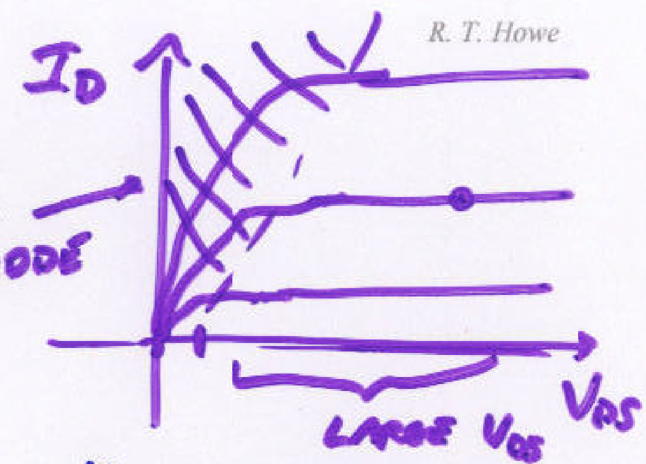
LAB 4 REPORT IS DUE AT BEGINNING OF YOUR LAB SECTION!

# Lecture 15

TRIODE




- Last time:
  - Square-law MOSFET model
  - Linear MOSFET model .

"PASS ZERO"

$$\boxed{I_D = -W Q_N(y)\, \underbrace{v_{dr}(y)}_{}}$$

CRUDE AVERAGES... GOT USEFUL RESULTS

- Today :
  - MOSFET small-signal model: three (four) terminal device → complicated!

$$i_D = f(\boxed{\underline{v_{GS},\ v_{DS}}},\ v_{BS})$$

NEXT TIME.

KNOW WHICH REGION YOU'RE OP. IN.

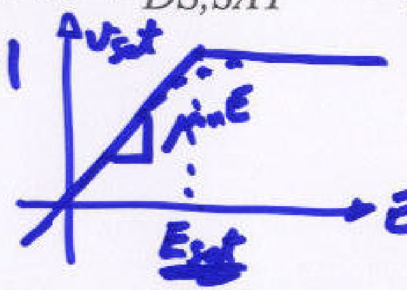
$$q_G = f(v_{GB})$$

C

# Linear MOSFET Model

- Channel (inversion) charge: neglect reduction at drain

Velocity saturation defines $V_{DS,SAT} = \overline{E_{sat}} L = \text{constant}$




$- v_{sat} / \mu_n$

source

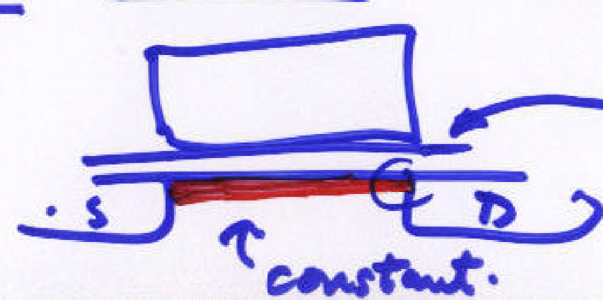
Drain current: vsat

EE 231

$$\boxed{I_{D,SAT} = -W v Q_N} = -W(v_{sat})[\underline{-C_{ox}(V_{GS} - V_{Tn})}],$$

VDS small.

$|E_{sat}| = 10^4$ V/cm, $L = 0.12$ μm → $V_{DS,SAT} = 0.12$ V!



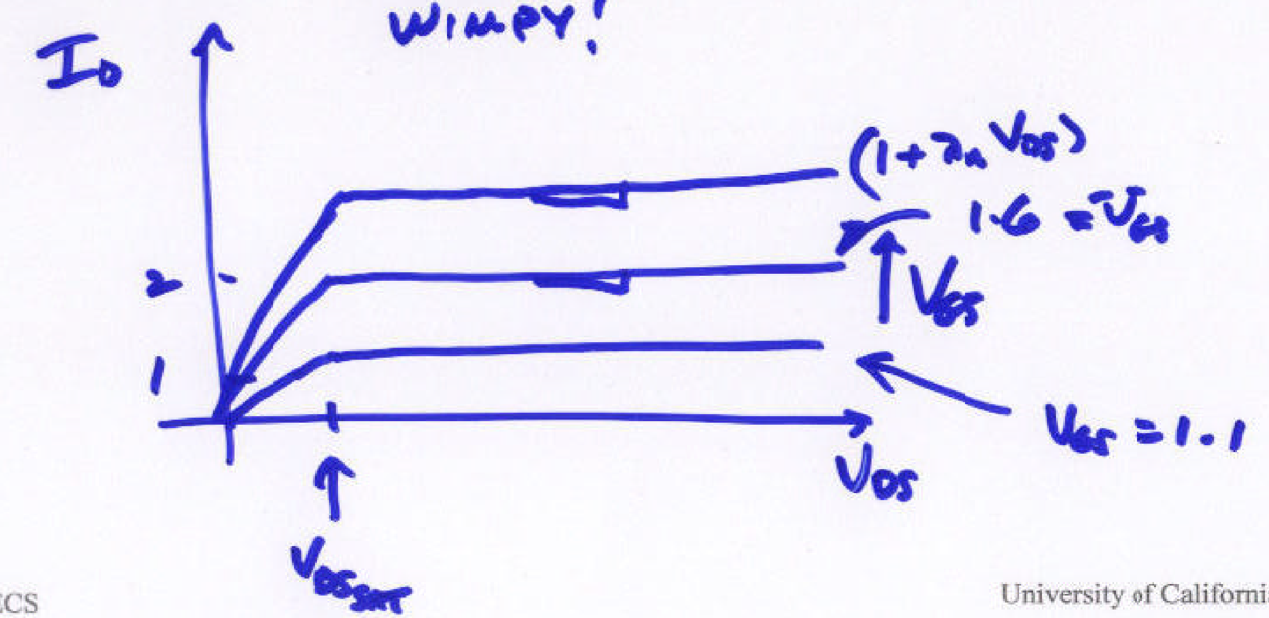
# Linear MOSFET in Saturation

0.6V

$$I_{D,SAT} = v_{sat} W C_{ox} (V_{GS} - V_{Tn}) \underbrace{(1 + \lambda_n V_{DS})}_{\text{FUDGE FACTOR}}$$

Implication of weaker dependence on $V_{GS}$:

WIMPY!



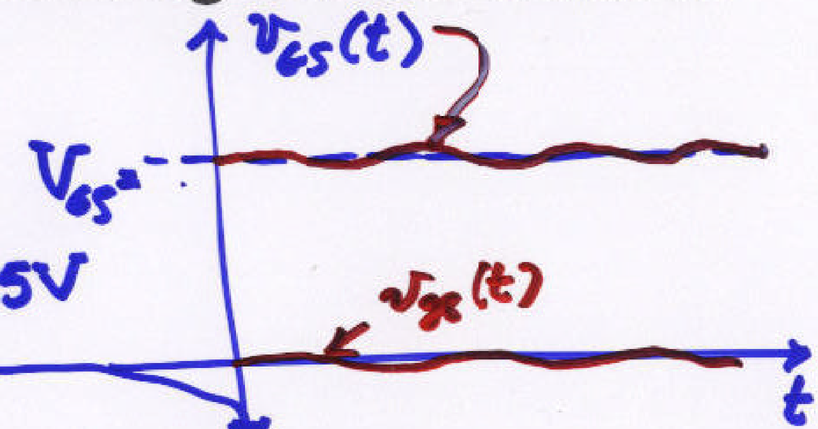
ASSUME OK. $I_D = f(V_{GS}, V_{DS}) \rightarrow i_D(t) = f(v_{GS}(t), v_{DS}(t))$

# Why Find an Incremental Model?

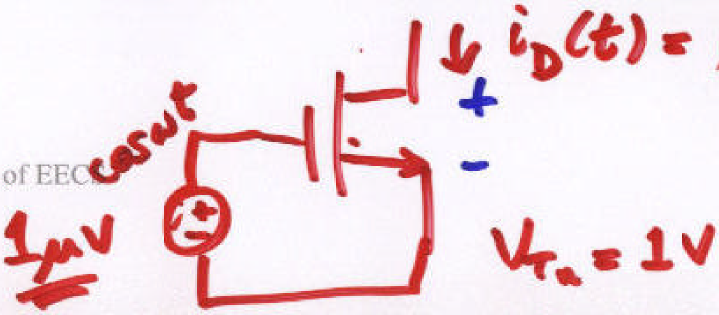
- Signals of interest in analog ICs are often of the form:

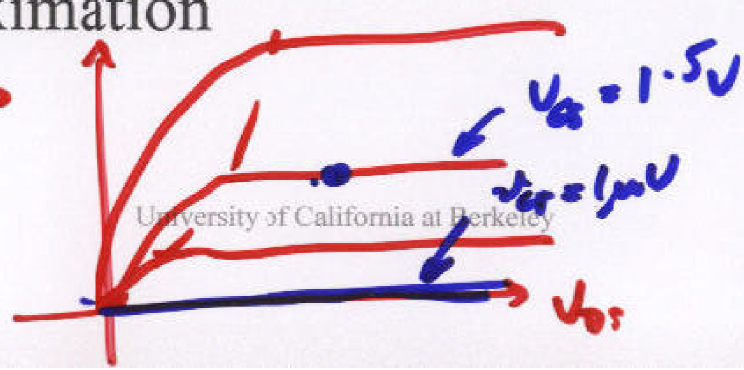
$$\boxed{v_{GS}(t) = V_{GS} + v_{gs}(t)}$$

SET UP THE MOSFET




Direct substitution into $i_D = f(v_{GS}, v_{DS})$ is tedious AND doesn't include charge-storage effects … pretty rough approximation

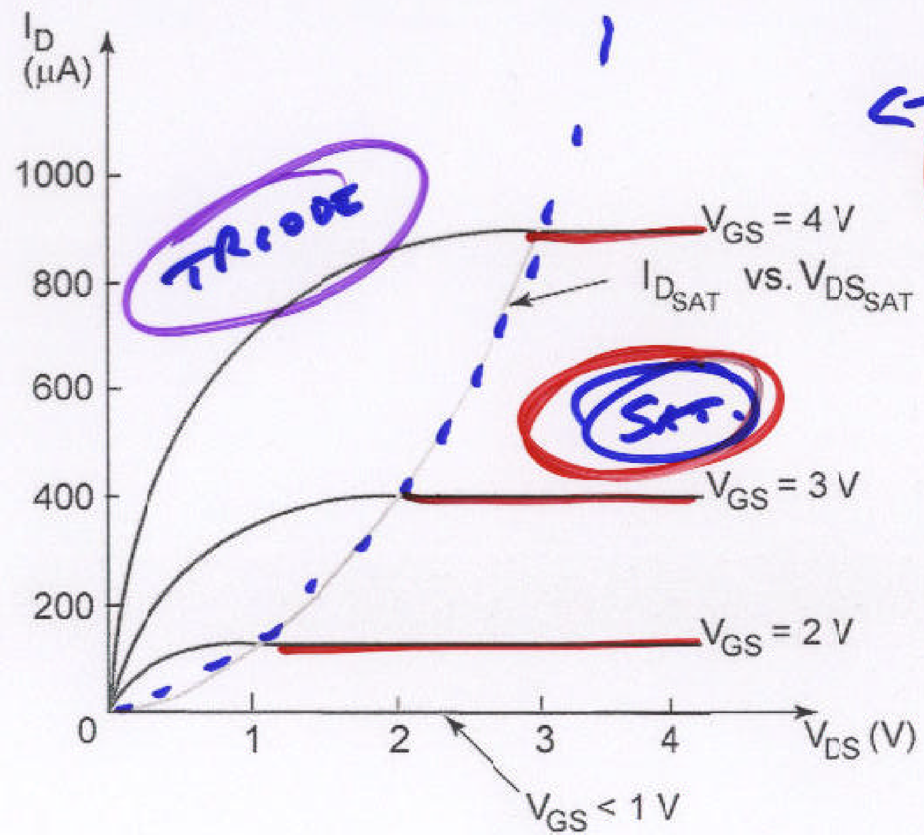


WHICH MODEL

# Which Operating Region?

USEFUL




SQUARE LAW.

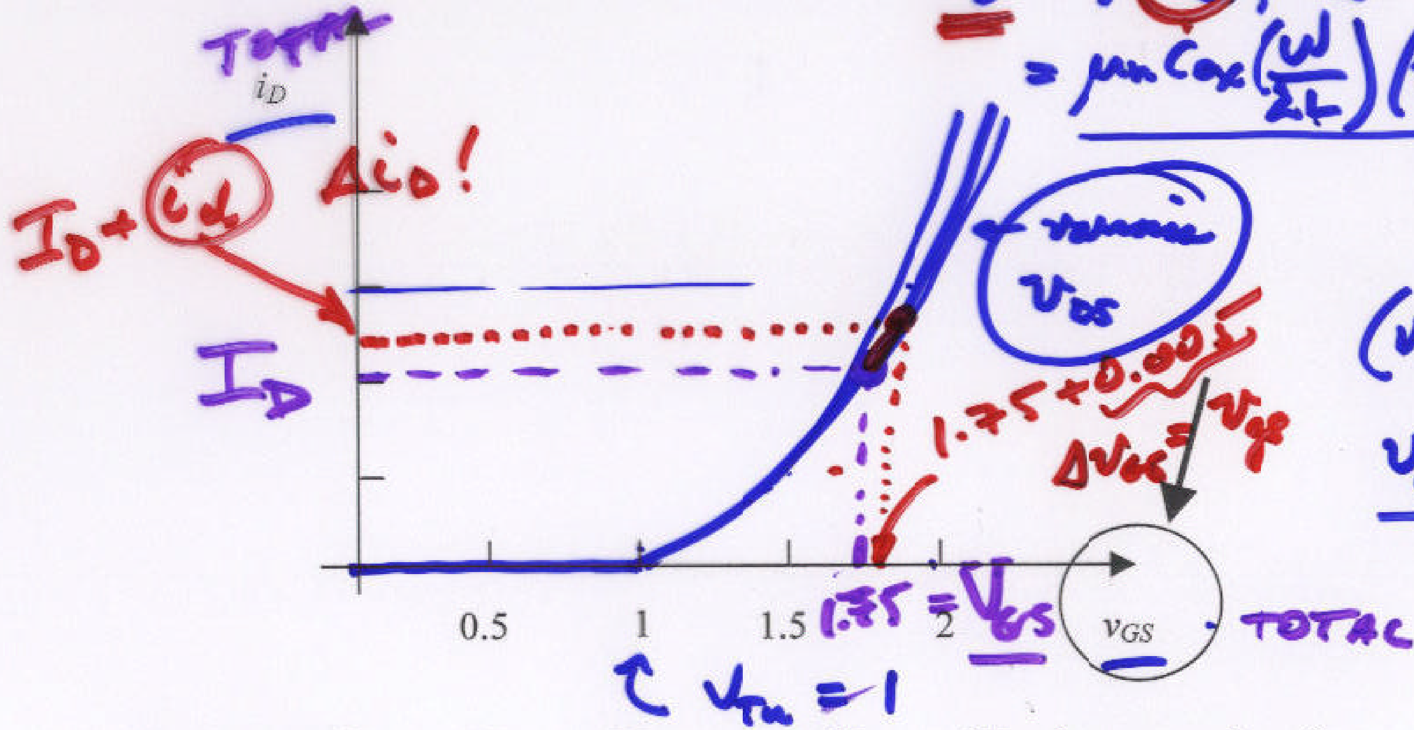
$\frac{d}{d()}$ $\frac{\partial}{\partial()}$

# Changing One Variable at a Time

$i_D = f(v_{GS}, v_{DS})$

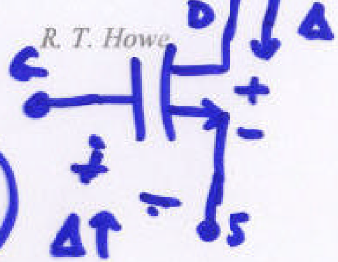
$= \mu_n C_{ox}\left(\frac{W}{2L}\right)(v_{GS} - V_{Tn})^2 \cdot (1 + \lambda_n v_{DS})$

$(v_{DS} \geq V_{DS,SAT},\ v_{GS} \geq V_{Tn})$




Assumption: $V_{DS} > V_{DS,SAT} = V_{GS} - V_{Tn}$ (square law)

R. T. Howe




# The *Transconductance* $g_m$

Defined as the change in drain current due to a change in the *gate-source* voltage, with *everything else constant*.

$$g_m = \left.\frac{\Delta i_D}{\Delta v_{GS}}\right|_{\boxed{V_{GS},V_{DS}}} = \left.\frac{\partial i_D}{\partial v_{GS}}\right|_{V_{GS},V_{DS}} = \left(\frac{W}{\cancel{2}L}\right)\mu_n C_{ox}\cdot\cancel{2}\,(V_{GS}-V_{Tn})(1+\lambda V_{DS})$$

BIAS POINT

1.75V 3V

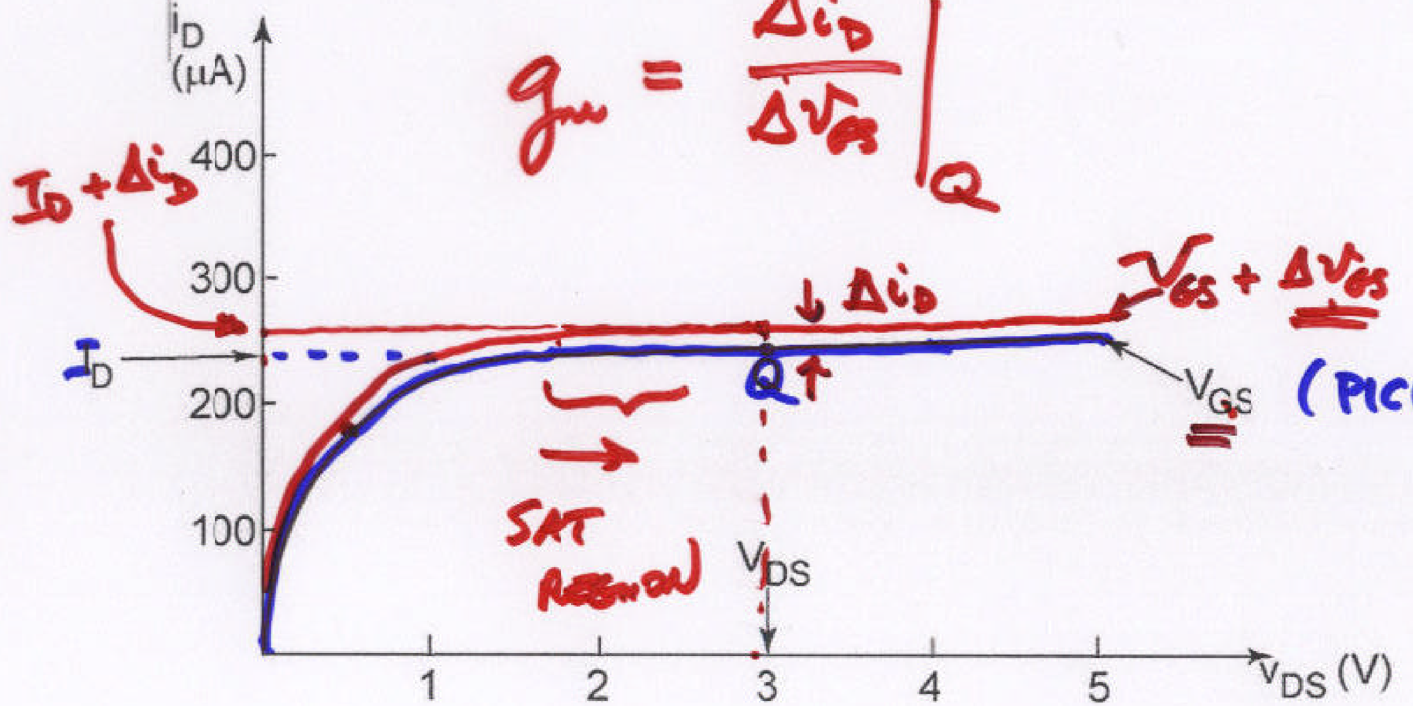
Square-law: MOSFET saturation region

$$i_D = (W/2L)\mu_n C_{ox}(v_{GS}-V_{Tn})^2(1+\lambda_n v_{DS})$$

$\rightarrow g_m = \mu_n C_{ox}(W/L)(V_{GS}-V_{Tn})(1+\lambda_n V_{DS})$

# Another Way to Find $g_m$ (LAB 5)

$$g_m = \left.\frac{\Delta i_D}{\Delta v_{GS}}\right|_Q$$




$Q = (V_{GS}, V_{DS})$

# Evaluating $g_m$

Square-law characteristic: H&S 1st Edition

$$g_m = \mu_n C_{ox}(W/L)(V_{GS} - V_{Tn})\underbrace{(1 + \lambda_n V_{DS})}_{\approx 1}$$

$$= \mu_n C_{ox}(W/L)(V_{GS} - V_{Tn})$$

$$\boxed{g_m = \sqrt{I_D \cdot 2 \mu_n C_{ox}(W/L)}} \propto \sqrt{I_D}.$$

WE NEED A SIMPLER EXPRESSION

Linear characteristic: better for submicron CMOS

$$i_{D,SAT} = v_{sat} W C_{ox}(v_{GS} - V_{Tn})\overset{1}{}(1 + \lambda_n v_{DS})$$

$\mu_n C_{ox} = 100\ \mu A/V^2$

$(W/L) = \cancel{100}\ 50$

$I_D = 100\ \mu A$

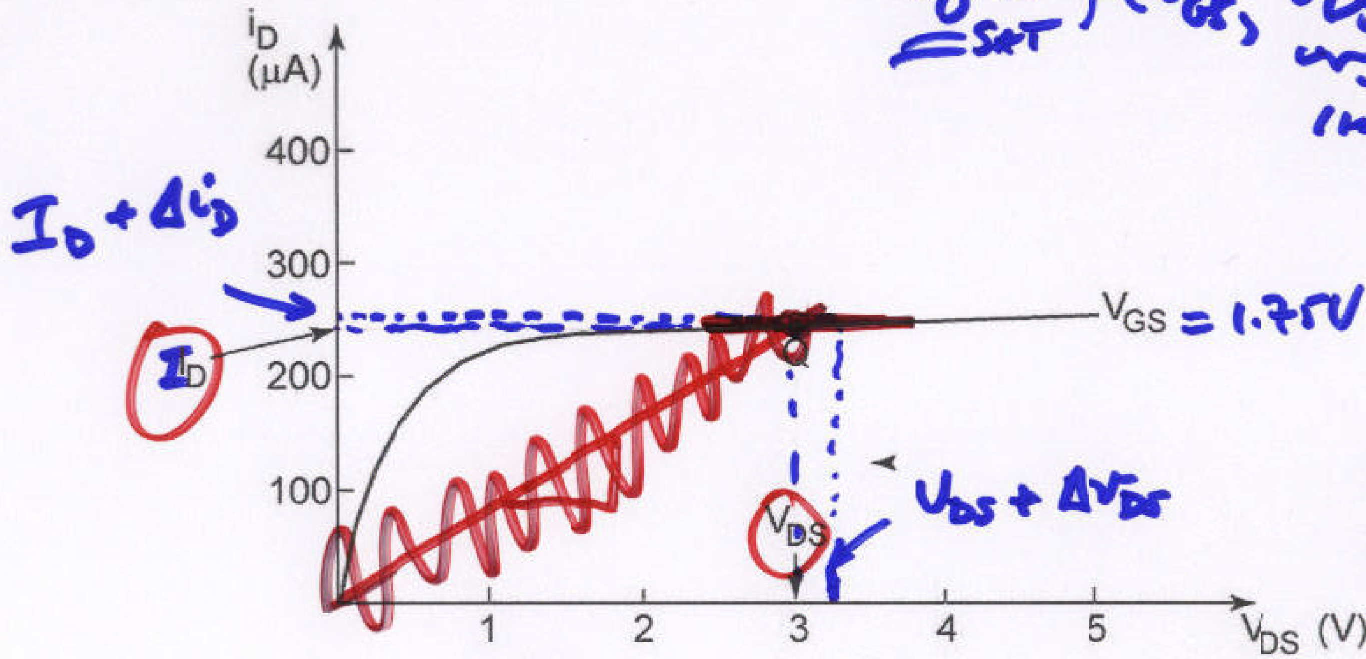
$$g_m = \{100 \cdot 2 \cdot 50 \cdot 100\}^{1/2} = 10^{6/2} = (100^{3/2})\ \mu S = \underline{1\ mS}$$

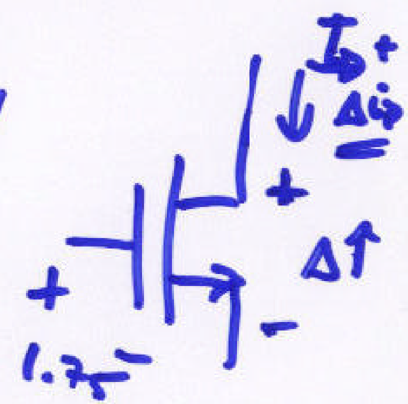
# Output Resistance $r_o$

Defined as the inverse of the change in drain current due to a change in the *drain-source* voltage, with *everything else constant*

$i_{D_{SAT}} = f(v_{GS}, v_{DS})$

increment




$$\left.\frac{\Delta i_D}{\Delta v_{DS}}\right|_{V_{GS}=1.75V,\ V_{DS}=3V} = \text{small.}$$

# Evaluating $r_o$

$$r_o = \underbrace{\left( \left. \frac{\partial i_D}{\partial v_{DS}} \right|_{V_{GS}, V_{DS}} \right)}_{g_o}^{-1} = \left[ \frac{\partial}{\partial v_{DS}} \left\{ \mu_n C_{ox} \left(\frac{W}{2L}\right) (V_{GS} - V_{Tn})^2 (1 + \lambda_n v_{DS}) \right\} \Big|_Q \right]^{-1}$$

$$= \left[ \mu_n C_{ox} \left(\frac{W}{2L}\right) (V_{GS} - V_{Tn})^2 \cdot \lambda_n \right]^{-1}$$

$$r_o = \frac{1}{\underbrace{\mu_n C_{ox} (W/2L) (V_{GS} - V_{Tn})^2}_{\approx I_D \text{ (with no fudge factor)}} \cdot \lambda_n} \cong \frac{1}{\lambda_n I_D}$$

Typical value:

$\cancel{r_o \neq \frac{V_{DS}}{I_D} \text{ !NO!}}$