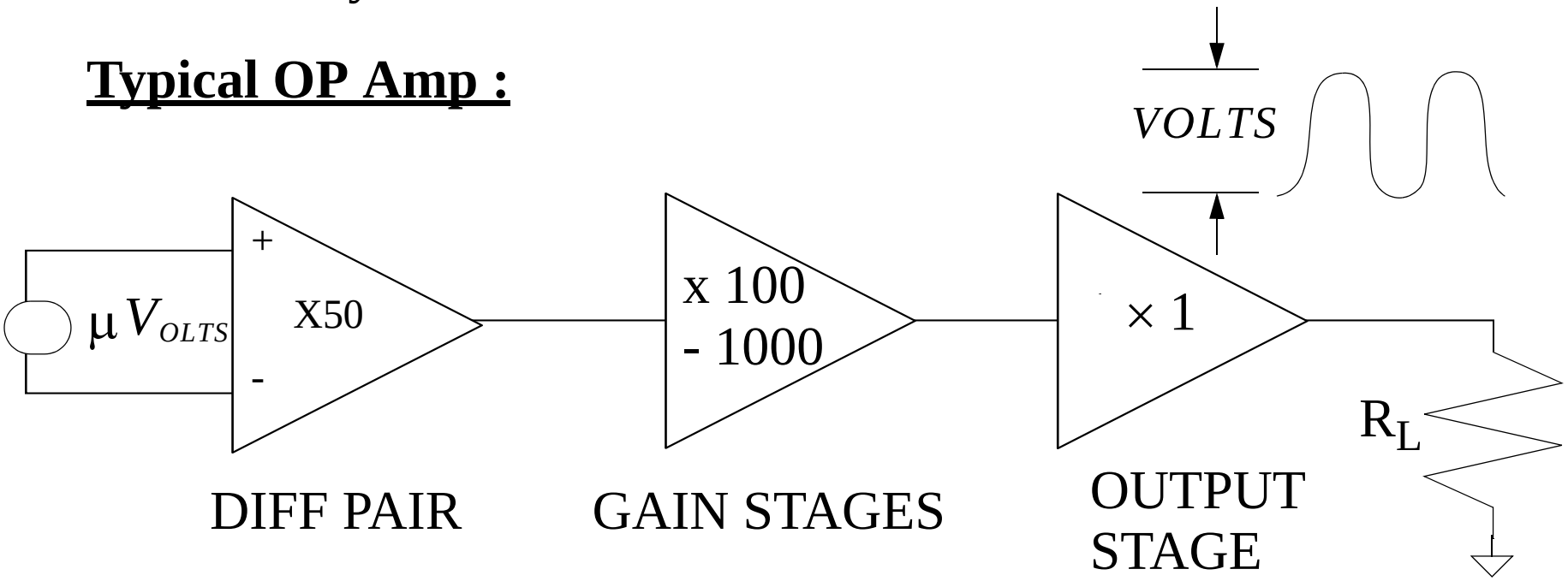
Analog Circuit Design

Lectures
on
OUTPUT STAGES

Output Stages

Large Signal Swing
Distortion
Power
Efficiency

Typical OP Amp :

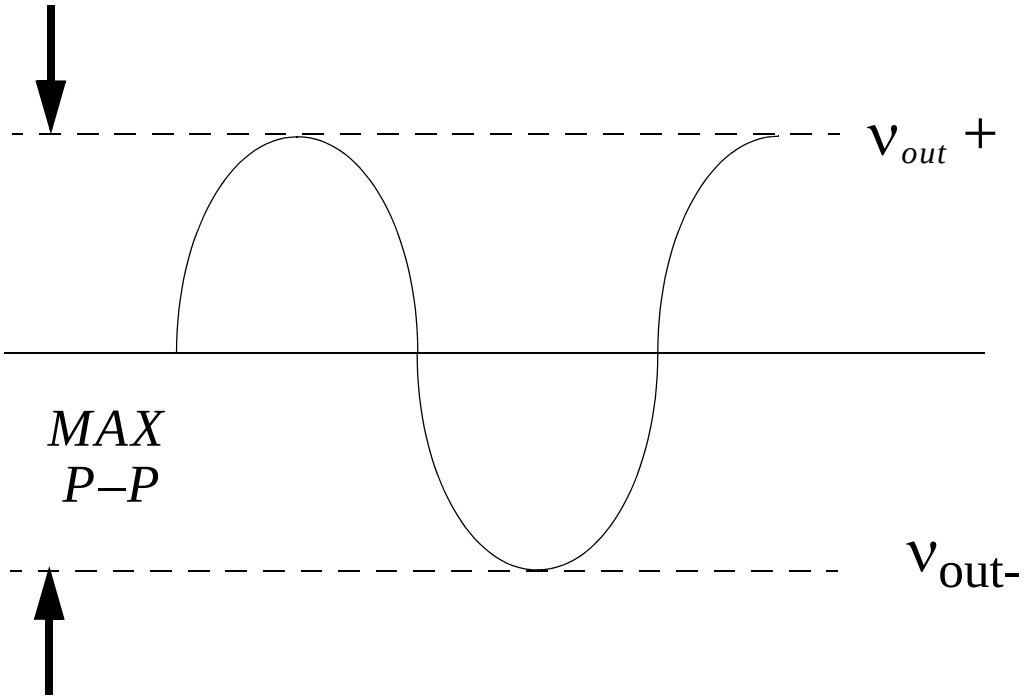


Power :

Total power from supplies = P_{SUPPLY}

Power into Load = P_{LOAD}

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

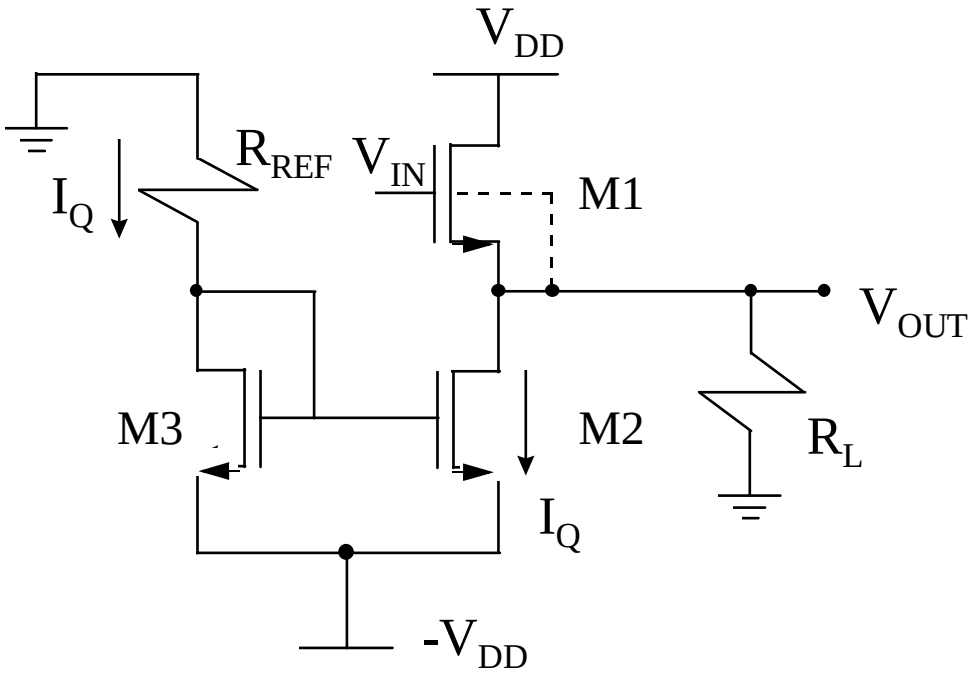


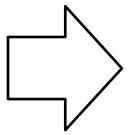
ν_{out+} = desired plus swing

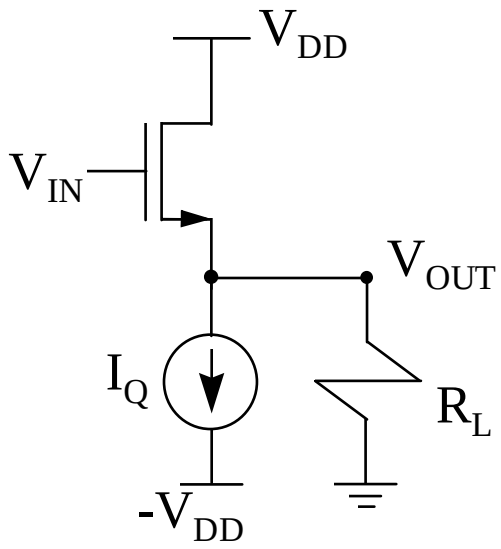
ν_{out-} = desired neg. swing

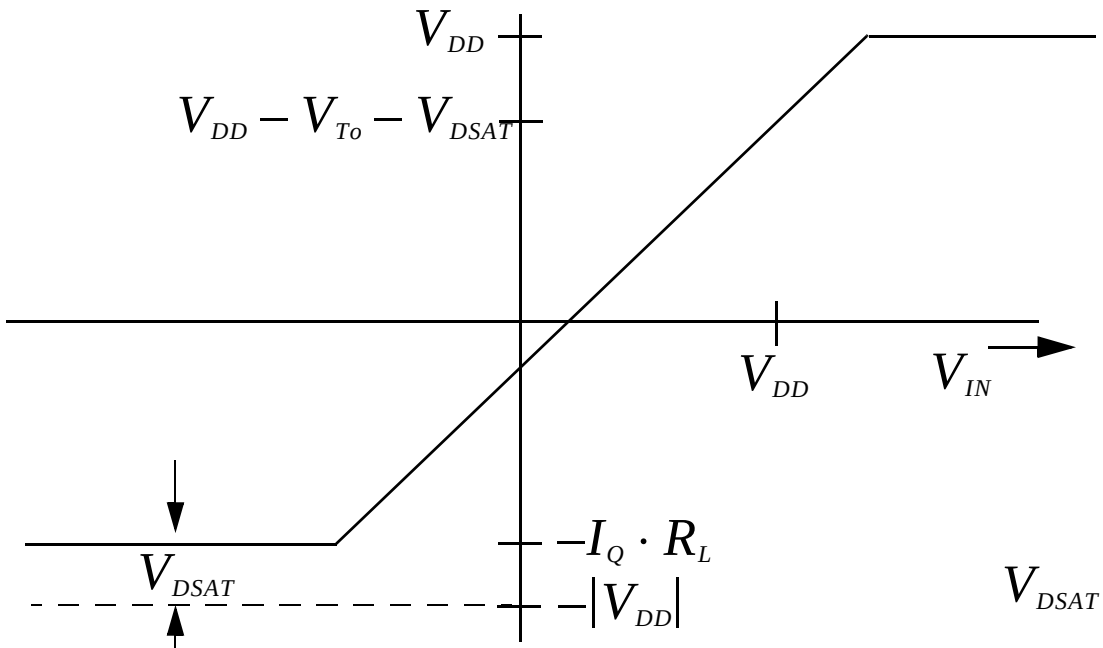
Typically output load is low impedance (but not always!)
If it is, a source follower is a possible output stage.

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









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

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

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

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

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

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

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

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

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

Find the W/L of M1:

$$I_{DS1} = I_Q + I_L = I_Q + \frac{V_{OUT+}}{R_L}$$

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

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

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

$$\left(\frac{W}{L}\right)_2 = \frac{2\times10^{-2}}{90\times10^{-6}}\cdot\frac{1}{(5-3)^2} = 56$$

$$\left(\frac{W}{L}\right)_1 = \frac{2\cdot(2\times10^{-2})}{90\times10^{-6}\cdot(5-3-0.7)^2} = 263$$

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

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

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

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

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

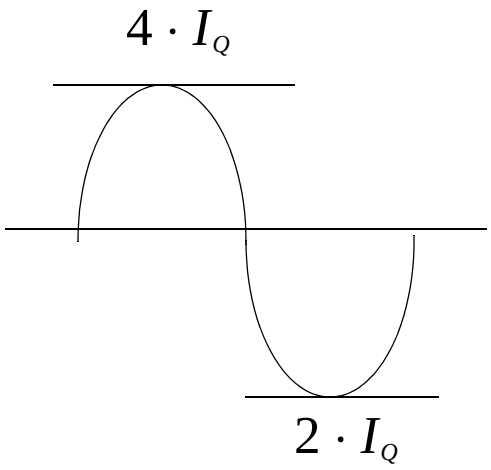
$$R_{OUT} = \frac{1}{g_m} \parallel R_L = 45 \parallel 300 \approx 40\Omega$$

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

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

$$Power = (-I_{M3}) \cdot (-V_{DD}) + (-I_{M2}) \cdot (-V_{DD}) + (I_{M1}) \cdot V_{DD}$$

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



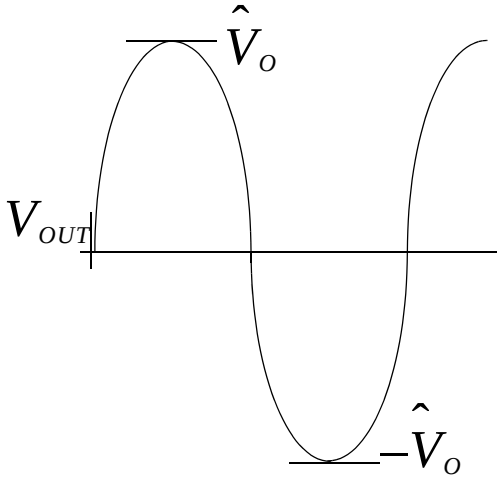
$$Average = 3 \cdot I_Q$$

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

$$V_{OFFSET} = V_{IN}\big|_{V_{OUT}=0V}$$

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

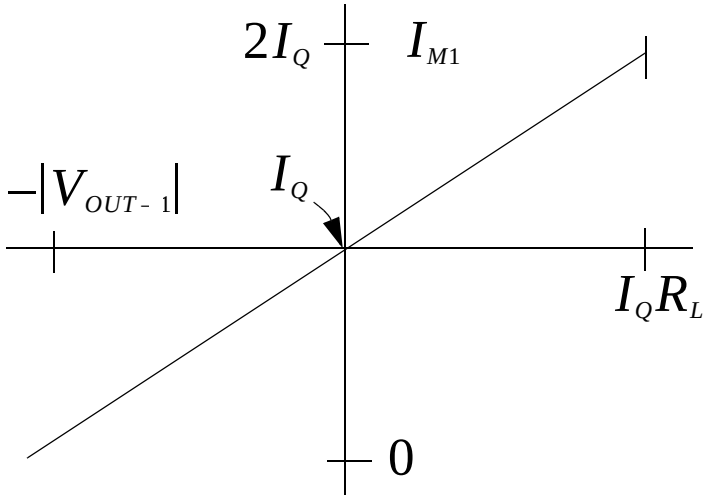
Efficiency (Sine Wave)



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

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

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



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

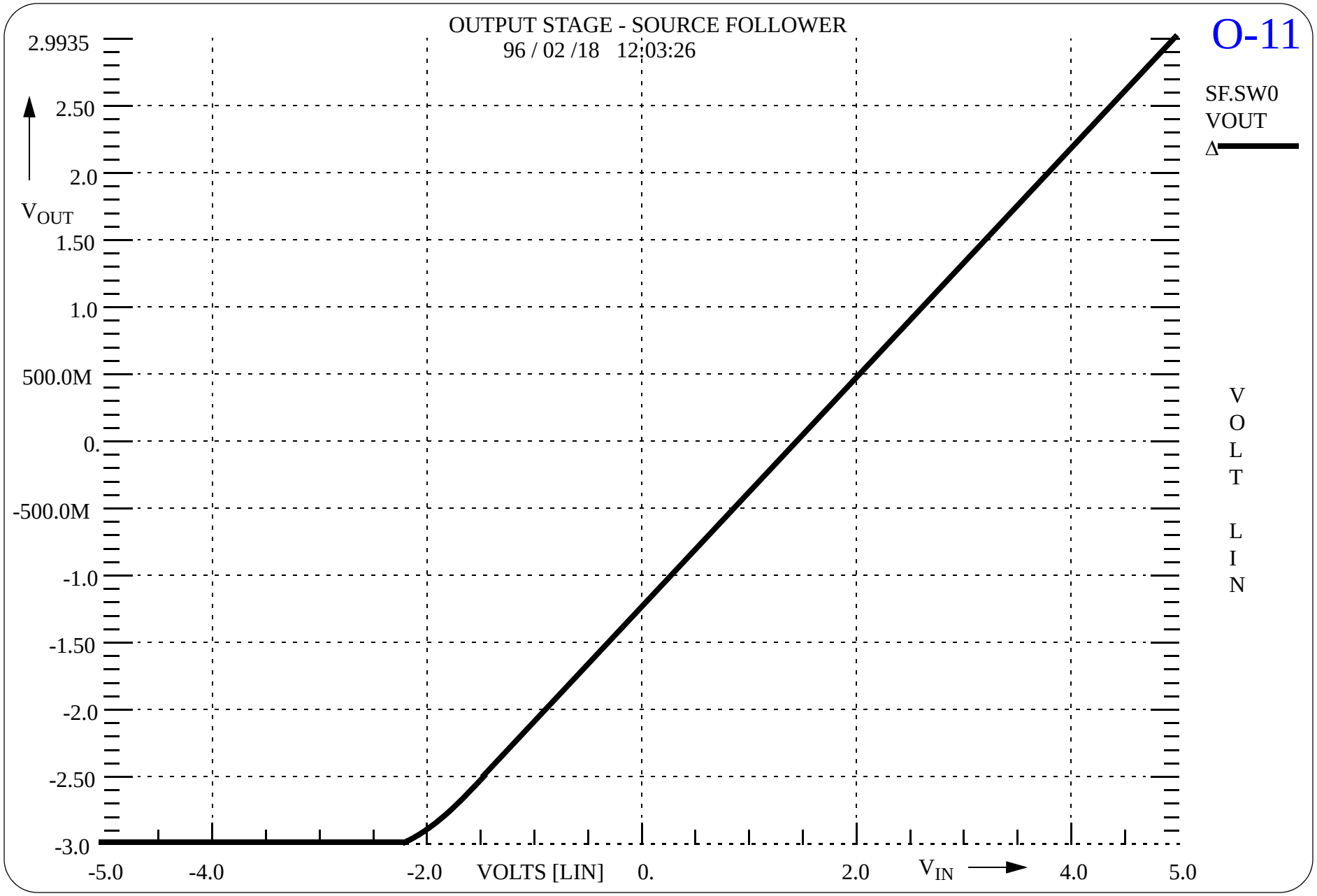
$$|V_{OUT-}| = |V_{OUT+}|$$

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

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

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

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


OUTPUT STAGE - SOURCE FOLLOWER
96 / 02 /18 12:03:26
O-11
SF.SW0
VOUT
Δ
2.9935
2.50
2.0
VOUT
1.50
1.0
500.0M
0.
-500.0M
-1.0
-1.50
-2.0
-2.50
-3.0
-5.0
-4.0
-2.0
VOLTS [LIN]
0.
2.0
VIN
4.0
5.0
VOLT LIN

output stage - source follower

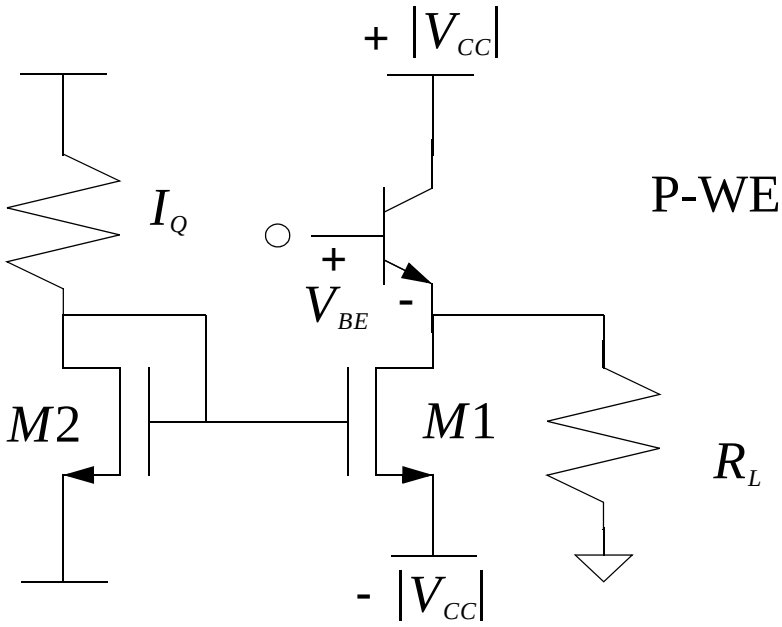
```
*****
* reading file: /bobtools/commercial/hspice/hspice.ini
*
.model nch nmos level = 1 tox = 170 vto = 0.7 kp = 90.0e-6 lambda = 0.01
+ gamma = 0.5 phi = 0.6 capop = 0 cgso=5.e-10 cgdo=5.e-10 cgbo=4.e-10 cj=1e-4

.model pch pmos level = 1 tox = 170 vto = -0.7 kp = 30.0e-6 lambda = 0.01
+ gamma = 0.5 phi = 0.6 capop = 0 cgso=3.e-11 cgdo=3.e-11 cgbo=4.e-10 cj=6e-4

.option nopage post=2 absi = 1e-10 reli = 1e-4 absmos = 1e-8 relmos=1e-4
+ absv=1e-6 relv=1e-4

.options nomod

*name drain gate source bulk model
m1 vdd vin vout vout nch l=1u w=263u
m2 vout d3 vdd- vdd- nch l=1u w=56u
m3 d3 d3 vdd- vdd- nch l=1u w=56u
rref 0 d3 230
*iload vout vdd- 1ma

rload   0   vout   300

vin     vin     0     1.6
vdd     vdd     0     5.0
vdd-    vdd-    0    -5.0

.dc vin -5 5 .1                          *sweep the input voltage
.print dc i(m1)  i(m2)  i(m3)  v(vout)
.op                                      *initial operating point
.tf v(vout,0)  vin
.measure tot_power avg power             *makes it do the power calculation
```

Small-signal transfer characterisitcs

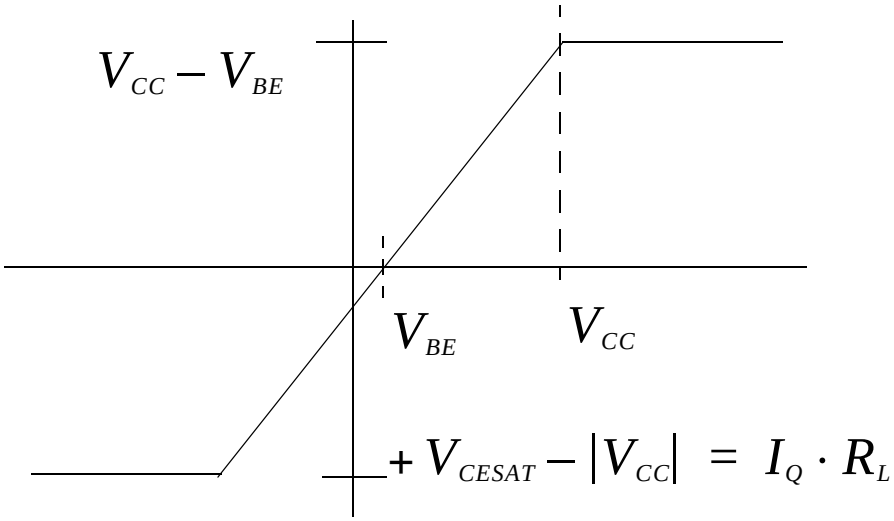
```
v(vout)/vin                                  = 865.0433m
input resistance at          vin             =  1.000e+20
output resistance at v(vout)                 =    38.2335
```

Bipolar version

Bipolar :



P-WELL



Bipolar (Cont.)

$$V_{MAX} = V_{CC} - V_{BE} = |V_{MAX-}| \qquad \text{for symmetry}$$

$$P_L = \frac{1}{2} \cdot (V_{CC} - V_{BE}) \cdot I_Q \cdot R_L$$

$$Efficiency = \frac{\frac{1}{2} \cdot (V_{CC} - V_{BE}) \cdot I_Q \cdot R_L}{3 \cdot I_Q \cdot V_{CC}} = \frac{1}{6} \cdot \frac{(V_{CC} - V_{BE})}{V_{CC}}$$

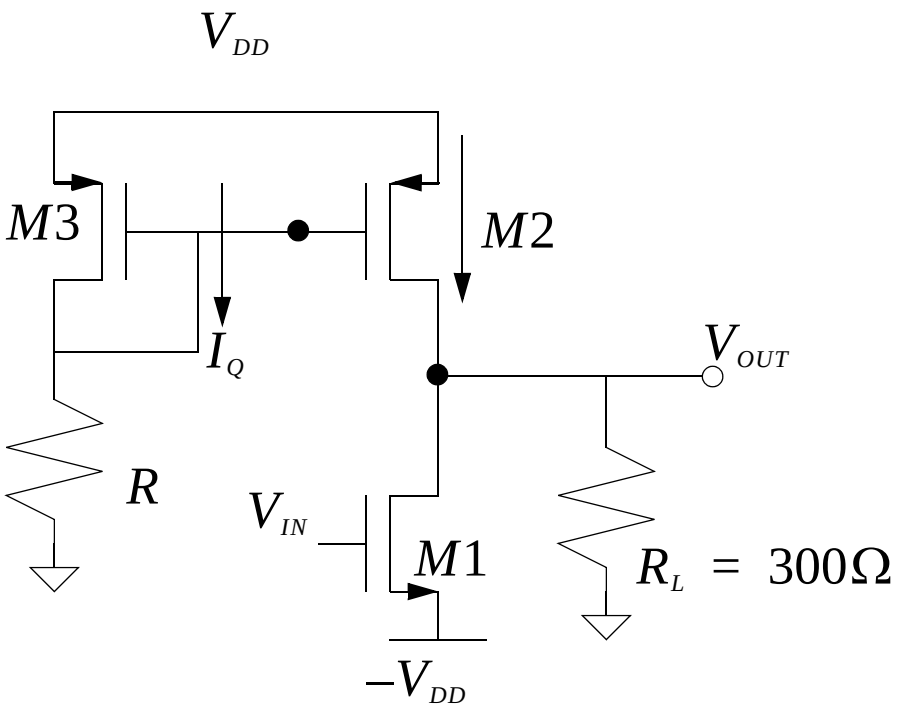
$$= \frac{1}{6} \cdot \left(\frac{5 - 0.6}{5}\right) = 15\%$$

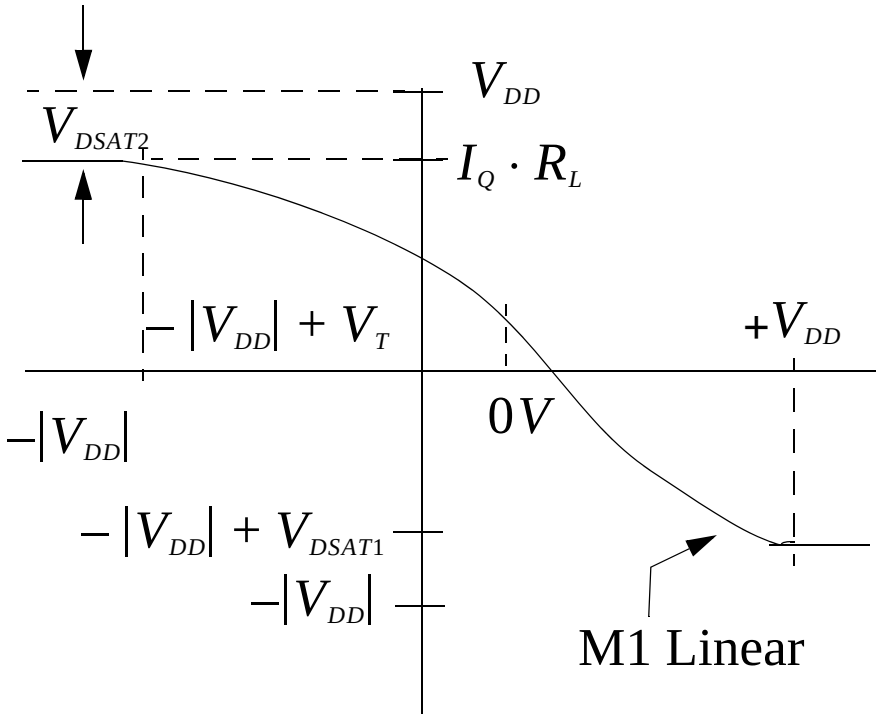
$$I_C = I_S \cdot e^{\frac{V_{BE}}{V_T}}$$

$$V_{BE} = V_{Th} \cdot \ln\frac{I_C}{I_S} = 0.06 \cdot \log\frac{I_C}{I_S}$$

More voltage range

Inverter Output Stage :





$$I_Q = \frac{|V_{MAX+}|}{R_L} = \frac{3V}{300} = 10^{-2}$$

$$V_{DSAT} = V_{DD} - V_{MAX+} = \left(\frac{2 \cdot I_Q}{k' \cdot \frac{W}{L}}\right)^{\frac{1}{2}}$$

① $$\left(\frac{W}{L}\right)_2 = \frac{2 \cdot I_Q}{k'} \cdot \frac{1}{(V_{DD} - V_{MAX+})^2} = 166$$

$$I_Q \cdot R_{REF} = V_{DD} - V_{SG} = V_{DD} - |V_T| - V_{DSAT} = V_{DD} - |V_T| - (V_{DD} - V_{MAX+})$$

② $$R_{REF} = \frac{V_{MAX+} - |V_T|}{I_Q} = \frac{3 - 0.7}{10^{-2}} = 230\Omega$$

$$= \frac{I_Q \cdot R_L - |V_T|}{I_Q} = R_L - \frac{V_{To}}{I_Q}$$

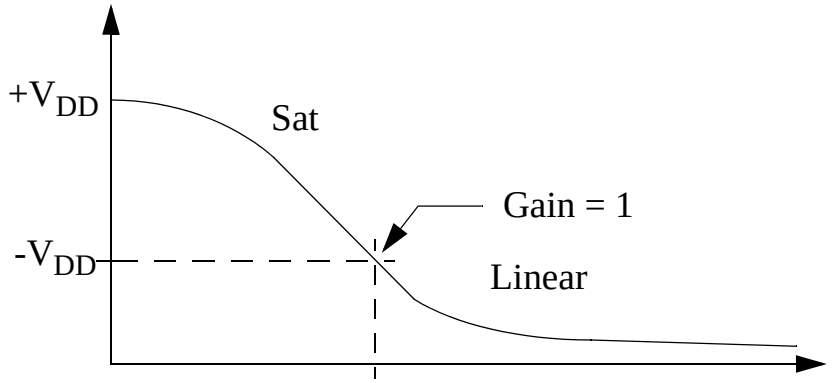
(Cont.)

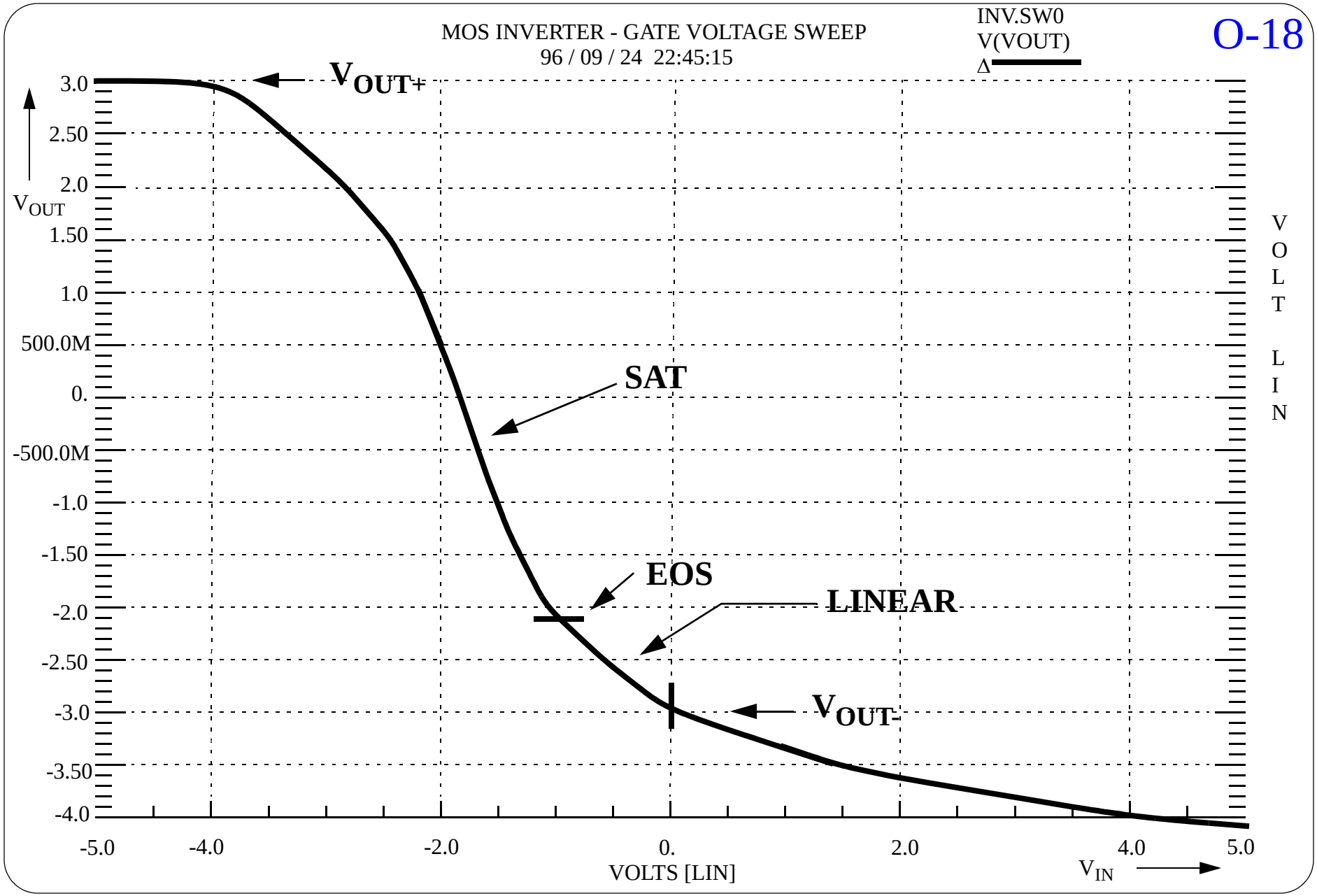
Let $V_{GS} = V_{DD}$

$$I_{DS,M1} = k' \cdot \left(\frac{W}{L}\right)_1 \cdot \left(V_{GS} - V_T - \frac{V_{DS}}{2}\right) \cdot V_{DS}$$

$$2 \cdot I_Q = k' \cdot \left(\frac{W}{L}\right)_1 \cdot \left(V_{GS} - V_T - \frac{(V_{DD} - |V_{OUT-}|)}{2}\right) \cdot (V_{DD} - |V_{OUT-1}|)$$

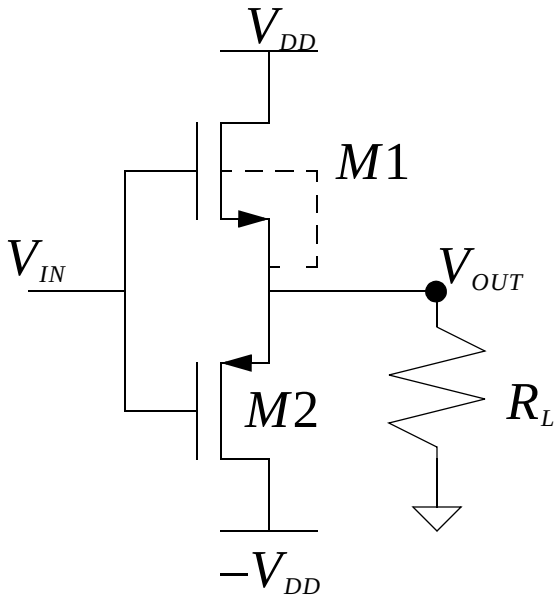
$$\left(\frac{W}{L}\right)_1 = \frac{2 \cdot I_Q}{k' \cdot \left(V_{DD} - V_{To} - \frac{(V_{DD} - |V_{OUT-}|)}{2}\right) \cdot (|V_{DD}| - |V_{OUT-}|)} = 34$$




MOS INVERTER - GATE VOLTAGE SWEEP
96 / 09 / 24 22:45:15
INV.SW0
V(VOUT)
Δ
O-18
VOUT+
SAT
EOS
LINEAR
VOUT-
VOUT
3.0
2.50
2.0
1.50
1.0
500.0M
0.
-500.0M
-1.0
-1.50
-2.0
-2.50
-3.0
-3.50
-4.0
-5.0
-4.0
-2.0
0.
2.0
4.0
5.0
VOLTS [LIN]
VIN
VOLT LIN

```
*****
* reading file: /bobtools/commercial/hspice/hspice.ini
*
.model nch nmos level = 1 tox = 170 vto = 0.7 kp = 90.0e-6 lambda = 0.01
+ gamma = 0.5 phi = 0.6 capop = 0 cgso=5.e-10 cgdo=5.e-10 cgbo=4.e-10 cj=1e-4

.model pch pmos level = 1 tox = 170 vto = -0.7 kp = 30.0e-6 lambda = 0.01
+ gamma = 0.5 phi = 0.6 capop = 0 cgso=3.e-11 cgdo=3.e-11 cgbo=4.e-10 cj=6e-4

.option nopage post=2 absi = 1e-10 reli = 1e-4 absmos = 1e-8 relmos=1e-4
+ absv=1e-6 relv=1e-4

.options nomod

*name drain gate source bulk model
*m1 vout vin vdd- vdd- nch l=1u w=34u
m1 vout vin vdd- vdd- nch l=1u w=34u
m2 vout vr vdd vdd pch l=1u w=166u
m3 vr vr vdd vdd pch l=1u w=166u

rref  vr  0  230
r1    vout  0  300

*vin     vin     0      sin(1 1 1)
vin     vin     0     -4.15
vdd     vdd     0     5.0
vdd-    vdd-  0     -5.0

.dc vin -5 5 .5                          *sweep the input voltage
.print dc i(m1)  i(m2)  i(m3)  v(vout)
*.tran .1 1
*.print  tran  i(m1)  v(vout)             * i is the ids of m1
.op                                      *initial operating point
.tf v(vout,0)  vin                       *transfer function between v(rd) an vin
.measure tot_power avg power             *makes it do the power calculation

.end
```

Class B : Push - Pull



$$V_{1,2} \approx V_{T0} + \gamma \cdot (V_{DD})^{\frac{1}{2}}$$

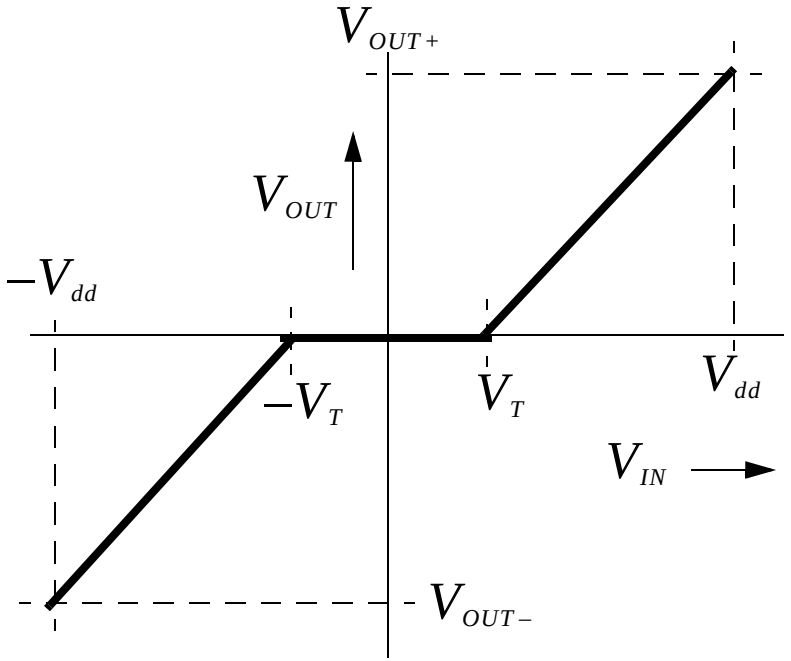
Push - Pull (Cont.)

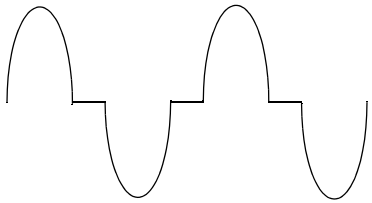
V_{OUT+} is set by M1; V_{out-} by M2

$$I_{DS1} = \frac{V_{OUT}^{+}}{R_L} = \frac{k'}{2} \cdot \left(\frac{W}{L}\right)_1 \cdot (V_{DD} - V_{OUT+} - V_T)^2$$

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

$$\left(\frac{W}{L}\right)_2 = \frac{2 \cdot V_{OUT}^{-}}{R_L \cdot k'_p \cdot (V_{DD} - V_{OUT-} - V_{TP})^2}$$





Crosover Distortion

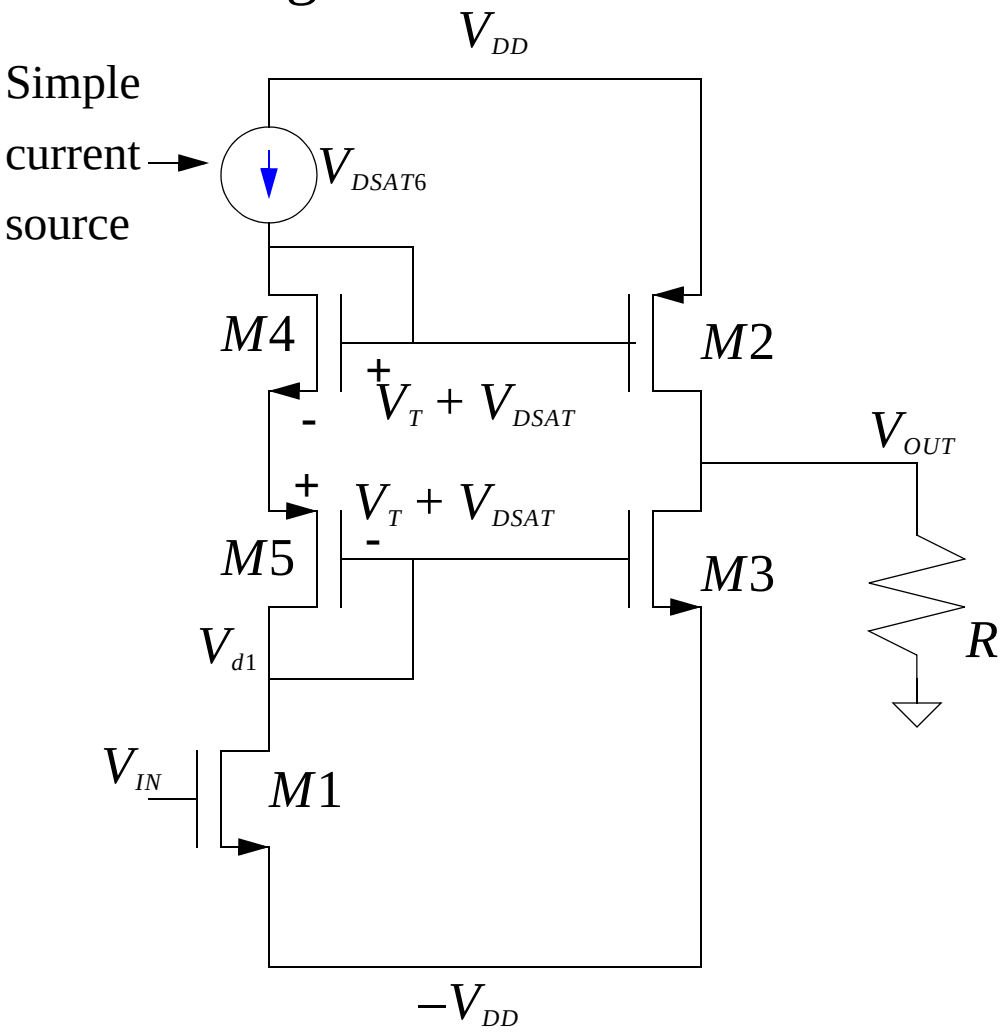
$$-V_{DD} + V_T$$

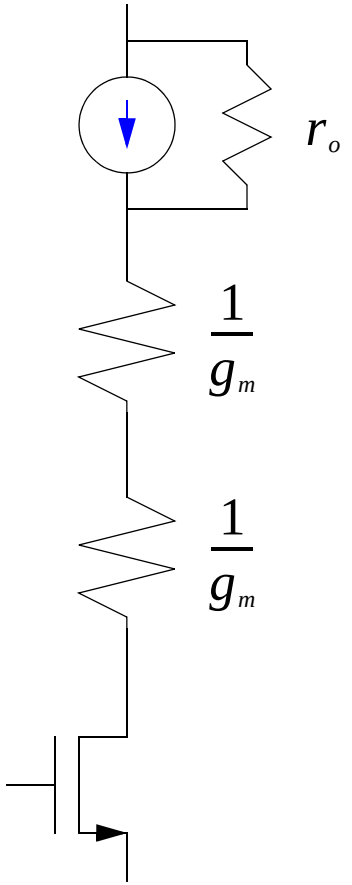
$$|V_T| \approx \left|V_{TO,P} + \gamma \cdot (V_{SB})^{\frac{1}{2}}\right|$$

$$\gamma \cdot [(2 \cdot \phi_f + V_{SB})^{1/2} - (2 \cdot \phi_f)^{1/2}]$$

Push - Pull (Cont.)

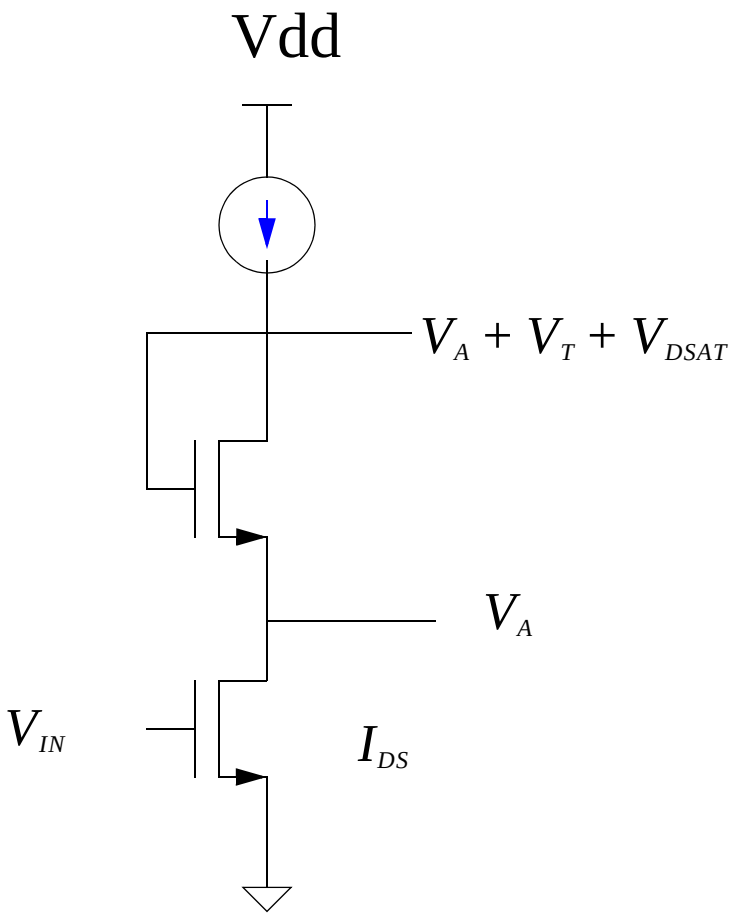
With Biasing - Remove Dead Zone which gives crossover distortion.



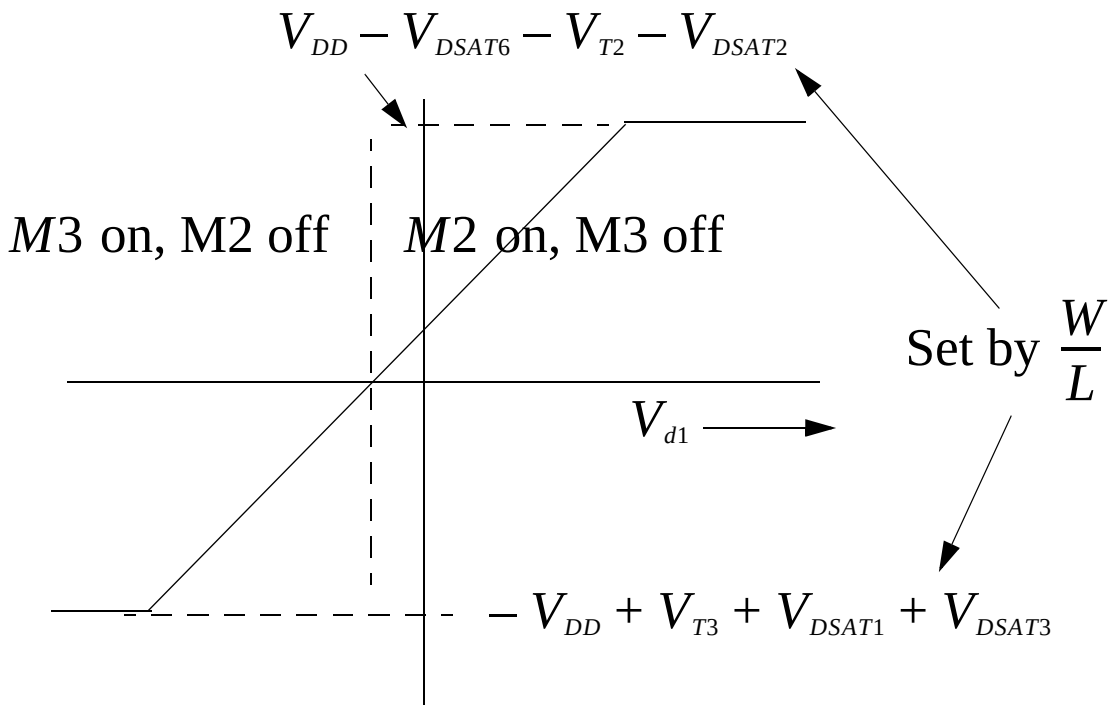


Push - Pull (Cont.)

Level Shifter :

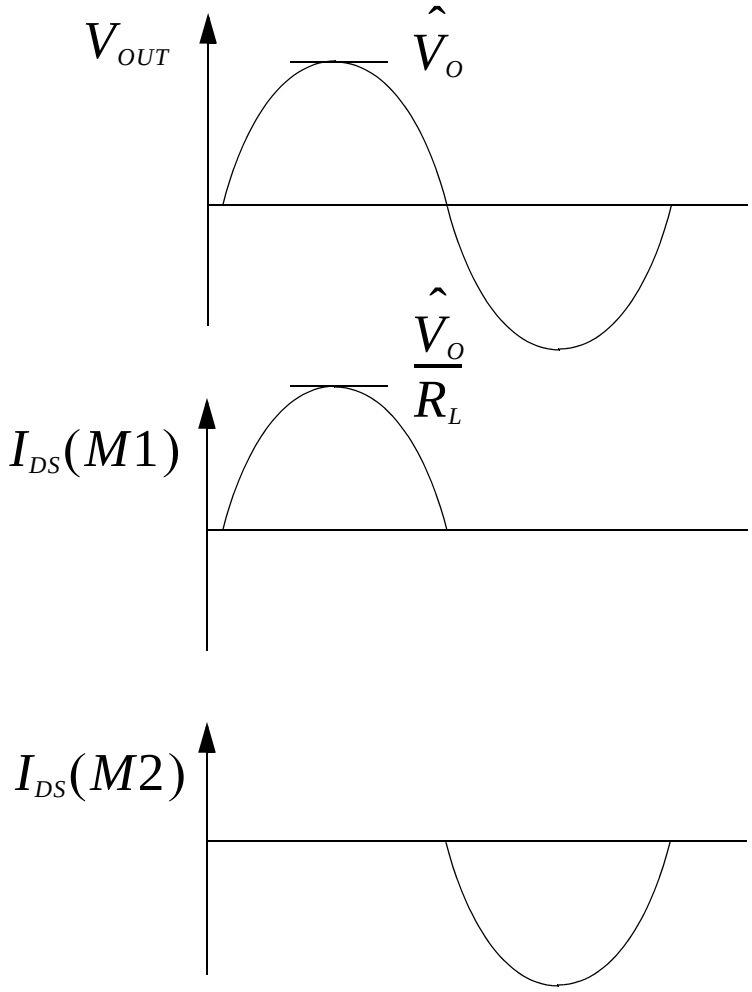


Push - Pull (Cont.)



Push - Pull (Cont.)

Efficiency with sine wave input :



$$\hat{V}_O = \text{Peak } V_{OUT}$$

$$I_{SUPPLY} = \frac{1}{T}\cdot\int_0^{T_C} I_{DS}(t)dt = \frac{1}{\pi}\cdot\frac{\hat{V}_O}{R_L} = \textit{Ave Current from each supply}$$

$$P_{SUPPLY} = 2\cdot V_{DD}\cdot I_{SUPPLY} = \frac{2}{\pi}\cdot\frac{V_{DD}}{R_L}\cdot\hat{V}_O$$

$$P_{LOAD} = \frac{1}{2}\cdot\frac{\hat{V}_O^2}{R_L}$$

$$Efficiency = \frac{P_{LOAD}}{P_{SUPPLY}} = \frac{\pi}{4}\cdot\frac{\hat{V}_O}{V_{DD}} \Rightarrow 79\ \%$$

$$If\ \ \hat{V}_O = V_{DD}$$