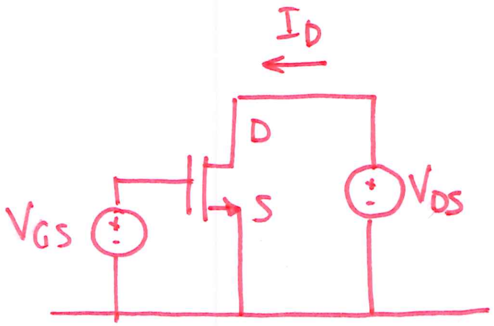
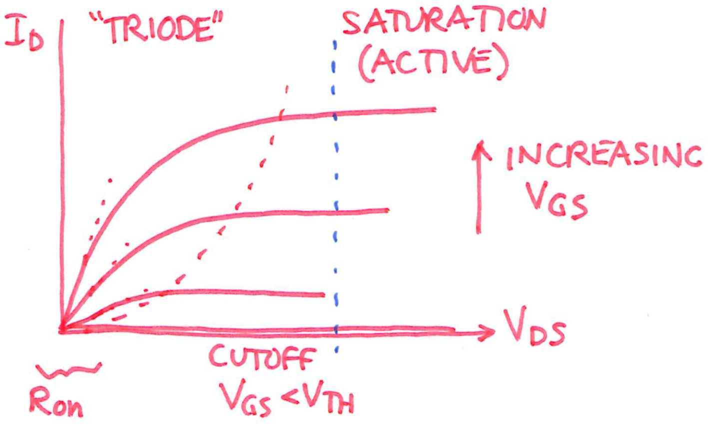
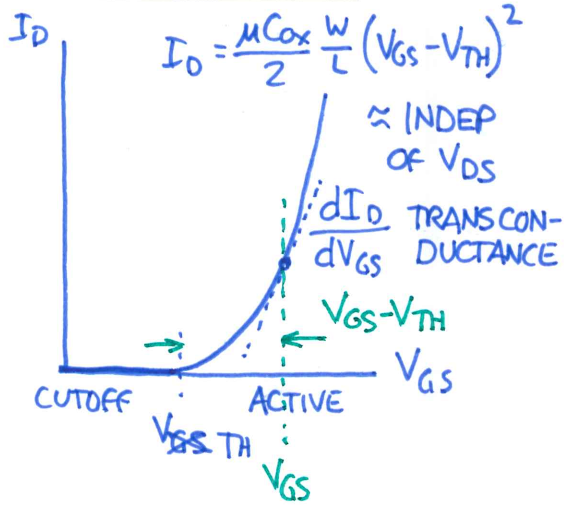
ECE4902 N-CHANNEL MOSFET OPERATING REGIONS

GATE	DRAIN	REGION	FIRST ORDER BEHAVIOR	NOT EXACTLY:
$V_{GS} > V_{TH}$	$V_{DS} > V_{GS} - V_{TH}$	SATURATION (ACTIVE)	DRAIN "LOOKS LIKE" CURRENT SOURCE; I_D DEPENDS ONLY ON $V_{GS} - V_{TH}$ $I_D = \frac{\mu_n C_{ox}}{2}\frac{W}{L}\underbrace{(\overbrace{V_{GS}-V_{TH}}^{\text{“OVERDRIVE”}})^2}_{\text{SQUARE LAW}}$	CHANNEL LENGTH MODULATION I_D DEPENDS SOMEWHAT ON V_{DS} $I_D = \frac{\mu_n C_{ox}}{2}\frac{W}{L}\overbrace{(V_{GS}-V_{TH})^2}^{\text{“SQUARE LAW”}}\underbrace{[1+\lambda V_{DS}]}_{}$
	$V_{DS} < V_{GS} - V_{TH}$	TRIODE	D-S CHANNEL "LOOKS" RESISTIVE $I_D = V_{DS} / R_{on}$ R_{on} DEPENDS ON $V_{GS} - V_{TH}$ $R_{on} = \frac{1}{\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})}$	NONLINEAR AS V_{DS} INCREASES $I_D = \mu_n C_{ox}\frac{W}{L}\left[(V_{GS}-V_{TH})V_{DS} - \underbrace{\frac{V_{DS}^2}{2}}_{\text{INTEGRAL}}\right]$
$V_{GS} < V_{TH}$	$\lvert V_{DS}\rvert < V_{bkd}$	CUTOFF	SWITCH "OFF" $I_D = 0$	$I_D \approx$ pA to nA SUBTHRESHOLD CURRENT BREAKDOWN IF $\lvert V_{DS}\rvert$ EXCEEDS V_{bkd}

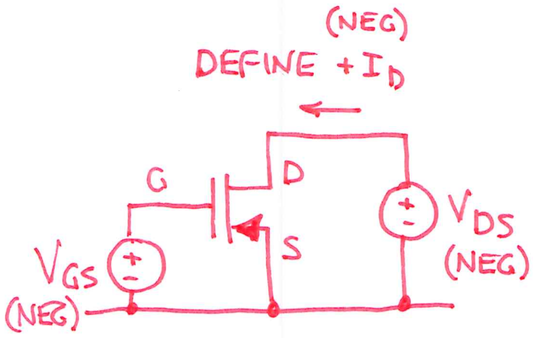


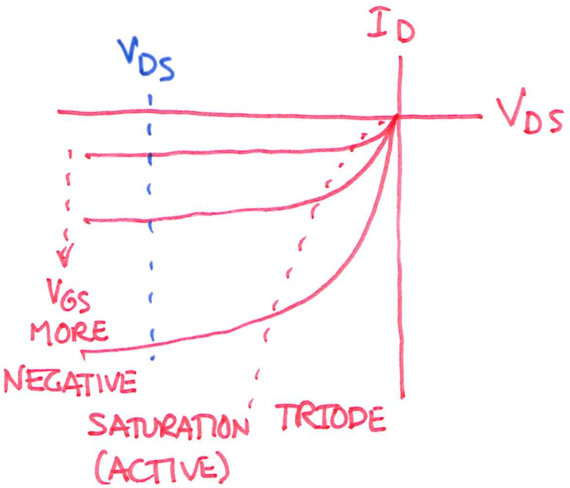


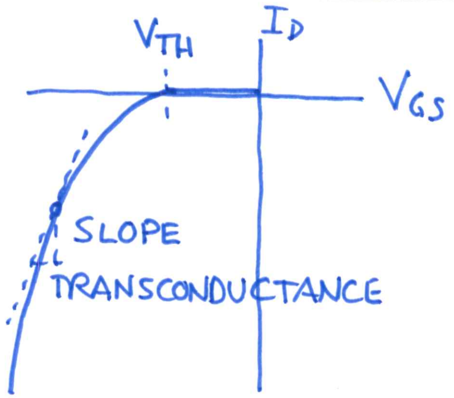


ECE4902 P-CHANNEL MOSFET OPERATING REGIONS

GATE	DRAIN	REGION	FIRST ORDER BEHAVIOR	NOT EXACTLY:
$V_{GS} < V_{TH}$	$V_{DS} < V_{GS} - V_{TH}$	SATURATION (ACTIVE)	DRAIN "LOOKS LIKE" CURRENT SOURCE; I_D DEPENDS ONLY ON $V_{GS} - V_{TH}$ $I_D = -\frac{\mu_p C_{ox}}{2}\frac{W}{L}(V_{GS}-V_{TH})^2$	CHANNEL LENGTH MODULATION I_D DEPENDS SOMEWHAT ON V_{DS} $I_D = -\frac{\mu_p C_{ox}}{2}\frac{W}{L}(V_{GS}-V_{TH})^2[1+\lambda\lvert V_{DS}\rvert]$
	$V_{DS} > V_{GS} - V_{TH}$	TRIODE	D-S CHANNEL "LOOKS" RESISTIVE $I_D = V_{DS} / R_{on}$ R_{on} DEPENDS ON $V_{GS} - V_{TH}$ $R_{on} = \frac{1}{\mu_n C_{ox}\frac{W}{L}\lvert V_{GS}-V_{TH}\rvert}$	NONLINEAR AS V_{DS} INCREASES $I_D = -\mu_p C_{ox}\frac{W}{L}\left[(V_{GS}-V_{TH})V_{DS}-\frac{V_{DS}^2}{2}\right]$
$V_{GS} > V_{TH}$	$\lvert V_{DS}\rvert < V_{bkd}$	CUTOFF	SWITCH "OFF" $I_D = 0$	$I_D \approx$ pA to nA SUBTHRESHOLD CURRENT BREAKDOWN IF $\lvert V_{DS}\rvert$ EXCEEDS V_{bkd}



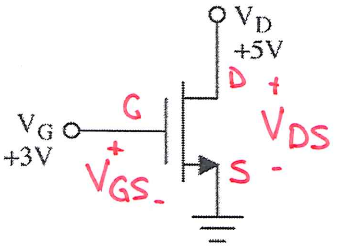




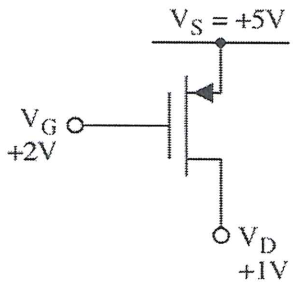
3) [MOSFET operating region practice]

For each MOSFET below, determine the MOSFET operating region (active, triode, cutoff). Assume NMOS $V_{TH} = +1V$ and PMOS $V_{TH} = -1V$.

a)



e)



$V_{GS} = +3V$ $V_{DS} = +5V$

$\underbrace{V_{GS}}_{+3V} > \underbrace{V_{TH}}_{+1V}$? ✓ ~~CUTOFF~~

~~TRIODE~~

$V_{DS} < V_{GS} - V_{TH}$?

+5V 3V - 1V

2V

SATURATION (ACTIVE)

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

4) [More MOSFET operating region practice]

For each MOSFET below, determine

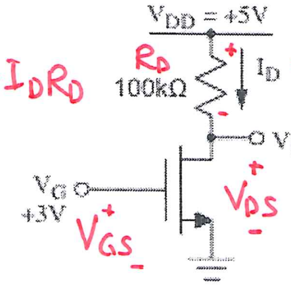
a) the MOSFET operating region (active, triode, cutoff), and
b) the drain voltage v_D and the DC drain current I_D.
Assume NMOS $V_{TH} = +1V$ and PMOS $V_{TH} = -1V$.

For both NMOS and PMOS, assume $\mu C_{ox}\frac{W}{L} = 2.0E-4\frac{A}{V^2}$

$V_{GS} \rightarrow I_D \rightarrow V_D = V_{DD} - I_D R_D$

OP REGION

a)

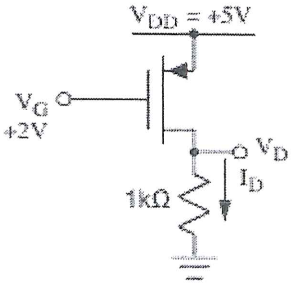


$I_D = \cancel{\frac{\mu C_{ox}}{2}\frac{W}{L}(V_{GS}-V_{TH})^2}$

$V_{GS} = +3V > 1V = V_{TH}$

~~CUTOFF~~

e)



GUESS OP REGION → ~~ACTIVE~~ (NO CHANNEL LENGTH MOD)

↳ SQUARE LAW

CHECK CONSISTENCY

REVISE IF NOT CONS

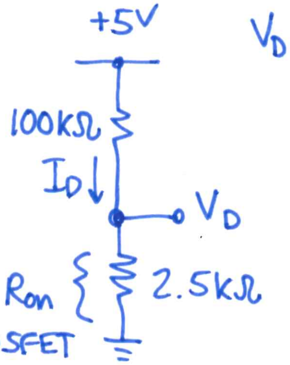
$I_D = \frac{2E-4}{2}(3V-1V)^2 = 400\mu A$

CHECK: $V_{DS} > V_{GS} - V_{TH}$? NO!

$V_D = 5V - \underbrace{(400\mu A)(100k\Omega)}_{40V} = -35V!? \ll \overbrace{2V}^{V_{GS}-V_{TH}}$

TRIODE: USE R_{on} EXPRESSION

$R_{on} = \frac{1}{\mu C_{ox}\frac{W}{L}(V_{GS}-V_{TH})} = \frac{1}{(2E-4\frac{A}{V^2})(2V)} = 2.5k\Omega$



OF MOSFET
IN TRIODE
V_{DS} SMALL

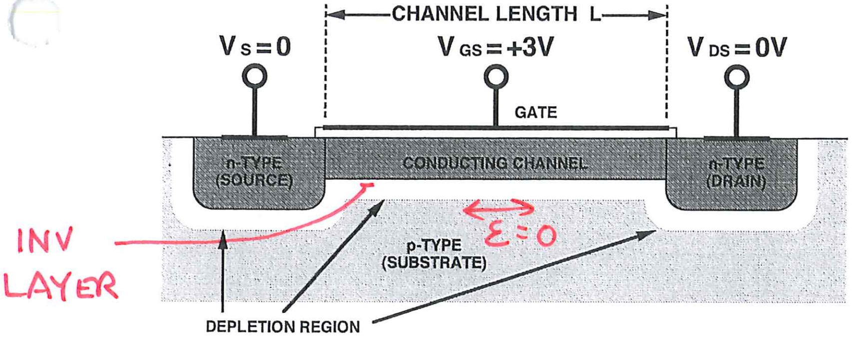
$I_D = \frac{5V}{102.5k\Omega} = 49\mu A$

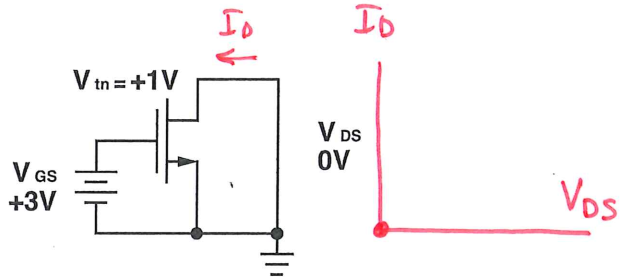
$V_D = 5V\left(\frac{2.5k}{102.5k}\right)$

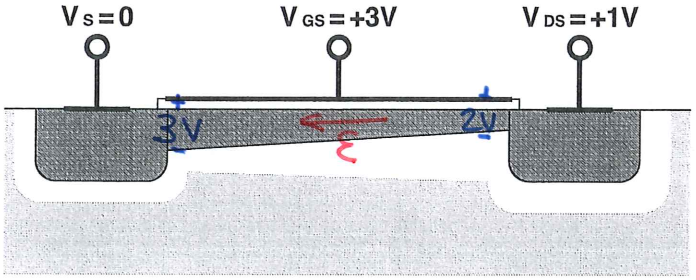
$= \underbrace{122\, mV}$

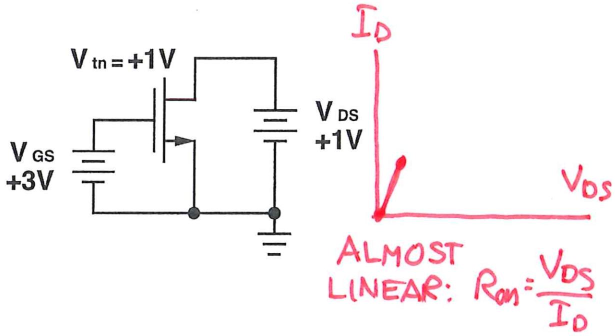
$V_{DS} < V_{GS} - V_{TH}$ ✓

EE4902 MOSFET CHANNEL LENGTH MODULATION

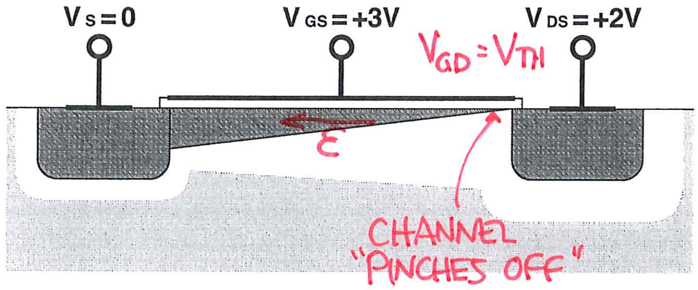


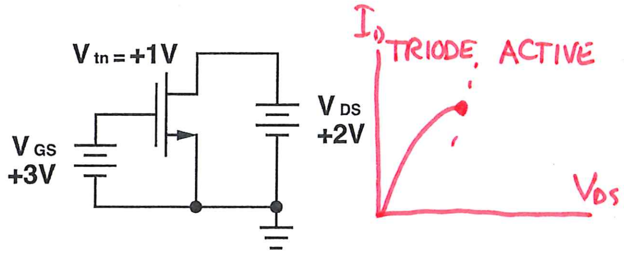


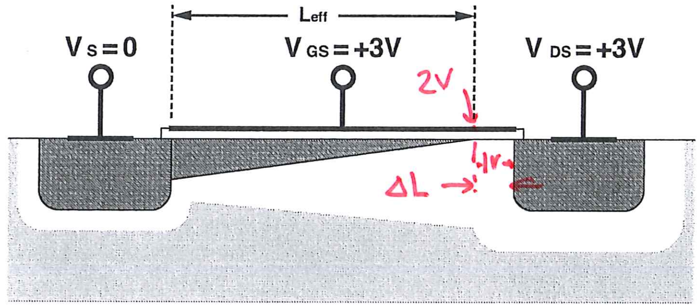


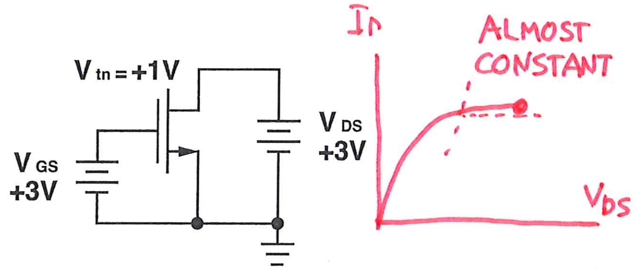


ALMOST LINEAR: $R_{on} = \frac{V_{DS}}{I_D}$

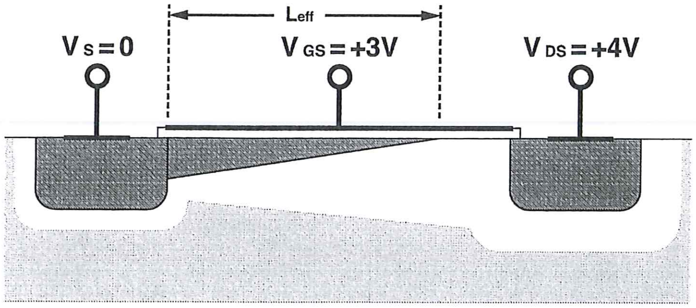


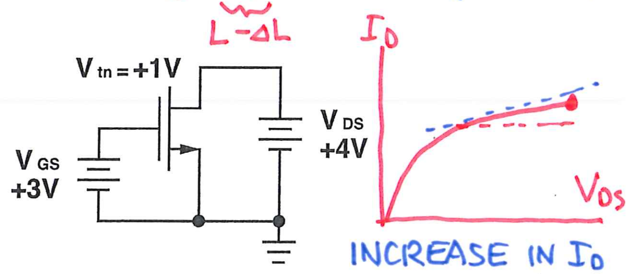






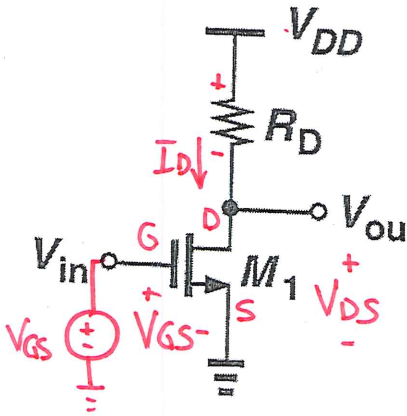
$$\uparrow I_D = \frac{\mu C_{ox}}{2}\frac{W}{\underbrace{L}_{L-\Delta L}}(V_{GS}-V_{TH})\left[1+\lambda V_{DS}\right]$$





INCREASE IN I_D ROUGHLY $\propto V_{DS}$

Sec. 3.2 Common-Source Stage



KVL

$V_{out} = V_{DD} - I_D R_D$

① $V_{IN} = 0$ INCREASING

$V_{IN} < V_{TH}$: CUTOFF : $I_D = 0$

$V_{OUT} = V_{DD}$

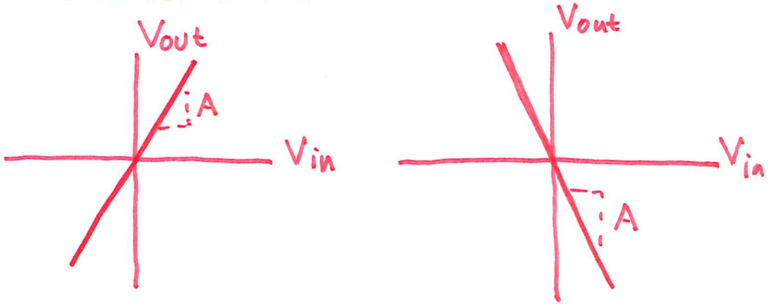
② V_{GS} A LITTLE > V_{TH} $V_{GS} - V_{TH}$ SMALL

$V_{DS} \approx V_{DD}$ BIG ← ACTIVE

$$V_{OUT} = V_{DD} - \underbrace{\frac{\mu C_{ox}}{2}\frac{W}{L}(V_{in} - V_{TH})^2}_{I_D\ \text{FROM SQ LAW}} R_D$$

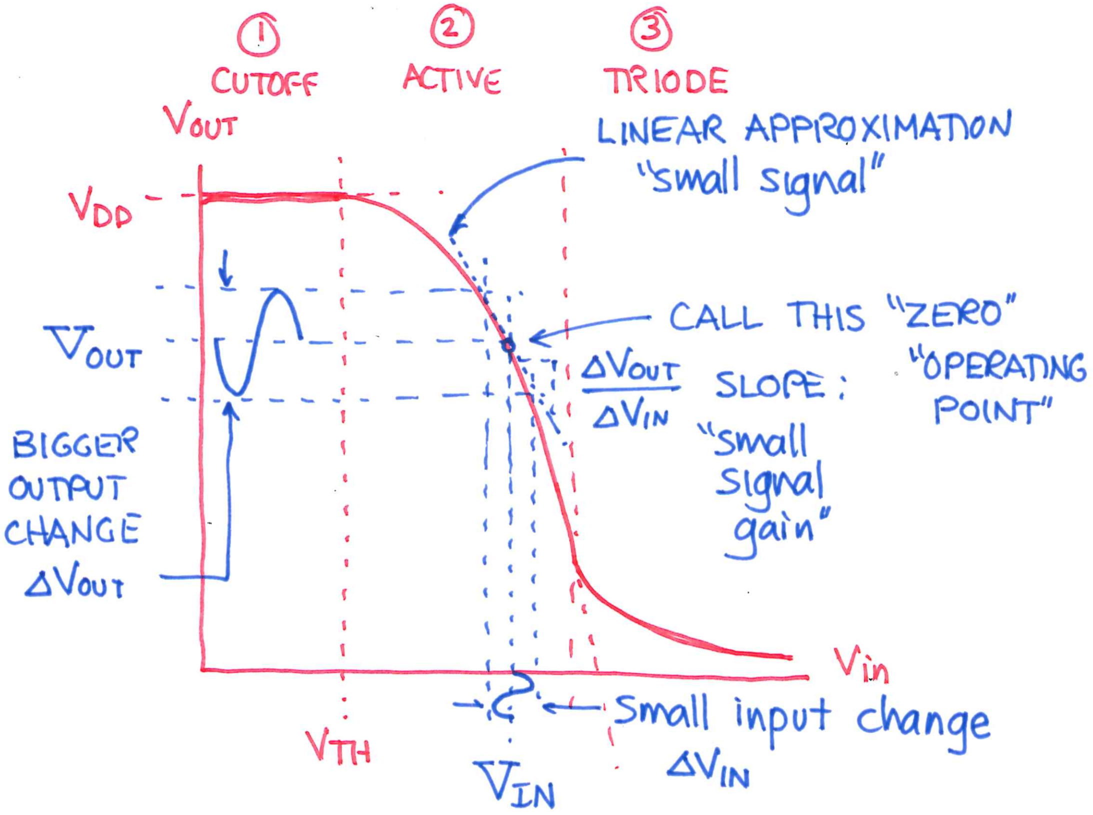
③ $V_{DS} < (V_{GS} - V_{TH})$ "TRIODE CRASH"

AMPLIFIER!? WANT:



$V_{out} = A V_{in}$

HOW WELL DOES CS DO AMPLIFIER ⤴?



INCREMENTAL (SMALL SIGNAL) ANALYSIS

What it is
A method of analysis that allows us to get approximate analytic expressions (equations) for nonlinear circuits which can't be solved easily.
Concept: "Take derivative first"

Why you do it
Linear signal analysis is such a powerful tool, we're going to use it to analyze systems that aren't linear. Anything (even a nonlinear circuit element) looks linear if you look at small enough changes from an operating point.

PROCEDURE:

1. First, find the DC (large signal) operating point for each element in the nonlinear circuit.

Possible methods:

Solve nonlinear equations (e.g. quadratic for active region MOSFET square-law model)
Iteratively solve nonlinear equations (e.g. SPICE)
Approximate analysis (e.g. for BJT, assume $V_{BE} = 0.7V$ in active region)
Graphical technique

Small signal solution will "ride on" bias levels provided by large signal operating point solution

2. Redraw the circuit: replace each circuit element with its small-signal model

Linear elements (e.g. pure R, L, C) stay the same

Constant V/I Sources: Gone! ("take derivative first"):

DC voltage sources: replace with short circuit
DC current sources: replace with open circuit

Nonlinear element: Replace with small-signal model

For each type of device, small-signal model is obtained by taking derivative of appropriate terminal characterstic to find linear approximation for behavior around operating point.
Usually just do this once for each type of device; small signal model parameters are a function of large signal operating point (e.g. small signal MOSFET model derived once; then for each application of model use operating point information to calculate small signal parameters).

3. Solve the small-signal circuit model using all the linear analysis tools you know and love:

Good Old Ohm's Law

All V-I characteristics are linear in small-signal model

Can use Thevenin's theorem to simplify large circuits

Attack them one block at a time

Helps to understand functions of each block; how well actual circuit is performing function

Can use superposition to calculate response to different inputs

Attack output behavior one signal at a time

Helps to understand response (output) as caused by each input

Can use transfer functions to express frequency-dependent behavior

Can always use KVL, KCL, nodal analysis

(apply to any circuit, linear or nonlinear)

4. Total behavior is sum of DC (large signal) operating point + small signal component "riding on" DC bias from large signal operating point solution

Cautions

Limitations

If actual signal isn't "small", then "solution" won't be valid!

How small is "small"? Depends on accuracy required. Need to look at derivation of model for individual devices used.

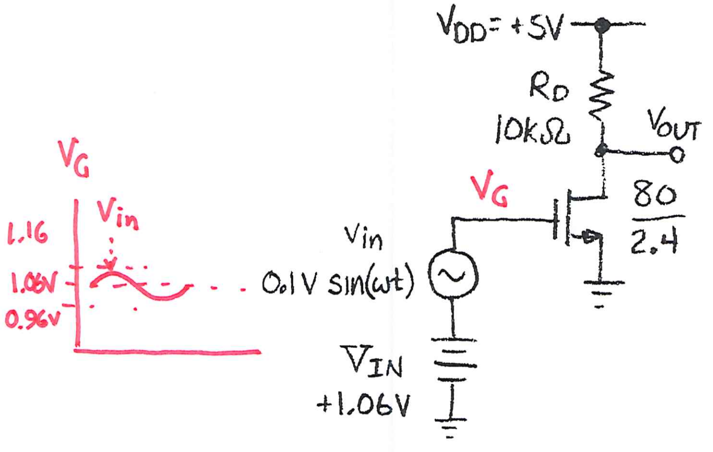
Common errors

Don't get large signal, small signal quantities confused! For example:

There should be no DC sources (e.g. supply rails) in a small signal model.

SMALL SIGNAL ANALYSIS SUMMARY

CIRCUIT

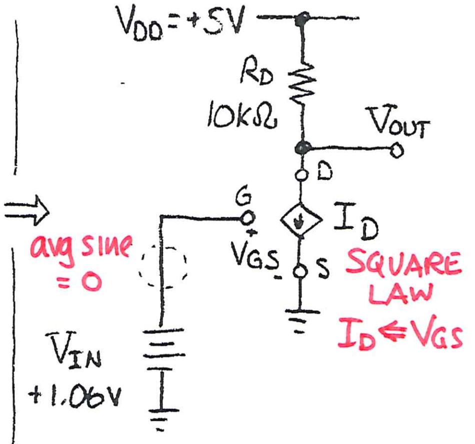


MOSFET:

$$\mu C_{ox} = 7.42E\text{-}5 \frac{A}{V^2}$$

$$V_t = 0.61V$$

LARGE SIGNAL MODEL



ACTIVE (SQ LAW) FOR I_D

$$I_D = \frac{7.42E\text{-}5}{2}\,\frac{80}{2.4}\,\underbrace{(1.06-0.61)^2}_{}$$

$V_{eff} = 0.45V$

$$\boxed{I_D = 251\mu A}$$

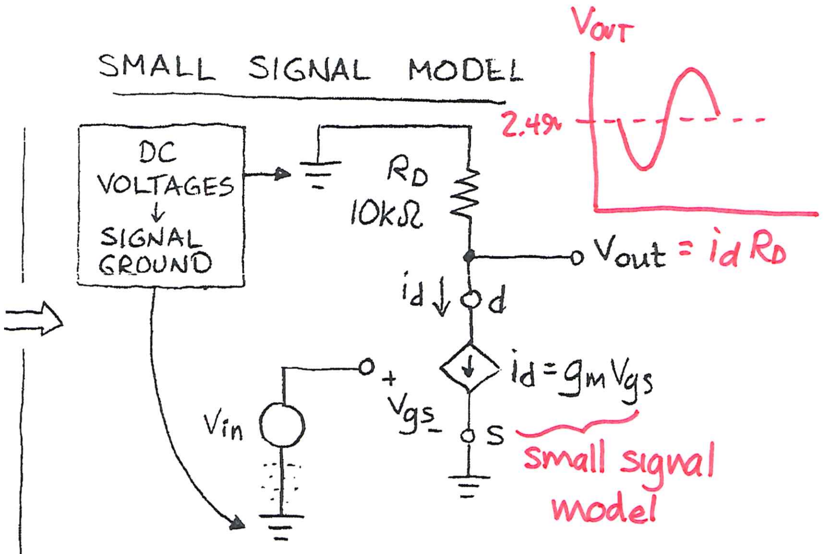
$$V_{OUT} = 5V - (251\mu A)(10k\Omega)$$

$$\boxed{V_{OUT} = +2.49\ V}$$

$$V_{DS} > \overset{\text{OVERDRIVE}}{V_{eff}}$$ ✓ ACTIVE

2.49V > 0.45V

SMALL SIGNAL MODEL



TRANSCONDUCTANCE g_m FROM DC BIAS

$$g_m = 7.42E\text{-}5\,\frac{80}{2.4}\,(1.06-0.61)$$

$$\boxed{g_m = 1.11\ mA/V}$$

−SIGN: INVERTING AMPLIFIER

$$V_{out} = -i_d R_D = -\overbrace{g_m \underbrace{V_{gs}}_{V_{in}}}^{i_d} R_D = \underbrace{(-g_m R_D)}_{-11.1} V_{in}$$

small signal gain

$$\boxed{\frac{V_{out}}{V_{in}} = -g_m R_D}$$

"BUILD UP" OUTPUT FROM DC, SMALL SIGNAL "PIECES"

AT INPUT:

$$\overbrace{v_{IN}}^{\text{TOTAL}} = \overbrace{+1.06\,V}^{V_{IN}} + \overbrace{(0.1V)\sin\omega t}^{v_{in}}$$

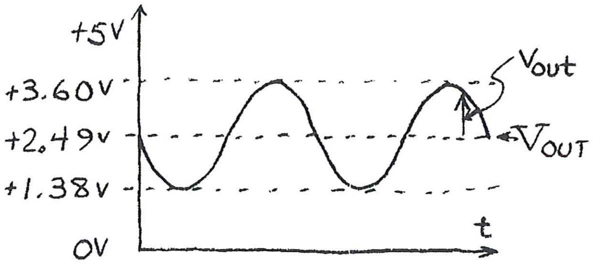
OUTPUT $\Downarrow$ $\qquad\Downarrow$ CHANGE $\qquad\Downarrow$ PROPORTIONAL GAIN

$$\underbrace{v_{OUT}}_{\text{TOTAL}} = \underbrace{+2.49V}_{V_{OUT}} + \underbrace{(-1.11V)\sin\omega t}_{v_{out} = \underbrace{(-g_m R_D)}_{\underbrace{-11.1}_{\text{FROM SMALL-SIGNAL ANALYSIS}}} v_{in}}$$

IN GENERAL

$$\underbrace{v_{OUT}}_{\text{TOTAL OUTPUT}} = \underbrace{V_{OUT}}_{\text{OUTPUT DC OPERATING POINT}} + \underbrace{A_v}_{\text{SMALL SIGNAL GAIN}} \underbrace{v_{in}}_{\text{SMALL SIGNAL INPUT}}$$

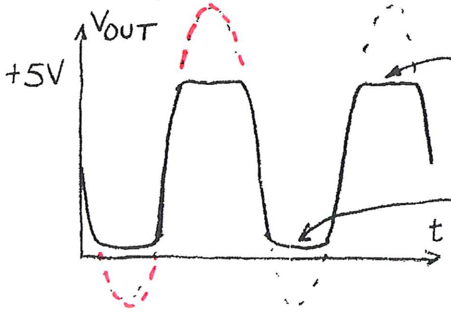
SKETCH v_{OUT}



CHECK MAX, MIN PEAKS: MEETS ACTIVE REGION CONDITIONS FOR ALL v_{OUT}

WHAT IF $v_{in} = (1.0\,V)\sin\omega t$? SMALL SIGNAL MODEL PREDICTS

$$v_{OUT} = 2.49 + (-11.1)\sin\omega t$$

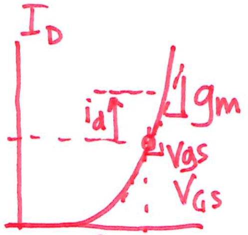


CUTOFF ⇐ MAX PEAK = 13.6 V ?

CHECK PEAK VALUES

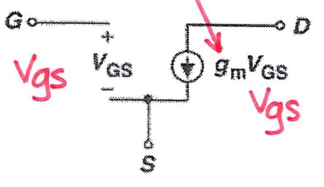
TRIODE ⇐ MIN PEAK = -8.6 V ?

$$g_m = \frac{dI_D}{dV_{GS}}$$

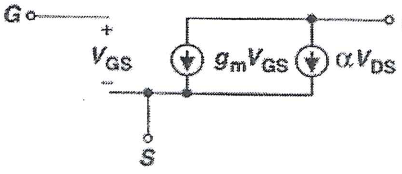


$$I_D = \frac{\mu C_{ox}}{2} \frac{W}{L} (V_{GS} - V_{TH})^2$$

$$\frac{dI_D}{dV_{GS}} = \mu C_{ox} \frac{W}{L} (V_{GS} - V_{TH}) = g_m$$



(a)



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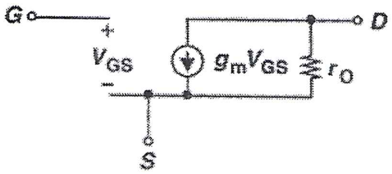

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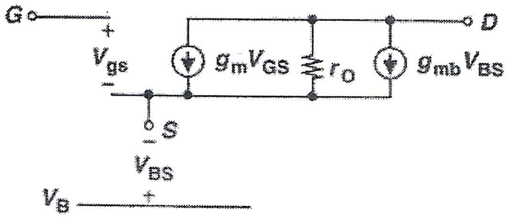

(d)