DEVICES ✓

Lecture 23

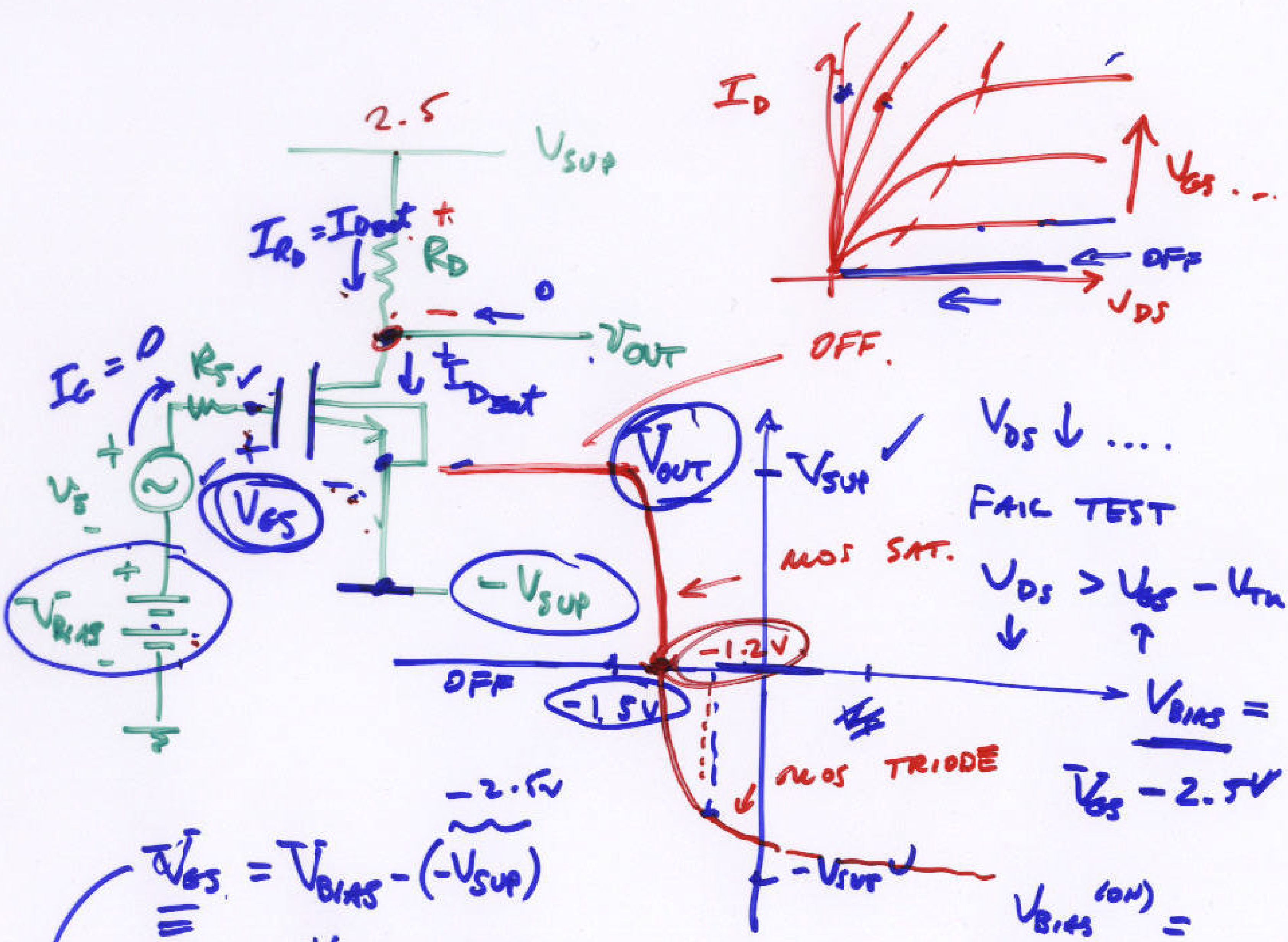
- Last time:
  - Introduction to amplifiers: a common-source MOS stage HARD WAY !

$v_{IN} = V_{BIAS} + v_s(t)$

$v_{OUT} = \underset{0V}{\cancel{V_{OUT}}} + v_{out}(t)$

- Today :
  - Small-signal model for the entire common-source amplifier
  - Limits to model

EASY WAY.



$V_{DS} \downarrow$ ....

FAIL TEST

$V_{DS} > V_{GS} - V_{TN}$

$\downarrow \quad \uparrow$

$V_{BIAS} =$

$V_{GS} - 2.5V$

$$V_{GS} = V_{BIAS} - (\overset{-2.5V}{-V_{SUP}})$$

$$= V_{BIAS} + 2.5V$$

$-1.2V.$

$1.3V$

$V_{BIAS}^{(ON)} =$

$V_{TN} - 2.5V =$

$1 - 2.5V = -1.5V$

Linearized Output Voltage

For this case, the total output voltage is

$$v_{OUT} \cong V_{SUP} - \underbrace{R_D I_D}_{\bar{V}_{SUP}}\left(1 + \frac{2v_s}{(V_{GS} - V_{Tn})}\right) = \cancel{V_{SUP}} - \cancel{V_{SUP}} - \frac{\overset{V_{SUP}}{2R_D I_D} v_s}{(V_{GS} - V_{Tn})}$$

The average output voltage $V_{OUT} = 0$ V so the total output voltage is the small-signal voltage in this special case:

$\bar{V}_{OUT} = 0V$

$$\boxed{v_{OUT}} = v_{out} = -\left[\frac{2R_D I_D}{(V_{GS} - V_{Tn})}\right] v_s = \boxed{-\left[\frac{2V_{SUP}}{(V_{GS} - V_{Tn})}\right]} v_s = \boxed{A_v v_s}$$

$+ \bar{V}_{OUT}$

$0V$

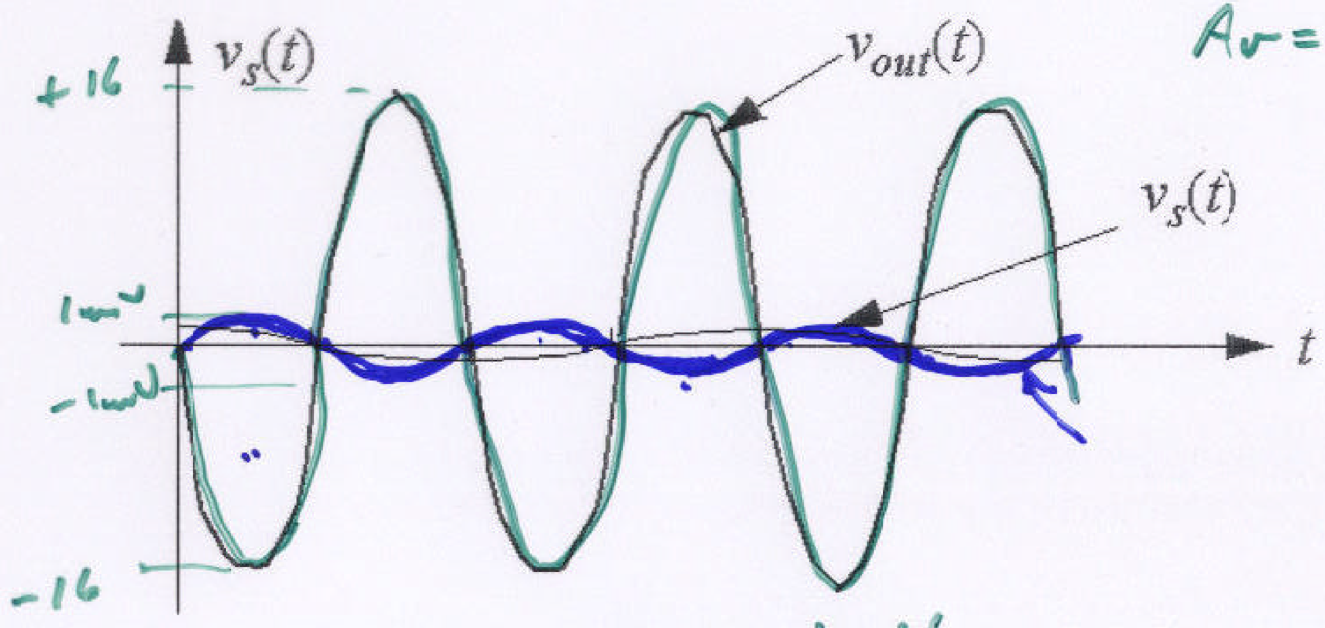
$$-\frac{2(2.5V)}{(0.3V)} \xrightarrow{} 5 \quad \approx -15.$$

A_v = voltage gain

Plot of Output Waveform

Numbers: $2\,I_D R_D\,/\,(V_{GS} - V_{Tn}) = (2 \text{ x } 2.5)\,/\,0.31 = 16.1$

$A_v = -16.1$



$v_s(t) = \hat{v}_s \sin \omega t$ ← 1 mV

Is there a Better Way?

→ What's missing: no inclusion of fudge factor term or of charge storage effects

$i_{D_{SAT}} = \ldots (1+\lambda_n v_{DS})$

EASY WAY → TOO MESSY !!

Approach 2. Do problem in two steps.

1. DC voltages and currents (ignore small signals sources): set bias point of the MOSFET ... we had to do this to pick V_{BIAS} already

BIAS

... DONE IT ...

CAPTAL CAPITAL V_{GS}

2. Substitute the small-signal model of the MOSFET and the small-signal models of the other circuit elements ...

NEW.

c) FIND/SET V_{OUT} ✓

d) FIND v_{out}

(e) PLOT $v_{OUT}(t)$ ← TOTAL

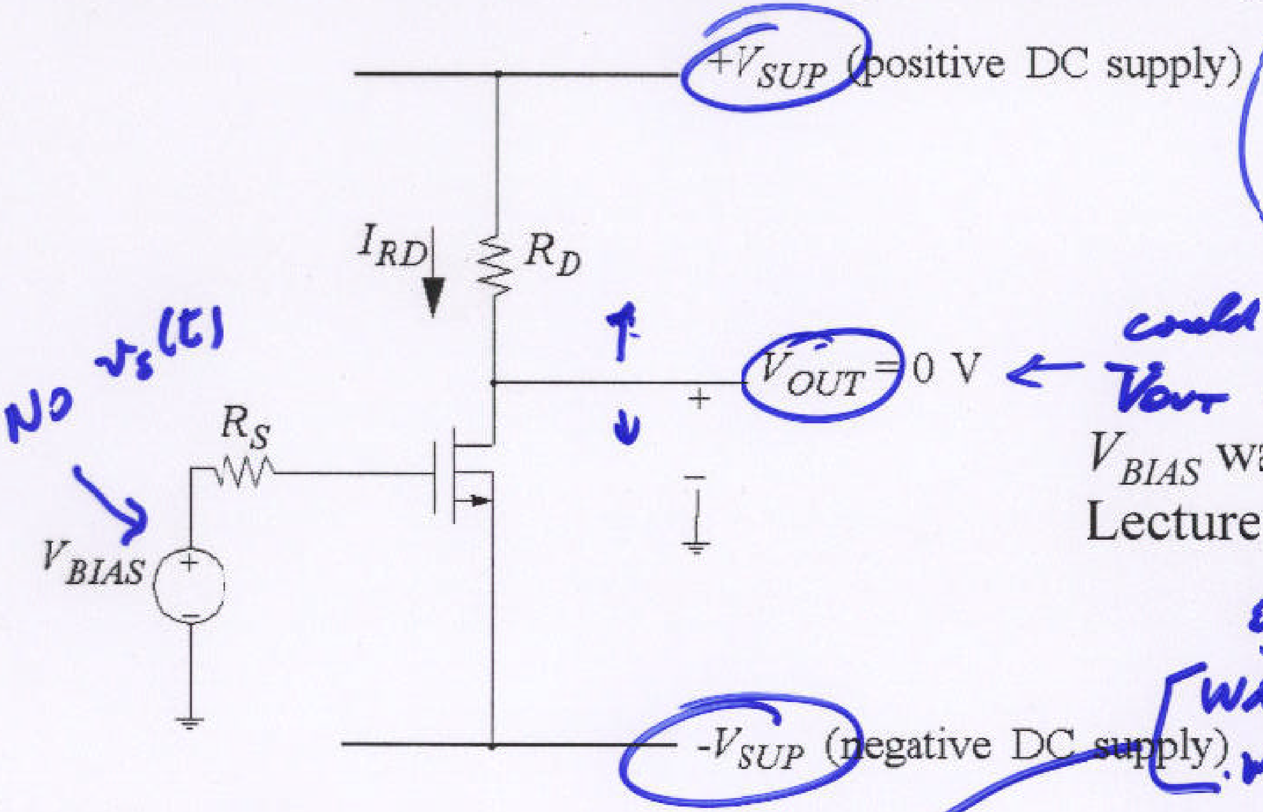
Small-Signal Analysis

↑ COMBINATION = SUM!!

Problem 1. Find DC Bias – ignore small-signal source

$v_{OUT} = V_{OUT} + v_{out}$

NO $v_s(t)$



could plot/sketch V_{OUT} vs. V_{BIAS}.

V_{BIAS} was found in Lecture 22

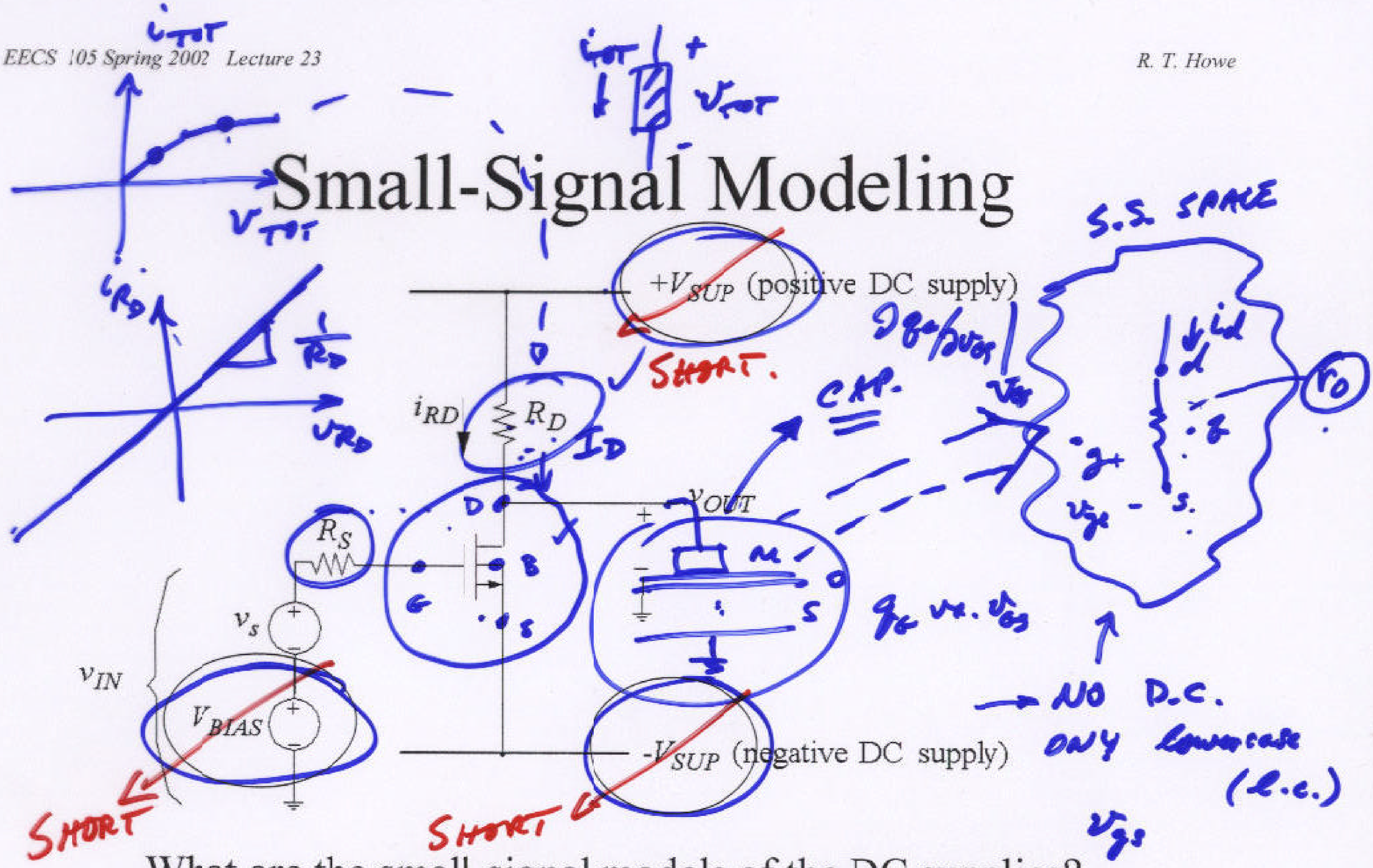
OVERKILL.

WANT MOS SAT

WANT 1/2 WAY BETWEEN "LIMITS"

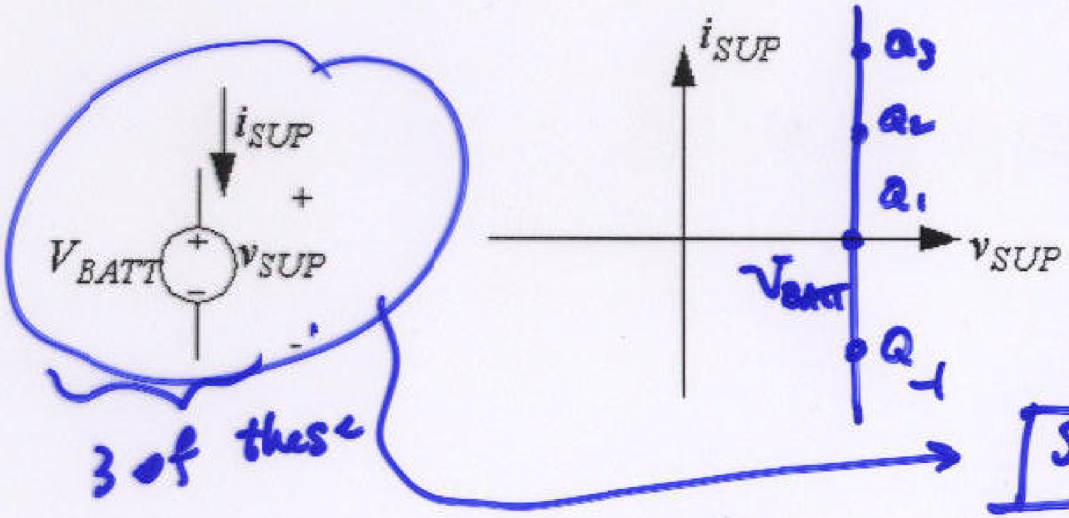
I_{DSAT} ✓ KNOW V_{OUT}.

Small-Signal Modeling



What are the small-signal models of the DC supplies?

Small-Signal Models of Ideal Supplies



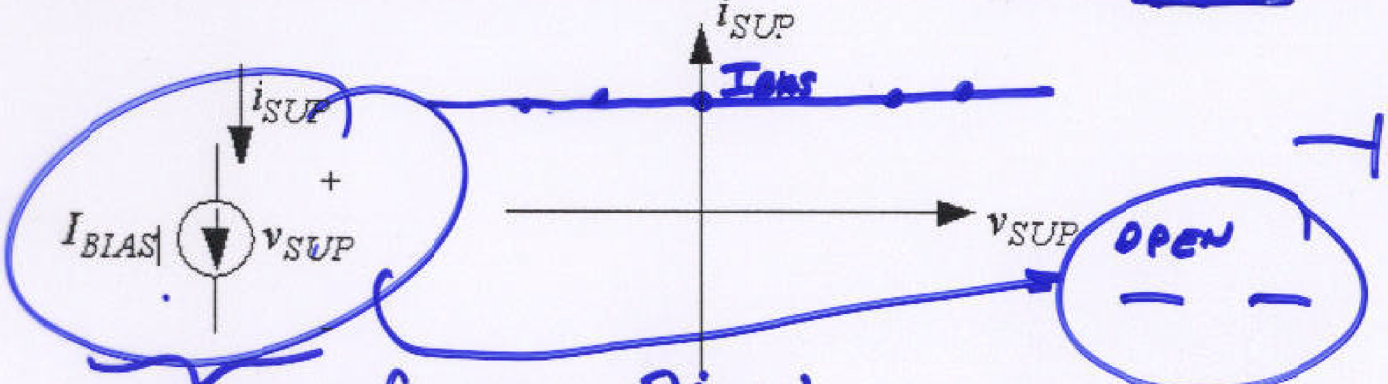
Small-signal model:

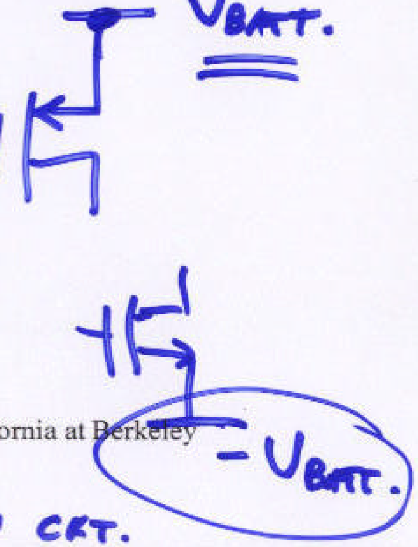
$$g_{batt} = \left.\frac{\partial i_{SUP}}{\partial v_{SUP}}\right|_Q = \infty$$

$$r_{batt} = 1/g_{batt} = 0\,\Omega$$

$\boxed{\text{SHORT CIRCUIT.}}$

SS.

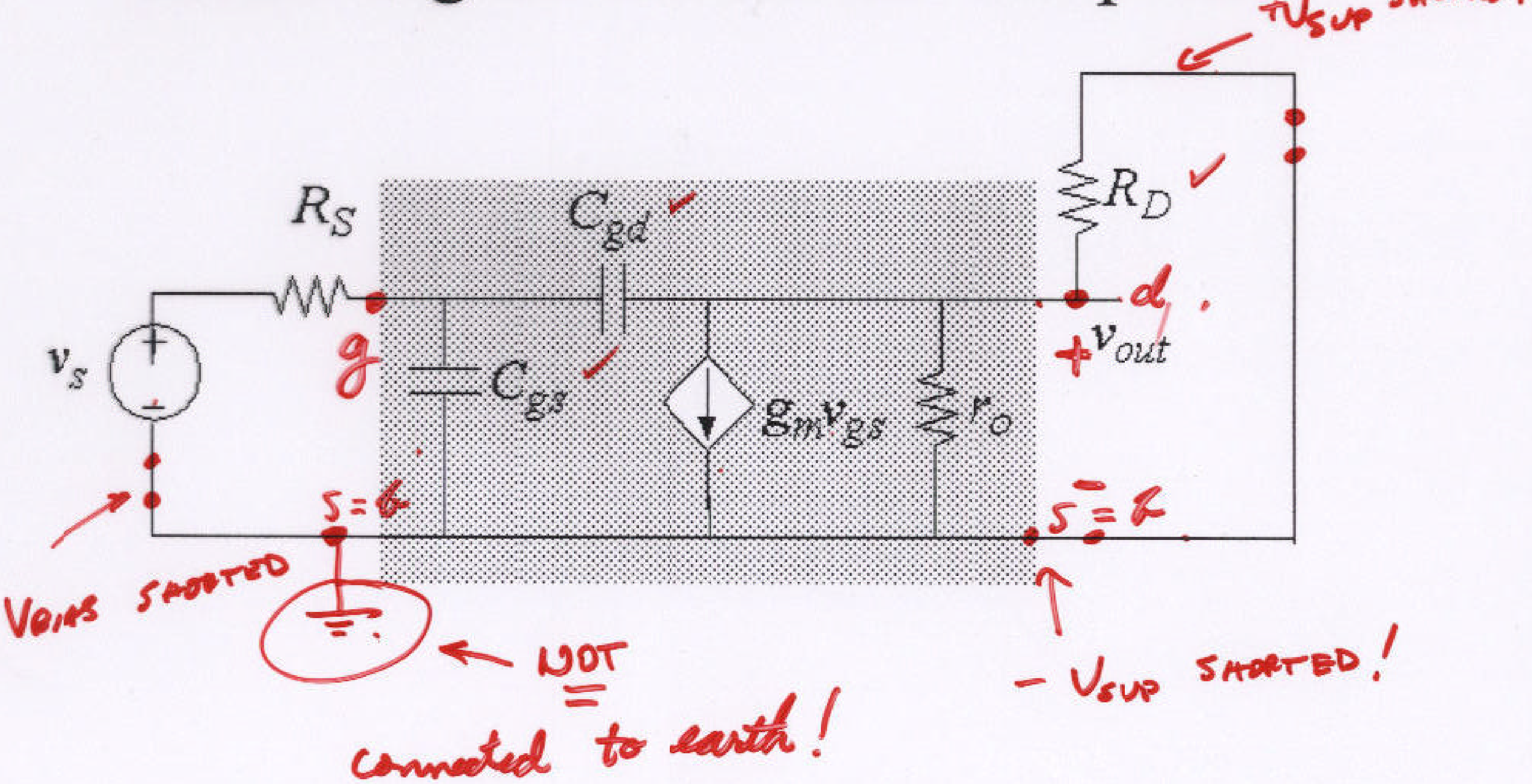




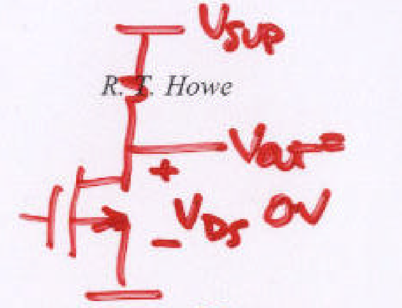
$$g_{sup} = \left.\frac{\partial i_{SUP}}{\partial v_{SUP}}\right|_Q = 0 \Rightarrow \boxed{r_{sup} = \infty}$$

OPEN CKT.

Small-Signal Circuit for Amplifier



$v_{out} = f(v_s)$

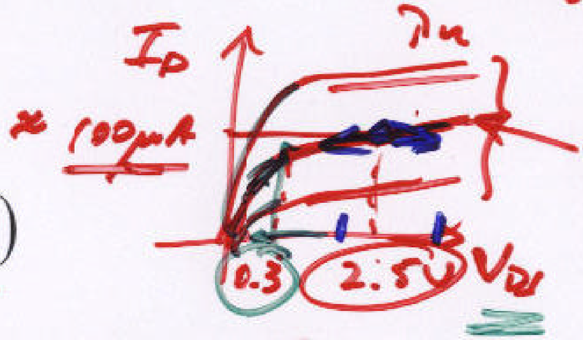


−V_SUP = −2.5V

Voltage Gain (Cont.)

Substitute transconductance:

$$A_v = \Big(\overbrace{-\frac{2I_{D,SAT}}{V_{GS}-V_{Tn}}}^{-g_m}\Big)\underline{(R_D \parallel r_o)}$$



V_GS = 1.3 V

FIT λ_n

Output resistance: typical value $\lambda_n = 0.05\ \mathrm{V}^{-1}$

$$r_o = \left(\frac{1}{\underline{\lambda_n}\,\underline{I_{D,SAT}}}\right) = \left(\frac{1}{\underset{\mathrm{V}^{-1}}{0.05}\cdot\underset{\leftarrow \mathrm{mA}}{0.1}}\right)\boxed{k\Omega} = \underline{200k\Omega}$$

$V_{DS} > V_{GS} - V_{Tn}$

$2.5V > 1.3 - 1$

$= 0.3V$

Voltage gain: $$A_v = -\underbrace{\left(\frac{2\cdot 0.1}{0.31}\right)}_{\underline{mS}}\underbrace{(25 \parallel \overset{r_o}{200})}_{\underline{k\Omega}} = \boxed{-14.3}$$

HARD / LONG WAY

$$\boxed{A_v = -g_m \underline{R_D}}$$

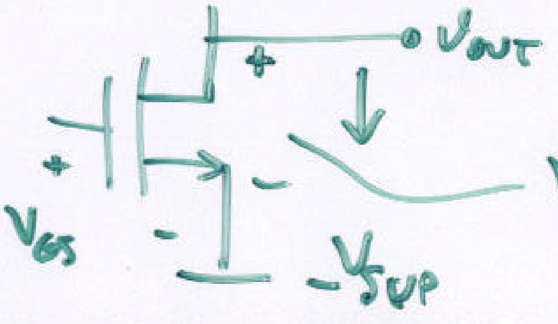
What Limits the Output Amplitude?

✓ 1. $v_{OUT}(t)$ reaches V_{SUP} or $-V_{SUP}$ … or

2. MOSFET leaves constant-current region and enters triode region

$$\underline{V_{DS}} \le V_{DS,SAT} = \underline{\overset{1.31V}{\cancel{V}_{GS}} - \overset{1}{\cancel{V}_{Tn}}} = \boxed{0.31V}$$

$$v_{OUT,MIN} = -V_{SUP} + V_{DS,SAT} = \underline{-2.5V} + 0.31V$$



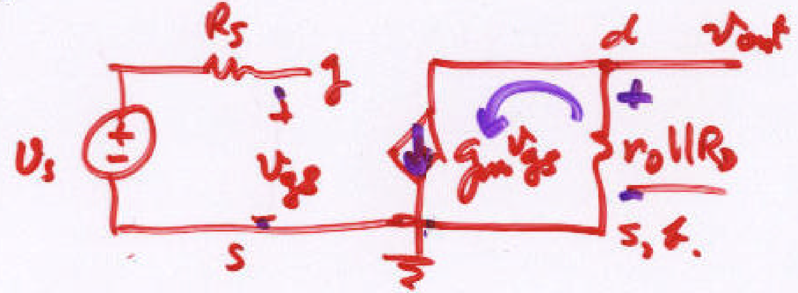
$V_{DS} \lesssim V_{DS,SAT}$.

Low-Frequency Voltage Gain

Consider first ω → 0 case … capacitors are open-circuits

$$v_{out} = -g_m v_s (R_D || r_o)$$

$$\boxed{A_v = -g_m (R_D || r_o)}$$



$v_{gs} = v_s$.

Transconductance

$$g_m \cong \mu_n C_{ox} (W/L)(V_{GS} - V_{Tn}) = \frac{2 I_{D,SAT}}{V_{GS} - V_{Tn}}$$

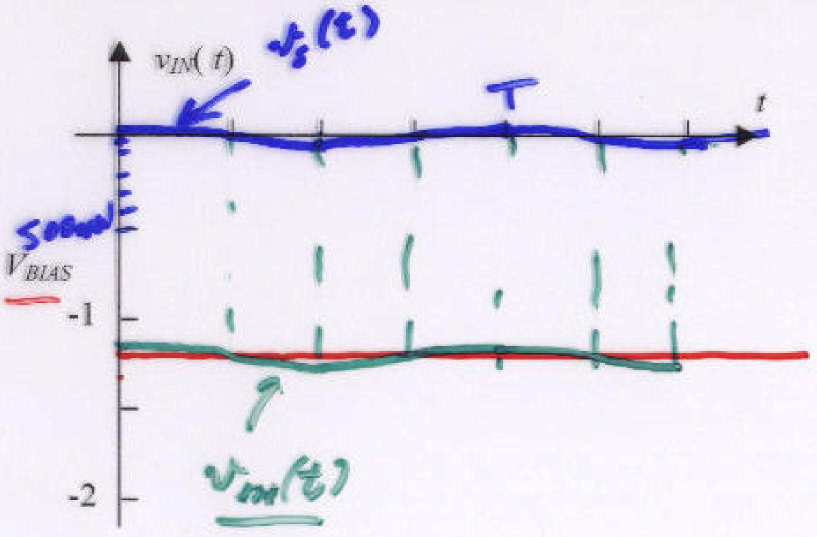
$$= \left.\frac{\partial i_{DSAT}}{\partial v_{GS}}\right|_Q \leftarrow \text{IGNORE } (1 + \lambda_n V_{DS})$$

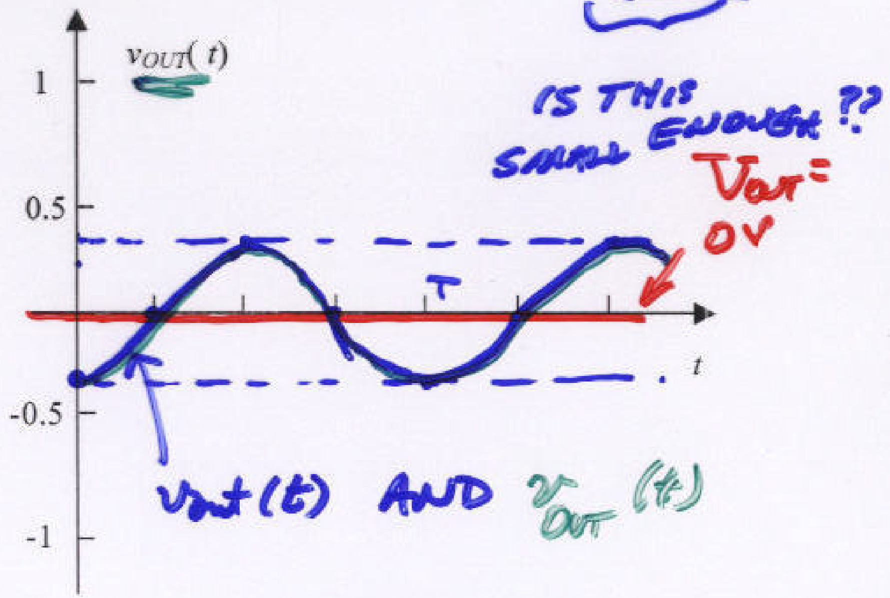
Input and Output Waveforms

$v_s(t) = 25 \text{ mV} \underline{\cos \omega t}$ ↑ $2\pi/T$

Input small-signal voltage amplitude: 25 mV

Output small-signal voltage amplitude: 14 x 25 mV = $\underbrace{350}$





$V_{GS} = 1.3 = \underbrace{V_{BIAS}}_{-1.2V} + \underbrace{2.5V}_{-(-V_{SUP})}$

$v_{out} \cong (-14)\, v_s$

$= \underbrace{(-350 \text{mV})}_{-0.35} \cos \omega t$

Maximum Output Amplitude

$$v_{s\,max} = \frac{v_{out\,max}}{|A_v|}$$

$v_{out}(t) = \underline{-2.19}$ V $\cos(\omega t) \rightarrow v_s(t) = \underline{153}$ mV $\cos(\omega t)$

How accurate is the small-signal (linear) model?

$\ll 1.$

LAST TIME

$$\left\{ \frac{v_s}{V_{GS}-V_{Tn}} = \frac{0.15}{0.31} \approx \underline{0.5} \right.$$

Significant error in neglecting third term in expansion of $i_D = i_D(v_{GS})$