C MOS.
REVIEW

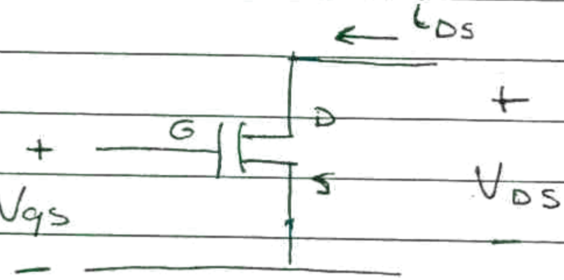
CHECK TEXTBOOK TO CORRECT
ANY ERRORS

TWEEDON

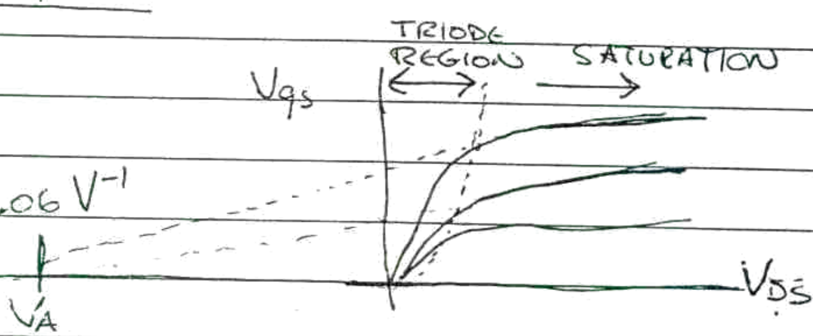
# Review Notes I



## N-Channel Enhancement Mode MOSFET




⇒ ~~Assumes substrate~~ connected to source




$\lambda = \frac{1}{V_A}$ typical $\approx .06\,V^{-1}$

## In Saturation Region $V_{DS} \geq V_{gs} - V_T$

$$i_{DS} = \frac{W}{L}\frac{k_P}{2}(V_{gs}-V_T)^2(1+\lambda V_{DS})$$

$W, L$ = gate width & length, $V_T$ = Threshold Voltage $\approx .8V$

$k_P = \mu_n C_{ox} = \frac{\mu_n \epsilon_{ox}}{t_{ox}} \approx \frac{4 \mu_n \epsilon_o}{t_{ox}}$ = Process Transconductance

$C_{ox}$ = capacitance/unit area, $\mu_n$ = Electron mobility
$t_{ox}$ = oxide thickness, typical $k_P \approx 20\mu A/V^2$

Output Resistance $= \frac{1}{d i_D/dV_{DS}} \approx \frac{1}{\lambda i_{DS}} = R_{DS}$

Note: $\frac{k_P}{2}$ = MOSIS $K'$ in process data

($\lambda$ = channel length modulation param.)

IN TRIODE Region. $V_{DS} < V_{gs} - V_T$

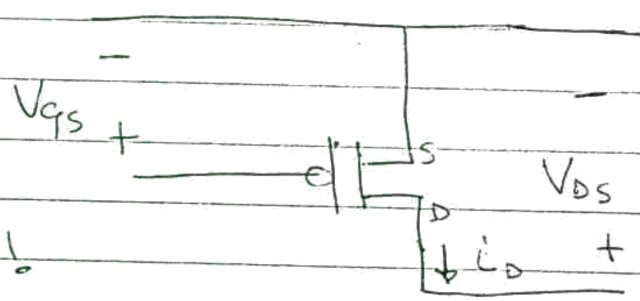
$$i_{DS} = k_P \frac{W}{L}\left[(V_{gs}-V_T)V_{DS} - \frac{V_{DS}^2}{2}\right]$$

here DRAIN = SOURCE BEHAVES LIKE A voltage VARIABLE RESISTOR where

$$R_{DS} = \frac{1}{k_P \frac{W}{L}(V_{gs}-V_T)}$$

Similarly

ENHANCEMENT MODE PFET




BOOK USES DIFFERENT CONVENTION!

Note: Different Direction, $i_D$ "OUT" of DRAIN
Also $V_T$ AND $V_{gs}$ ARE Typically Negative

$$i_D = \frac{W}{L}\frac{k_P}{2}(V_{gs}-V_T)^2(1+|\lambda V_{DS}|)$$

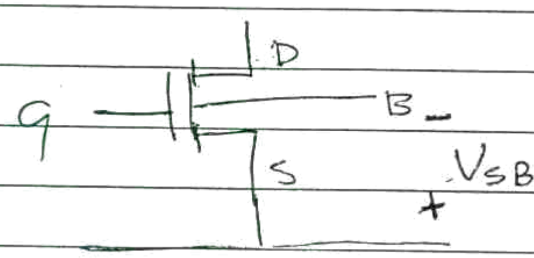
## Body Effect



If source is not connected to bulk

$$V_T = V_{TO} + \gamma'\left(\sqrt{|2\phi_f| + V_{SB}} - \sqrt{|2\phi_f|}\right)$$

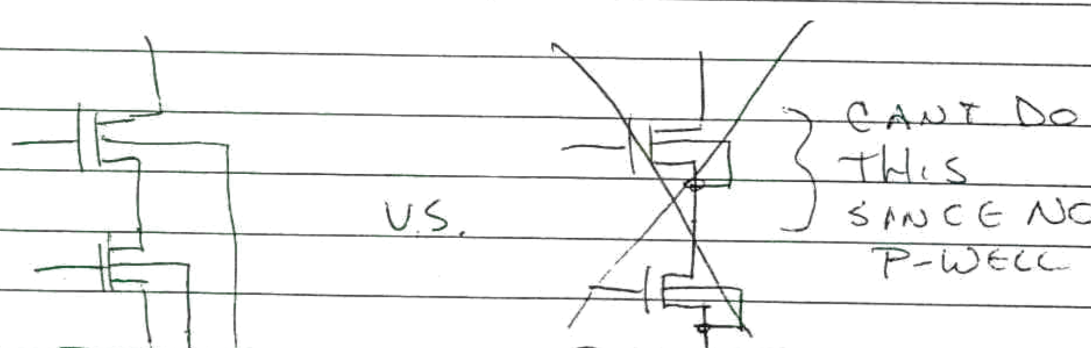
↑ Normally positive for N-channel




$\phi_f \approx -.3V$

So $V_T$ increases as $V_{SB}$ increases.

Consider

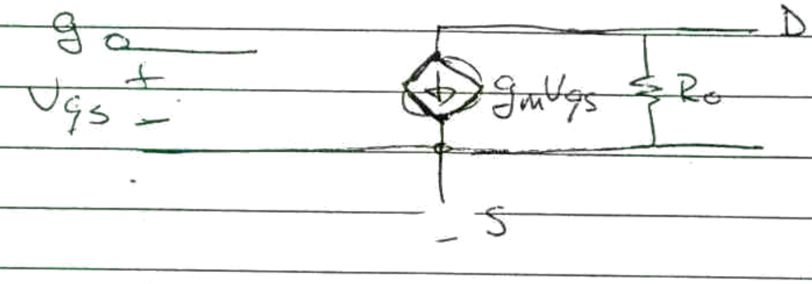



In our process all NFETs bulk is grounded

So! Left case holds!

# Small Signal Models






In Saturation

$$g_m = \frac{\partial i_D}{\partial V_{gs}} = \frac{W}{L} k_p (V_{gs} - V_T)(1 + \lambda V_{DS})$$

$$\approx \frac{W}{L} k_p (V_{gs} - V_T)$$

$$= \sqrt{2 \frac{W}{L} k_p i_D}$$

AND

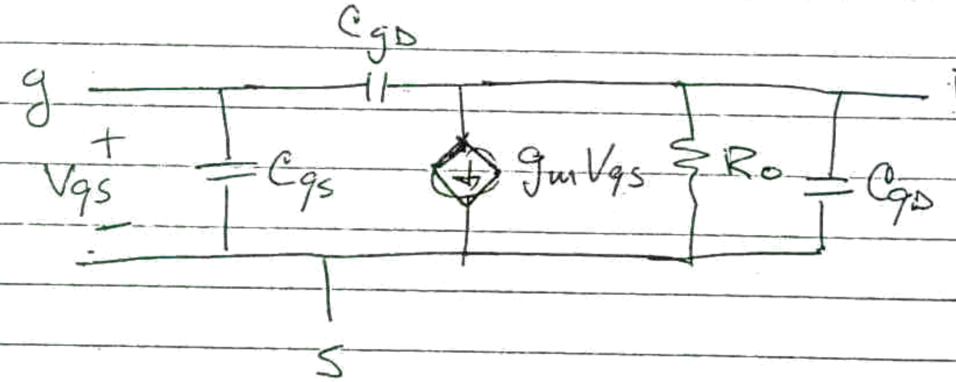
$$R_o = \frac{1}{\lambda i_{DS}} \quad \text{as before.}$$

---

Another useful form, where $i_D \approx \frac{W}{L} \frac{k_p}{2} (V_{gs} - V_T)^2$

$$g_m \approx \frac{W}{L} k_p (V_{gs} - V_T) = \frac{2 i_D}{V_{gs} - V_T}$$

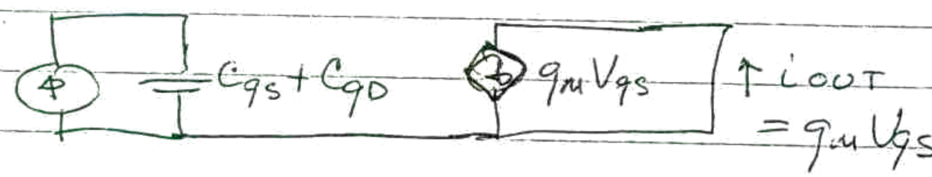
# ADDING CAPACITANCES




CONSIDER

(1) CURRENT SOURCE IN (2) short CIRCUIT OUT


⇓




$$\frac{i_{OUT}}{i_{in}} = \frac{g_m V_{gs}}{i_{in}} = \frac{g_m \frac{i_{in}}{j\omega(C_{gs}+C_{gD})}}{i_{in}} = \frac{g_m}{\omega(C_{gs}+C_{gD})}$$

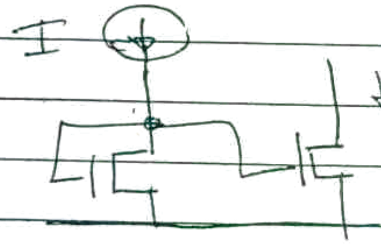
Unity GAIN FREQUENCY FIGURE OF MERIT

$$f_T = \frac{\omega_T}{2\pi} = \frac{g_m}{2\pi(C_{gs}+C_{gD})}$$

# CMOS Circuits

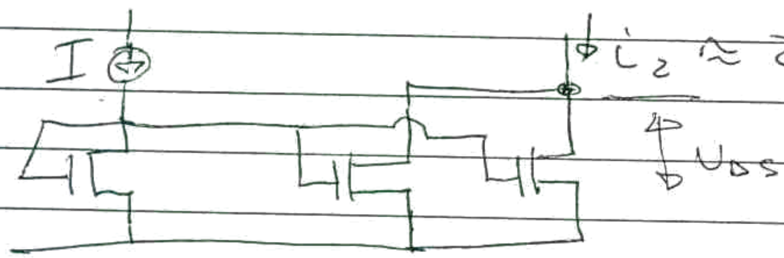


## Current Mirror




$\downarrow i_2 \approx I$ if $\frac{W}{L}$ same for both devices

(Actually $i_2 = \frac{k_P}{2}\frac{W}{L}(V_{GS}-V_T)^2(1+\lambda V_{DS})$)



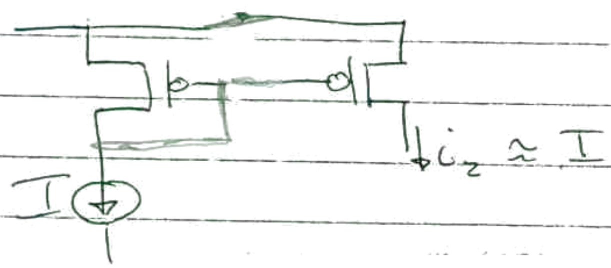

In above, "minimum voltage" of useful range is when output FET is in saturation, i.e.

<u>Keep</u> $V_{DS} \geq V_{GS} - V_T$ at output

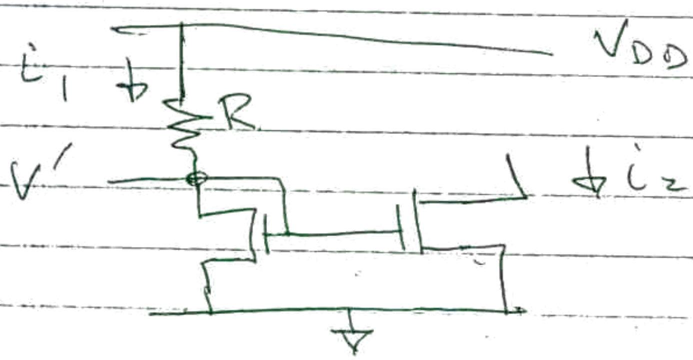
In first case above, note

$$R_o \approx \frac{1}{\lambda i_2}$$

## OTHER CURRENT SOURCES!




## Example SIMPLIFIED Analysis

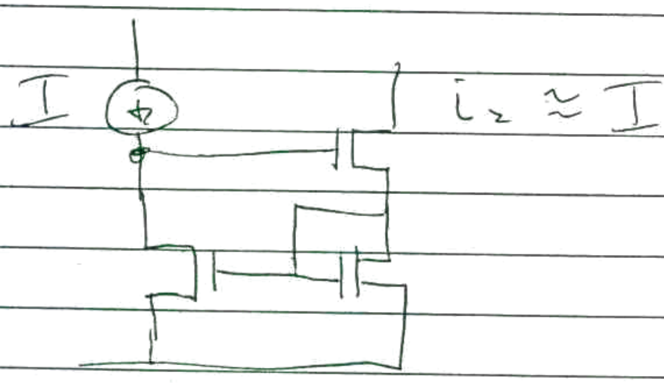



if R is VERY LARGE, $V' \approx V_T$

So $i_1 \approx \frac{V_{DD} - V_T}{R} \approx i_2$

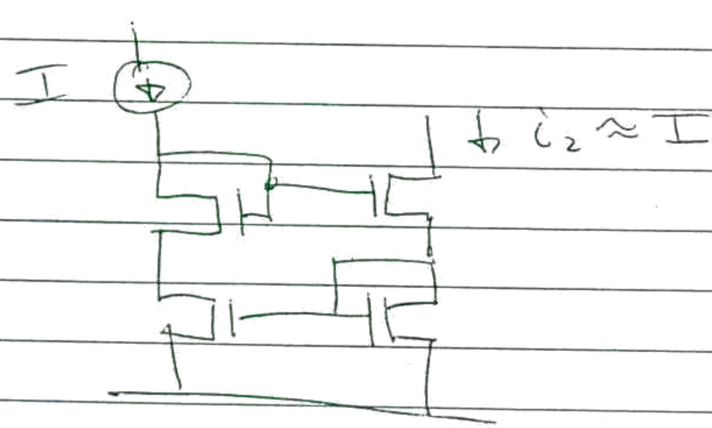
## Higher output impedance source

(Wilson Current Mirror)



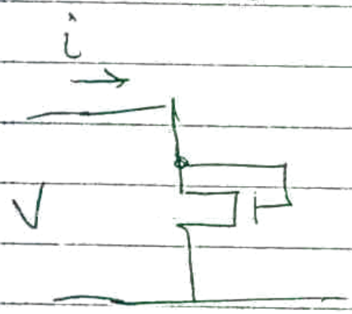

Disadvantage: output voltage must be higher to bias 2 devices in output.

## Even Better (Modified Wilson)



## Note

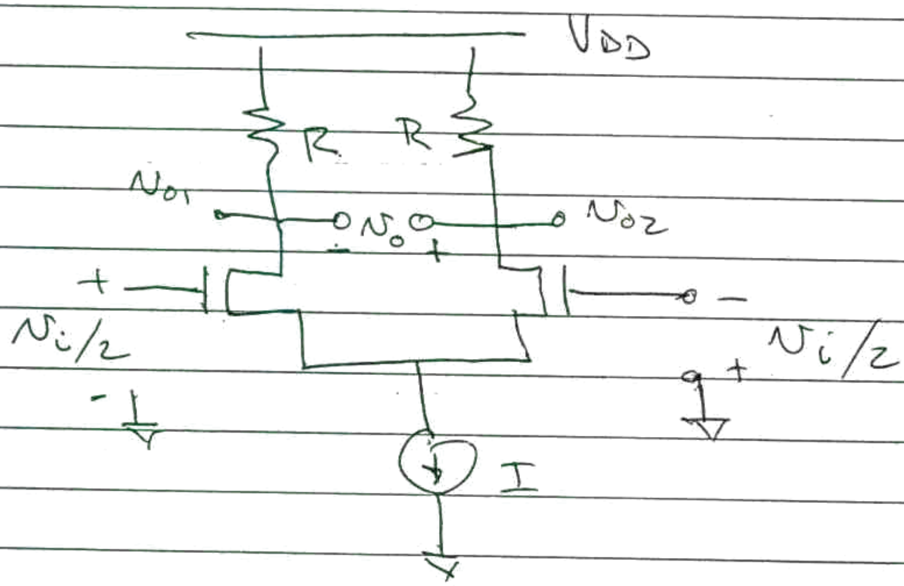
"Diode Connected" FET




Above $V_T$; $V > V_T$
FET is "ON" $(i > 0)$

Below $V_T$; $V < V_T$
FET is "OFF" $(i = 0)$

# Differential Amplifier




$v_{o1} = -g_m (R \| r_o) \frac{v_i}{2}$ $\quad r_o$ = FET OUTPUT RESISTANCE $= \frac{1}{\lambda i_D} = \frac{2}{\lambda I}$

$v_{o2} = -g_m (R \| r_o) \left(\frac{-v_i}{2}\right)$

$v_o = v_{o2} - v_{o1} = g_m (R \| r_o) v_i$

DIFFER. GAIN $= \frac{v_o}{v_i} = g_m (R \| r_o)$

Recall $g_m \approx \frac{W}{L} k_p (V_{gs} - V_T) = \sqrt{2 \frac{W}{L} k_p i_D}$

$= \frac{2 i_D}{V_{gs} - V_T}$

So

DIFF GAIN $\simeq \sqrt{\frac{W}{L} I k_p}\,(R \| r_o) = \frac{I (R \| r_o)}{V_{gs} - V_T}$

Since $r_o \approx \frac{2}{\lambda I}$

$$\text{Diff Gain} = \frac{v_o}{v_i} = \frac{I(R \| r_o)}{V_{gs} - V_T} = \frac{I\left(R \| \frac{2}{\lambda I}\right)}{V_{gs} - V_T}$$

Max Gain is $R \to \infty$, $R \| \frac{2}{\lambda I} \Rightarrow \frac{2}{\lambda I}$

$$\text{Max Gain} = \frac{2}{\lambda (V_{gs} - V_T)}$$

Similarly

$$\text{Diff Gain} = \sqrt{\frac{W}{L} k_p I}\,(R \| r_o) = \sqrt{\frac{W}{L} k_p I}\left(R \| \frac{2}{\lambda I}\right)$$

$$\text{Max Gain} \approx \sqrt{\frac{W}{L} k_p I}\left(\frac{2}{\lambda I}\right)$$

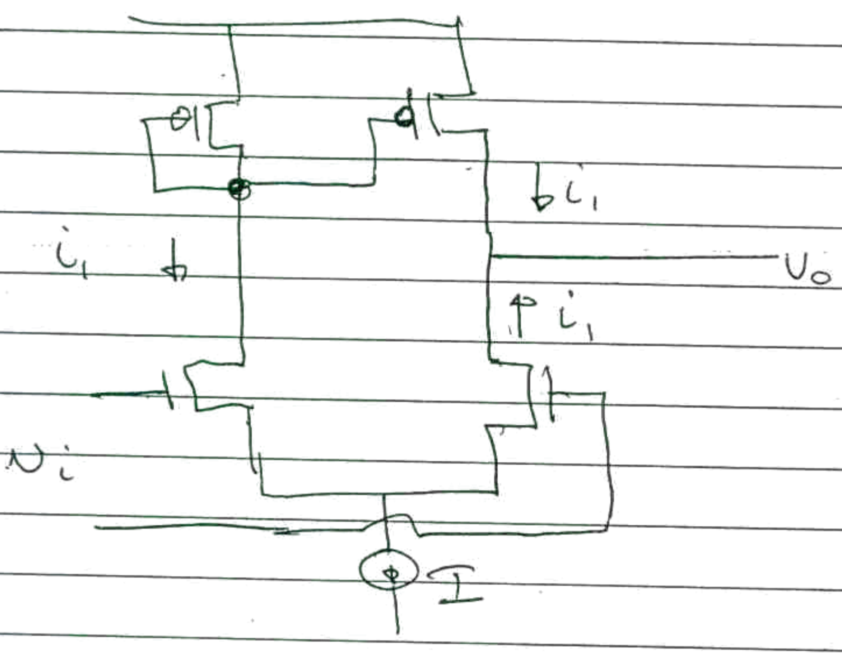
$$= \sqrt{4 \frac{W}{L} k_p \left(\frac{1}{I}\right)\left(\frac{1}{\lambda^2}\right)}$$

So Higher Gain:

- Increase $W/L$
- Reduce $I$

# Active Load





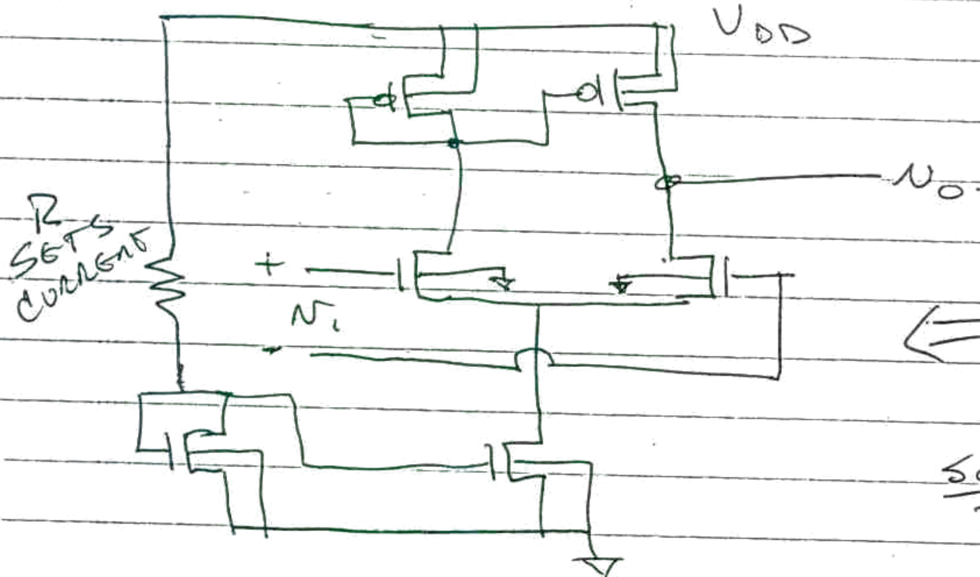

Current mirror drives $i_1$ down on right top so get 2x current.
However, get $\frac{1}{2}$ voltage since output here isn't differential (it is single-ended)
So these two effects cancel
Finally $R = r_o$ since it is replaced by the upper FET

So $\Rightarrow$ $\text{Gain} = \frac{v_o}{v_i} = g_m (r_o \| r_o) = g_m \frac{r_o}{2}$

$$= \frac{1}{\lambda(V_{GS}-V_T)} = \frac{1}{\lambda I}\sqrt{\frac{W}{L} k_p I}$$

$$= \sqrt{\frac{W}{L} k_p \left(\frac{1}{\lambda^2 I}\right)}$$

# Implementation




⟸ NFETS MUST HAVE BULK GROUNDED IN OUR PROCESS

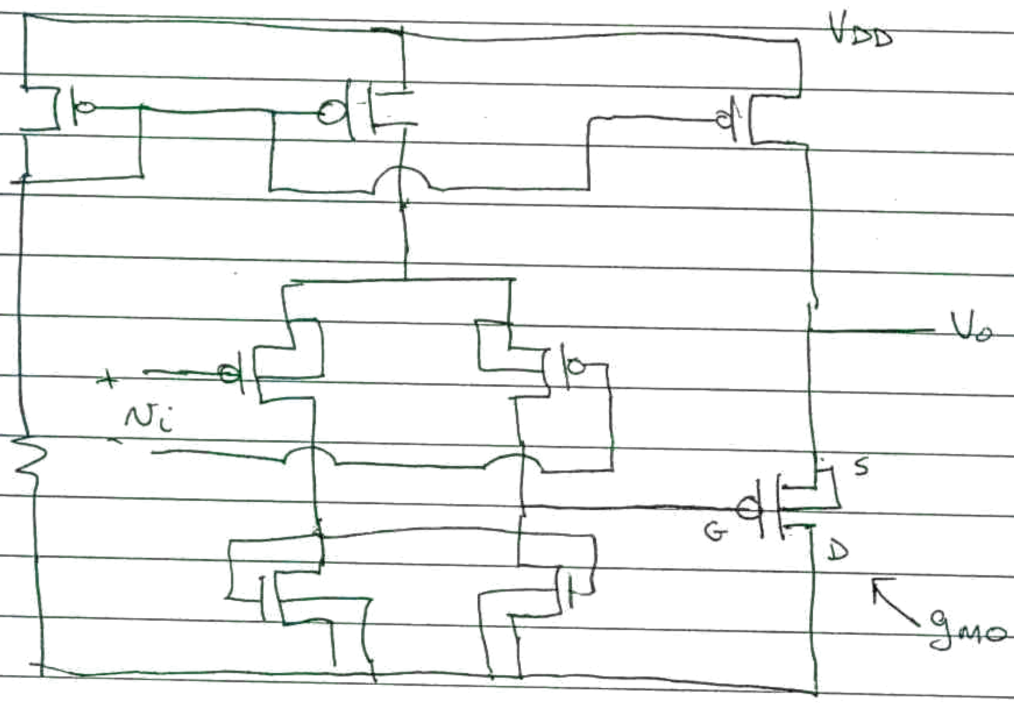
SO

BULK EFFECT ON $V_T$

# BETTER


All DEVICES BULK CONNECTED TO SOURCE.

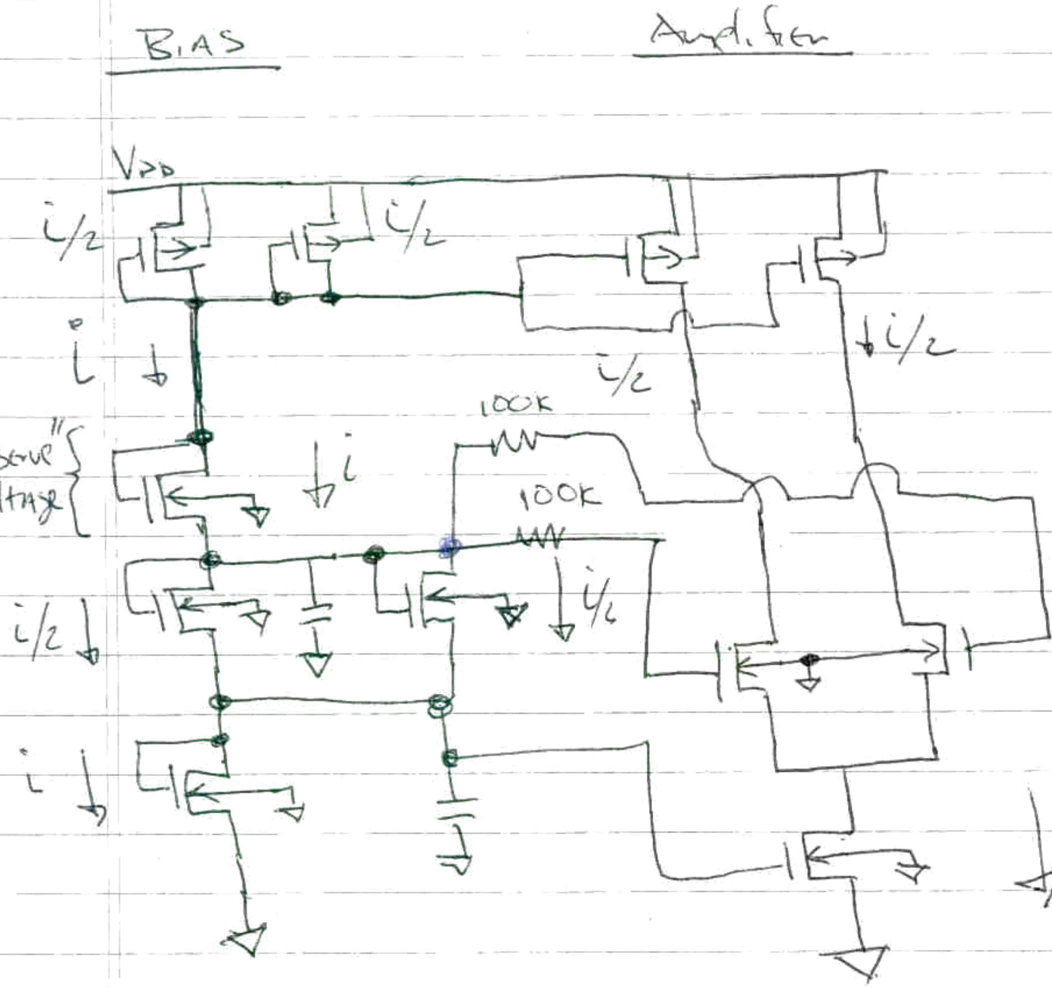
Finally
Add Source Follower w/active load




Source Follower
Gain ≈ 1
$R_{OUT} \approx \frac{1}{g_{mo}}$

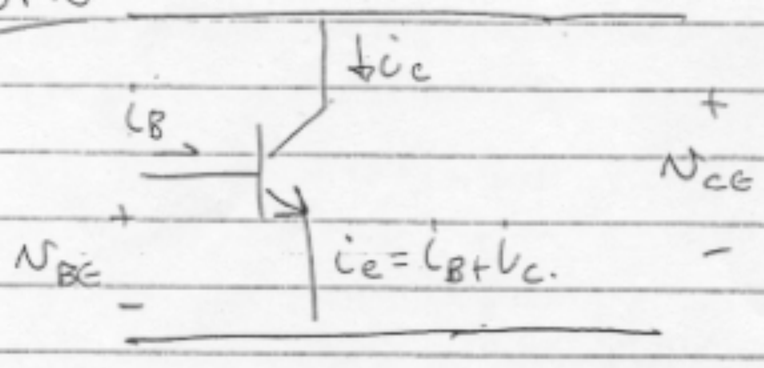
⇒ Lower Output Impedance
⇒ Larger Bandwidth.
(Driving Capacitance.)

# Simple Bias Scheme



# BJT

## NPN

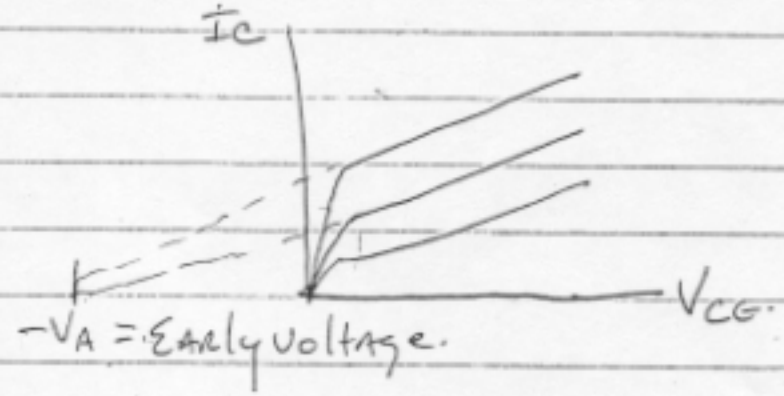



$$i_C = I_S e^{v_{BE}/V_T}\left(1 + \frac{v_{CE}}{V_A}\right); \quad V_T = \frac{kT}{q} = .025V$$

Also $i_C = \beta i_B = \alpha i_E \qquad \alpha = \dfrac{\beta}{\beta + 1}$

Typical $\quad \beta = 100 \quad I_S = 10^{-15}$ Amp.

In Normal Operation $\quad v_{BE} \simeq .7 V_{DC}$

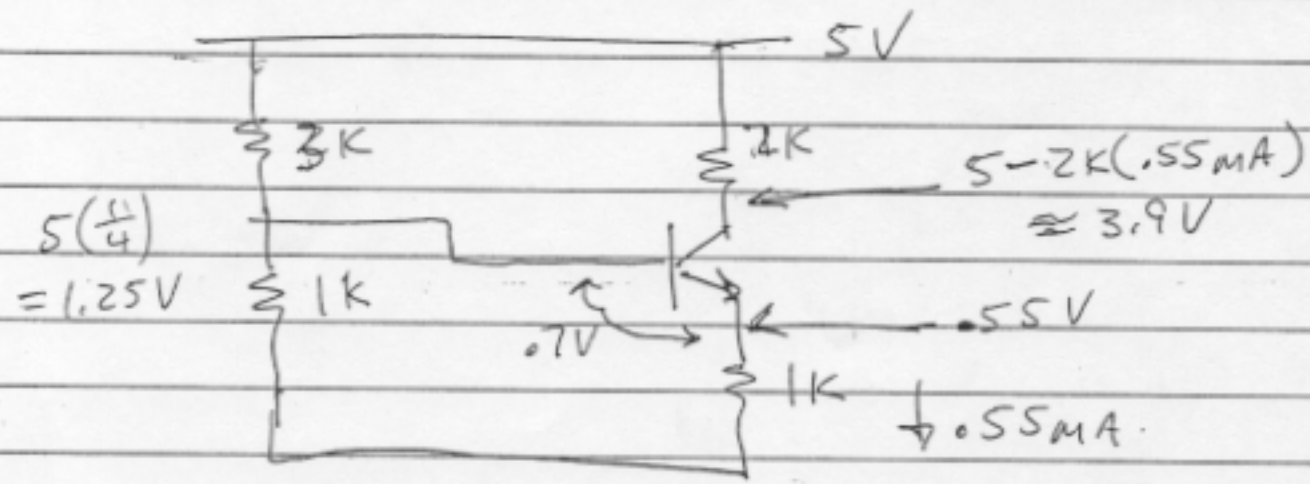



$$i_C = I_S e^{v_{BE}/V_T}\left(1 + \frac{v_{CE}}{V_A}\right)$$

$$r_o \approx \frac{V_A}{i_C}$$

# DC Analysis

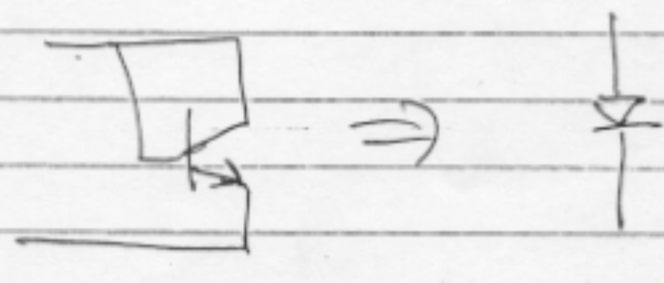




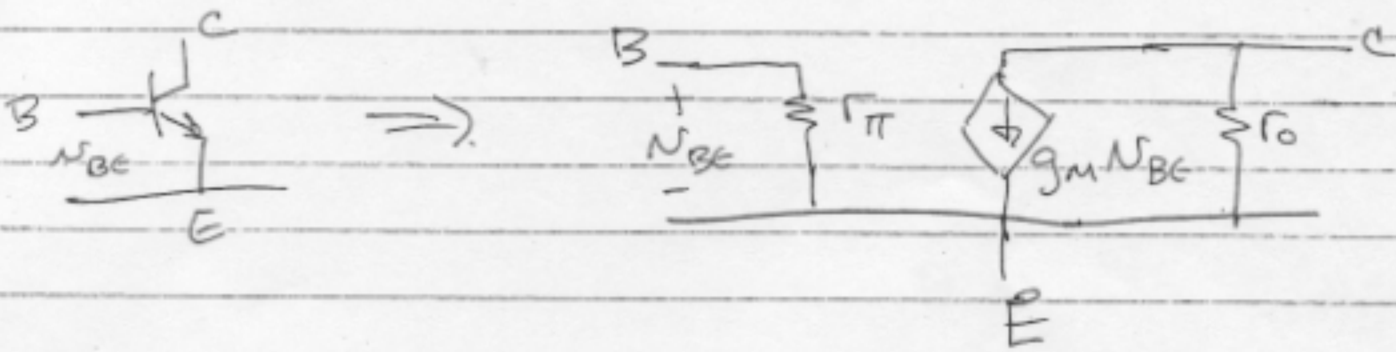

1. Find Base Voltage
2. Emitter = Base − .7V.
3. Find Emitter current
   = Emitter Voltage / Resistor Value.
4. Find Collector Voltage
   = 5V − (Collector Resistance)(Emitter Current)

# Diode Connected BJT

Usually



## Small Signal Model




$$g_m = \frac{di_c}{dv_{BE}} \approx \frac{\partial}{\partial v_{BE}} I_s e^{v_{BE}/V_T} = \frac{1}{V_T} I_s e^{v_{BE}/V_T}$$

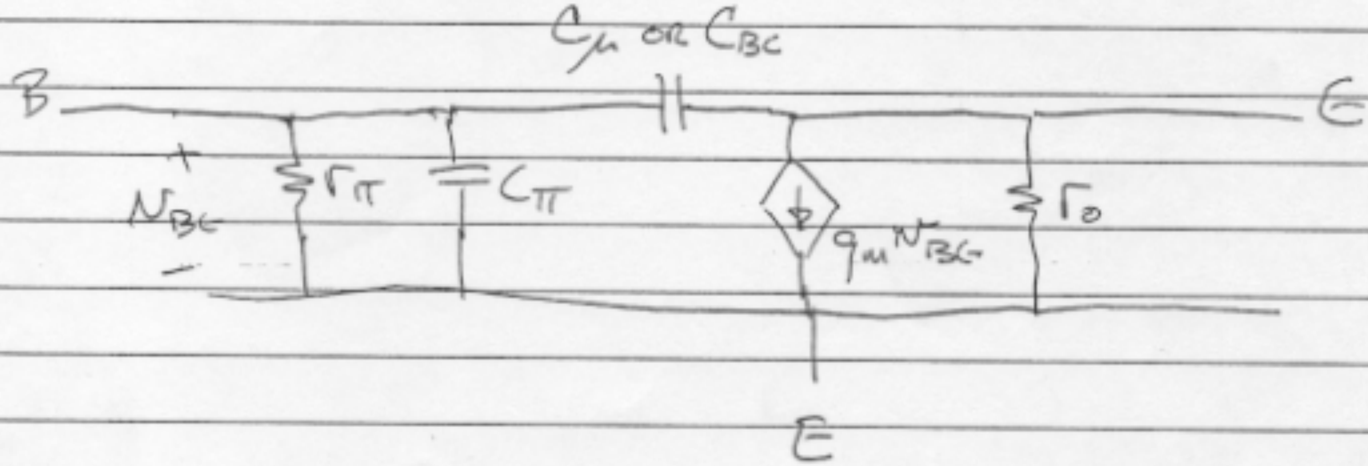
$$g_m \approx \frac{I_C}{V_T}$$ ← DC collector current

$$\frac{1}{r_\pi} = \frac{di_B}{dv_{BE}} = \frac{1}{\beta}\frac{di_c}{dv_{BE}} = g_m/\beta.$$

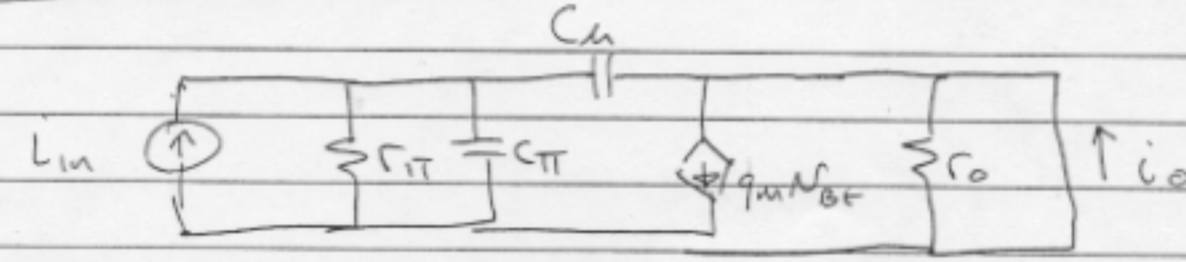
So $r_\pi = \beta/g_m$.

And $r_o = V_A/I_C$ as before

# BJT High Freq Model




## Figure of Merit




$$i_o = g_m v_{BE} = g_m\, i_{in}\left(r_\pi \,\|\, \left(\frac{1}{s(C_\pi + C_\mu)}\right)\right)$$

solve $\quad \dfrac{i_o}{i_{in}} = \dfrac{g_m r_\pi}{1 + s\, r_\pi (C_\pi + C_\mu)} \qquad \leftarrow = \beta / g_m$

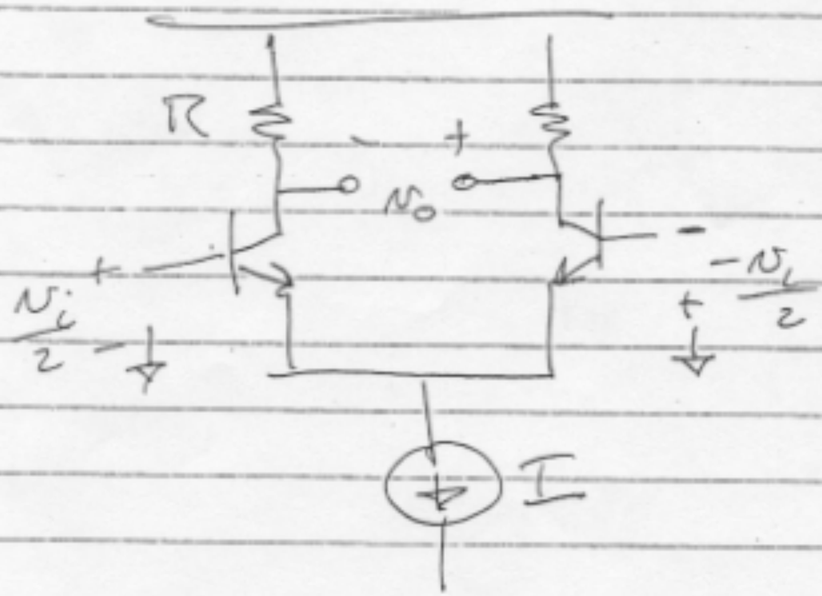
$$= \frac{\beta}{1 + s\, r_\pi (C_\pi + C_\mu)}$$

Unity current gain at (assuming $\beta >> 1$)

"Cutoff frequency" $\quad \omega_T = 2\pi f_T = \dfrac{\beta}{r_\pi (C_\pi + C_\mu)} = \dfrac{g_m}{C_\pi + C_\mu}$

$$= \frac{I_C / V_T}{C_\pi + C_\mu}$$

# BJT Differential Amp.



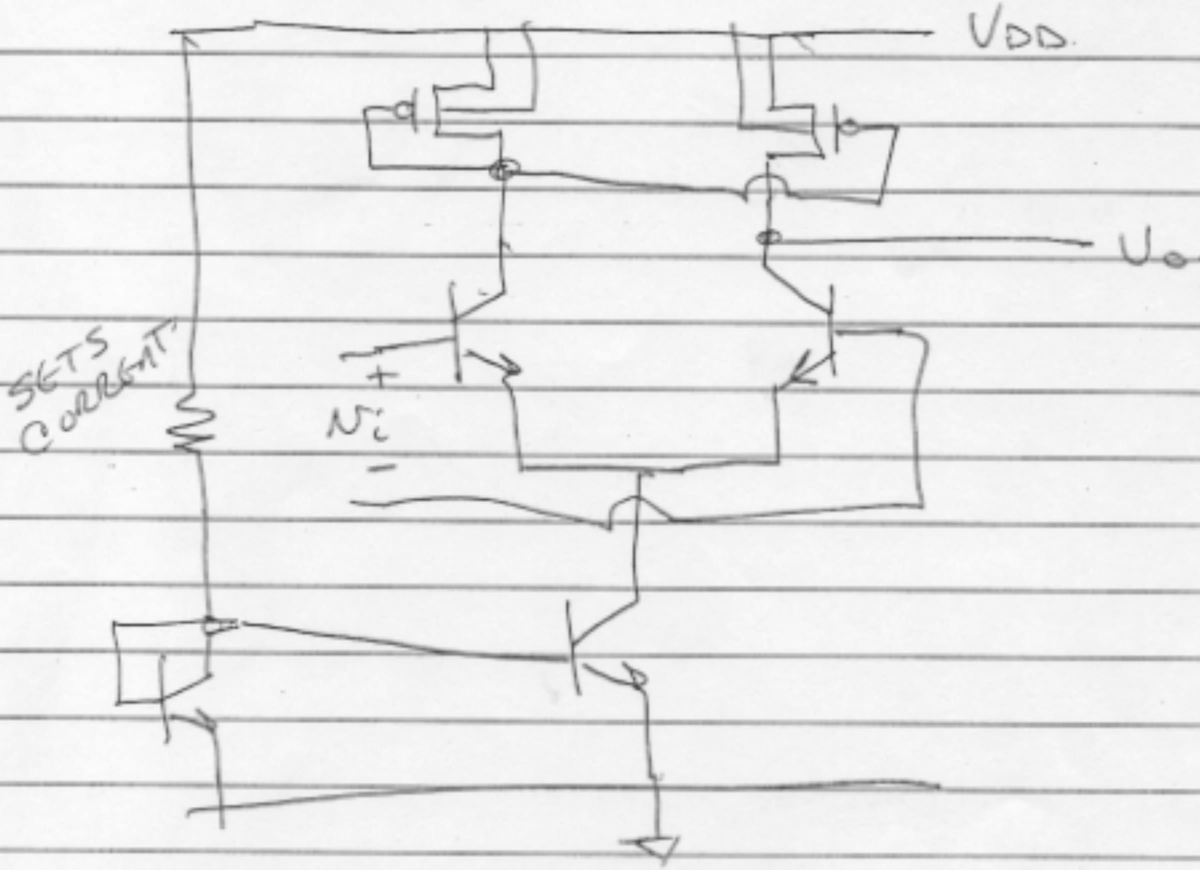

Same Analysis as FET

$$\text{DIFF GAIN} = \frac{v_o}{v_i} = g_m(R \| r_o)$$

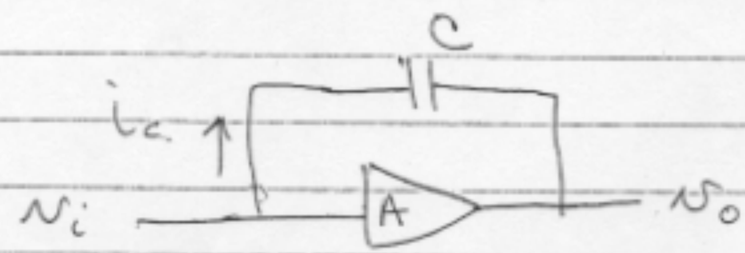
No BJT Active Load in our Process, since we dont have PNP Devices!

However, you can use a FET Active Load

BJT Diff Amp w/ Fet Active Load



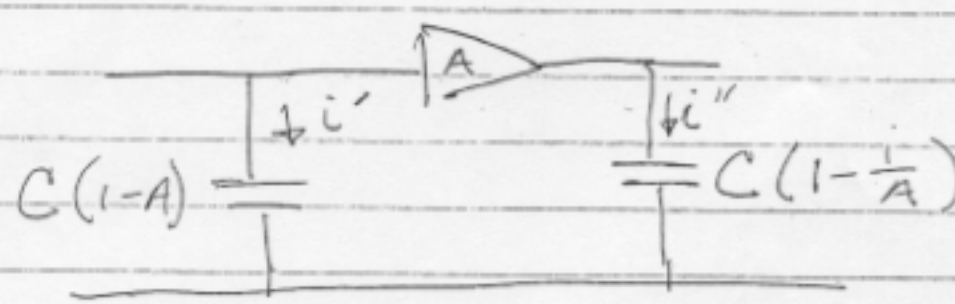
# Miller Effect




$v_o = A v_i$

$$i_c = \frac{v_i - v_o}{X_c} = \frac{v_i(1-A)}{X_c} = \frac{v_o\left(\frac{1}{A} - 1\right)}{X_c}$$

Same As.




Check

$$i' = \frac{v_i}{X_{CIN}} = \frac{v_i}{\frac{1}{j\omega C(1-A)}} = \frac{v_i(1-A)}{X_c} \quad \checkmark\checkmark$$

$$i'' = \frac{v_o}{\frac{1}{j\omega C(1-\frac{1}{A})}} = \frac{v_o(1-\frac{1}{A})}{X_c} \quad \checkmark\checkmark$$

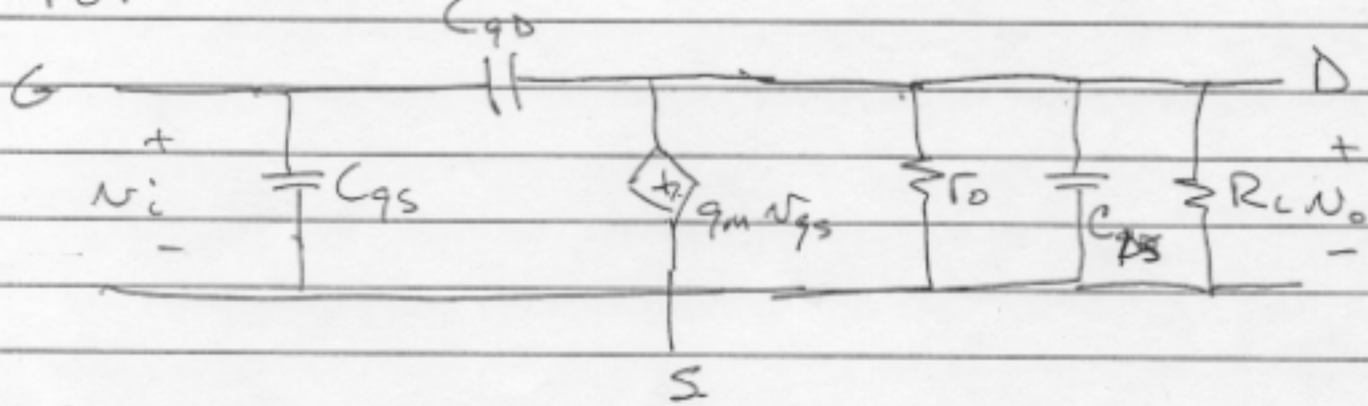
So same currents drained from both ports.

Note A is usually negative!!

# High Frequency Modeling

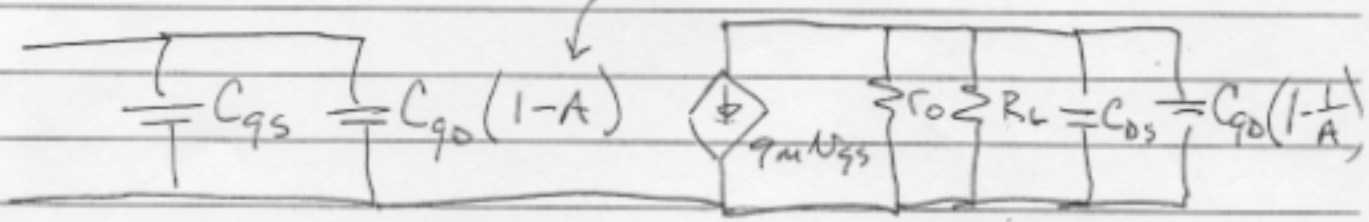
Common Source.

FET




Gain (ignoring $C_{gd}$) $= \frac{v_o}{v_i} = -g_m(r_o \| R_L) = A$

Then use Miller Effect.

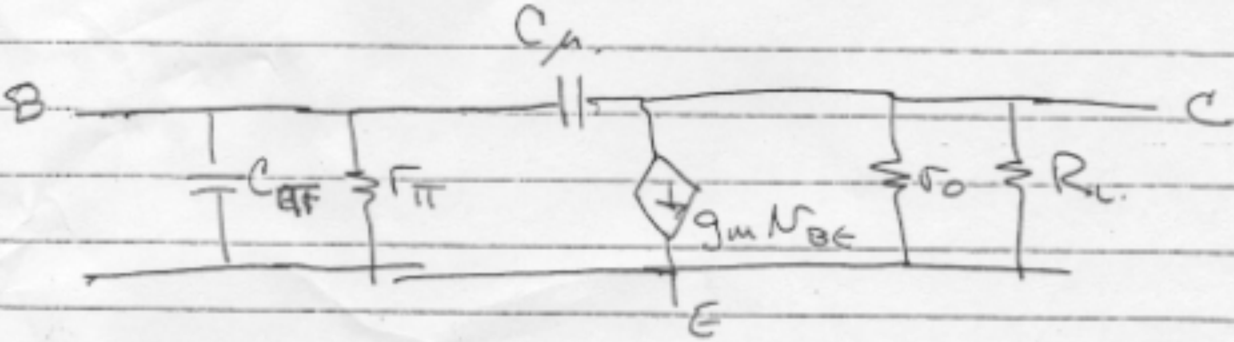



Simplifies analysis

Note for large gain A,
this leads to large capacitance

$\Rightarrow$ Multiplies $C_{gd}$ !!

# BJT High Freq.




Gain (without Caps) $\frac{v_o}{v_i} = -g_m (r_o \| R_L) = A$

Then use Miller Effect