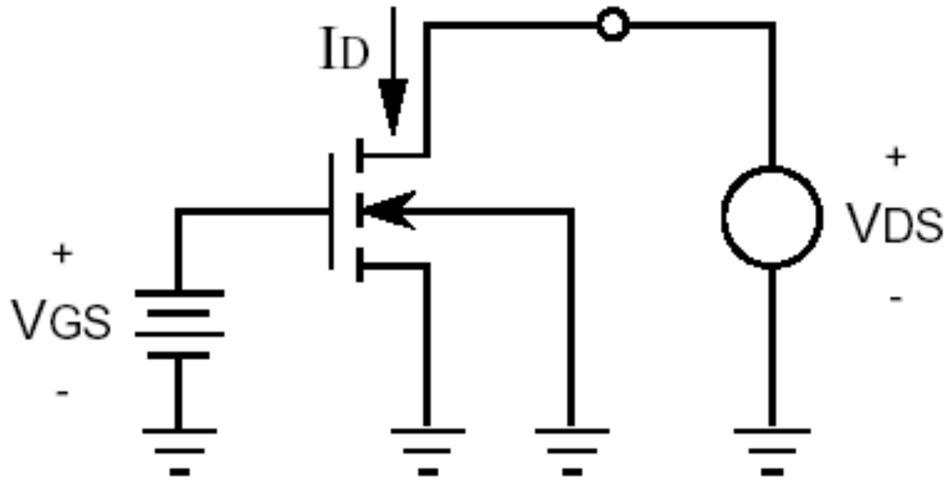
Studio 4 Review

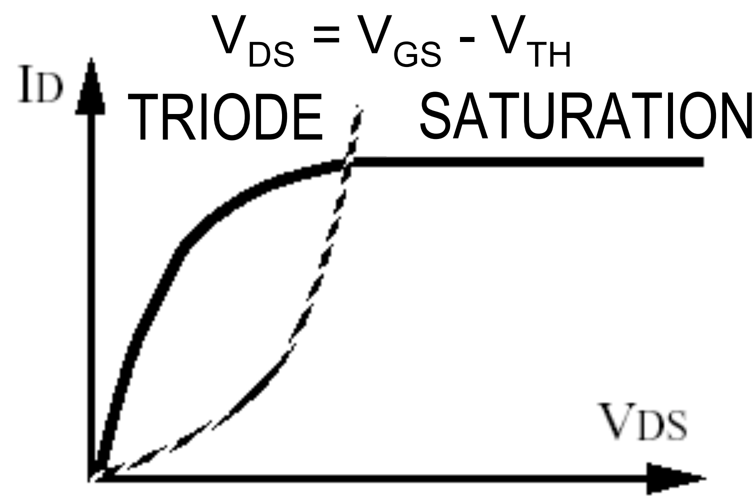
- **Common Source Amplifier, Resistive Load**
- **Small Signal Modeling**

Review operating regions: N-channel MOSFET

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

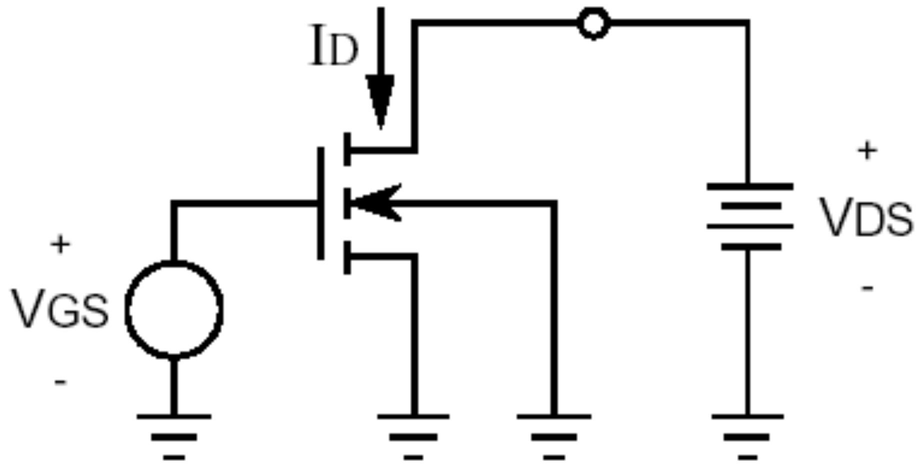
Review MOSFET: Vary V_{DS} (V_{GS} fixed)

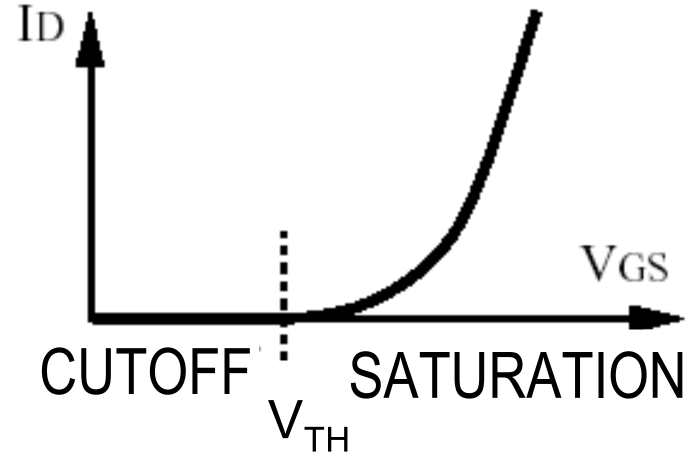




- **Need $V_{GS} > V_{TH}$ (avoid cutoff region)**

Review MOSFET: Vary V_{GS} (V_{DS} fixed)

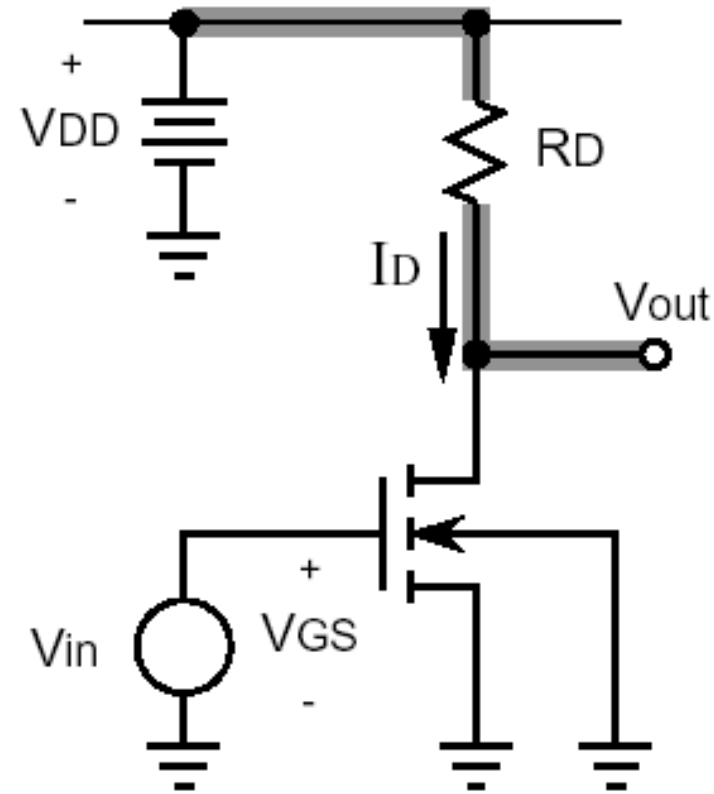




- **Need $V_{DS} > V_{GS} - V_{TH}$ (avoid triode region)**

Common Source Amplifier

- V_{IN} goes up $\Rightarrow$
  Increase V_{GS} $\Rightarrow$
  Increase I_D
- KVL path for V_{out}
  $V_{out} = V_{DD} - I_D R_D$
- MOSFET in saturation:
- I_D increases $\Rightarrow$
  $I_D R_D$ drop increases $\Rightarrow$
  V_{OUT} goes down

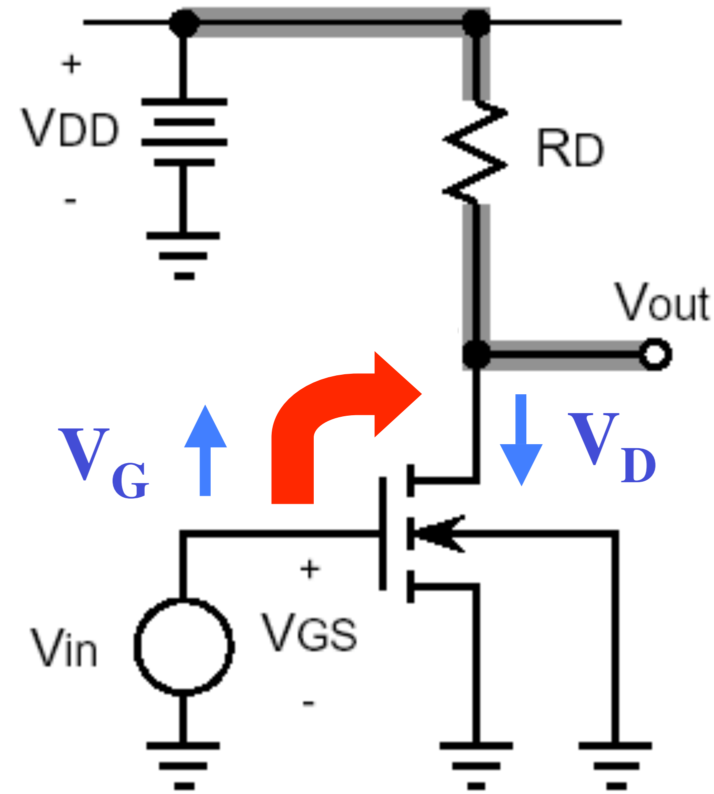


$\boxed{V_{IN} \text{ goes up} \Rightarrow V_{OUT} \text{ goes down}}$

Common Source Amplifier

- **INVERTING GAIN**

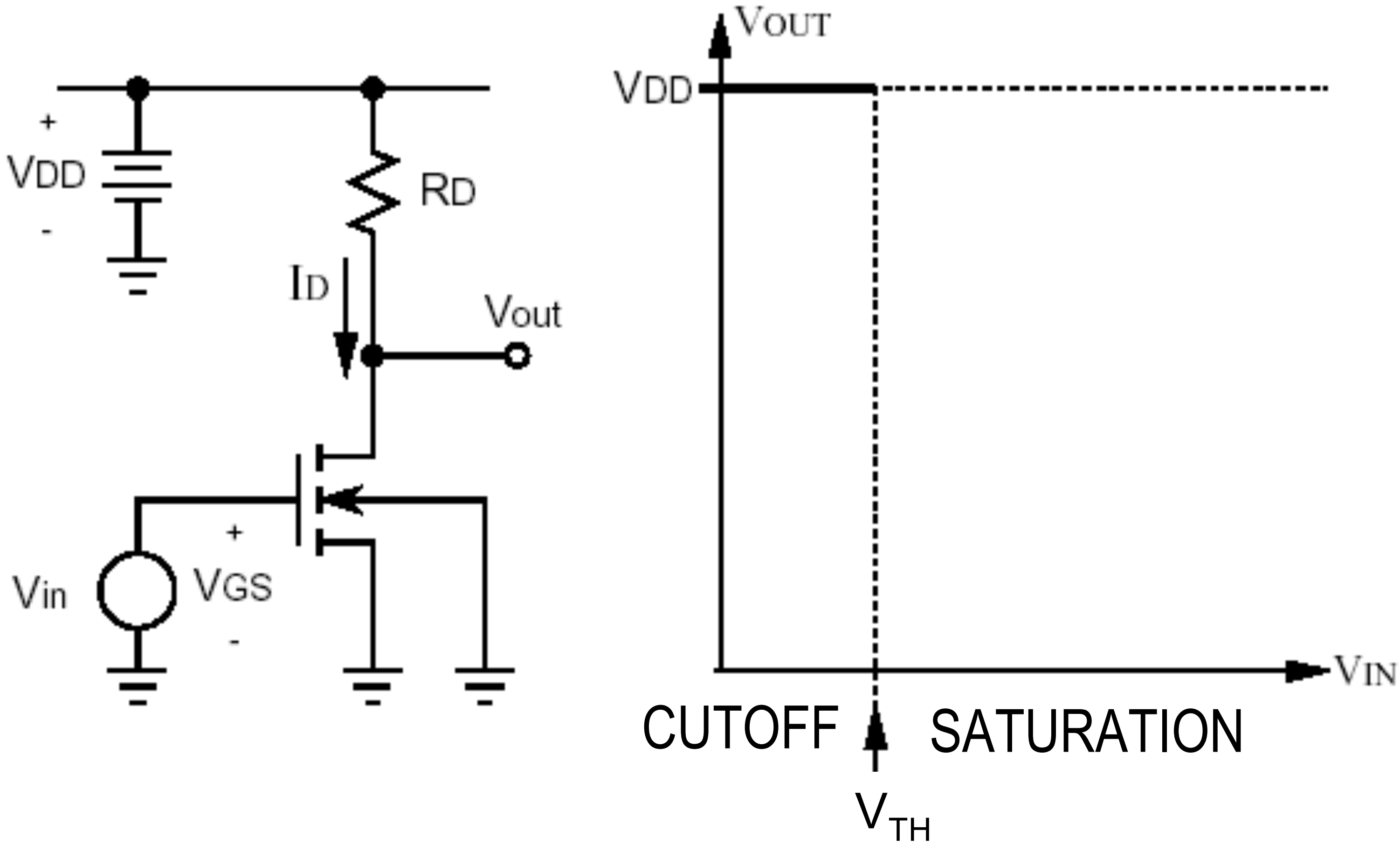
  GATE $\Rightarrow$ DRAIN



$$\boxed{\mathbf{V_{IN}\ goes\ up \Rightarrow\ V_{OUT}\ goes\ down}}$$

Build up input-output characteristic

- $V_{IN} < V_{TH} \Rightarrow V_{GS} < V_{TH} \Rightarrow$
  Cutoff: $I_D = 0$ $V_{OUT} = V_{DD}$

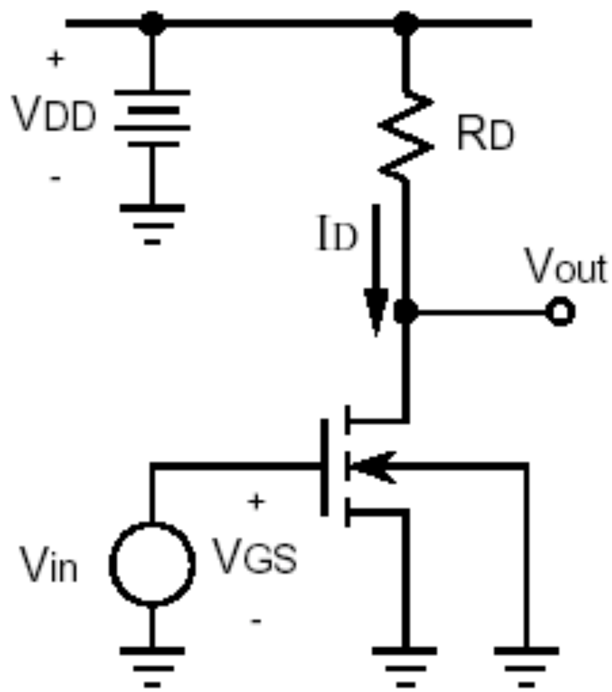


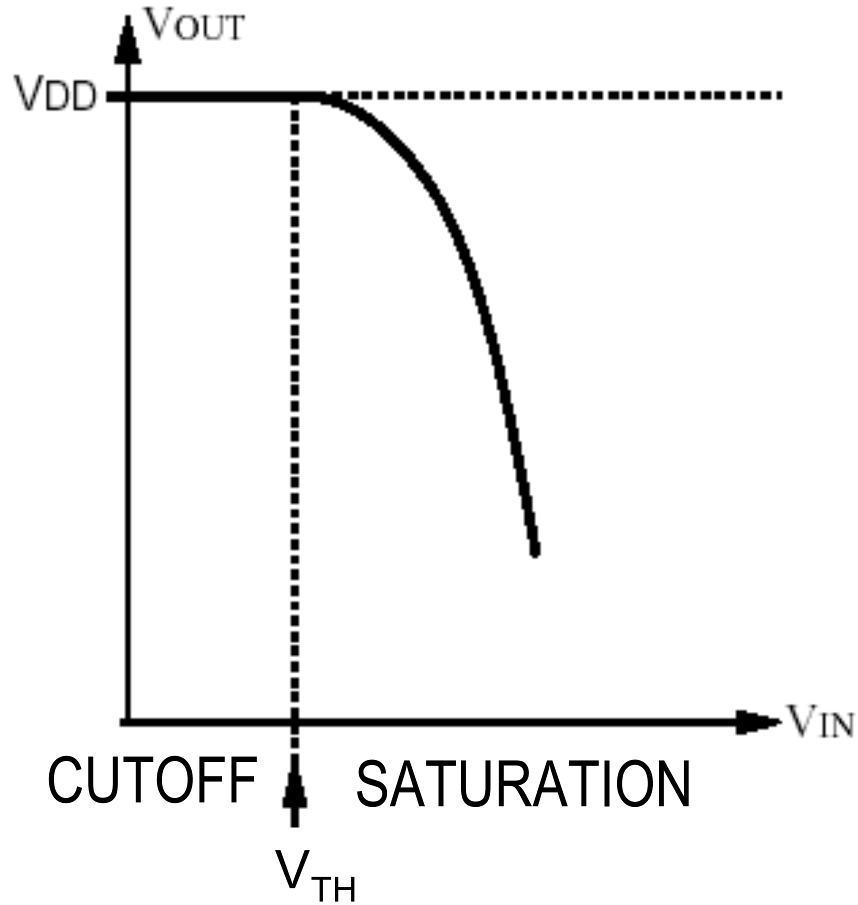
Build up input-output characteristic

- **$V_{IN} > V_{TH}$ $V_{GS} > V_{TH}$**

$$V_{OUT} = V_{DD} - \underbrace{\frac{\mu_n C_{ox}}{2}\frac{W}{L}\left(V_{in} - V_{TH}\right)^2}_{I_D} R_D$$

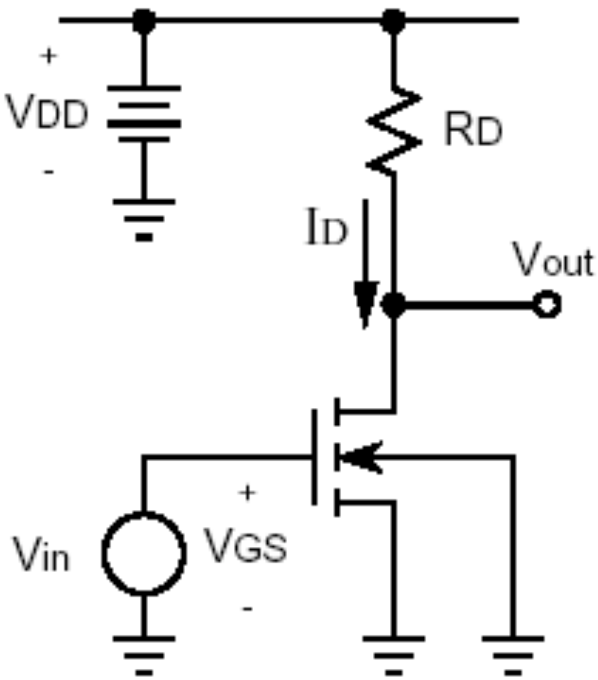
- **Saturation: I_D from square law**

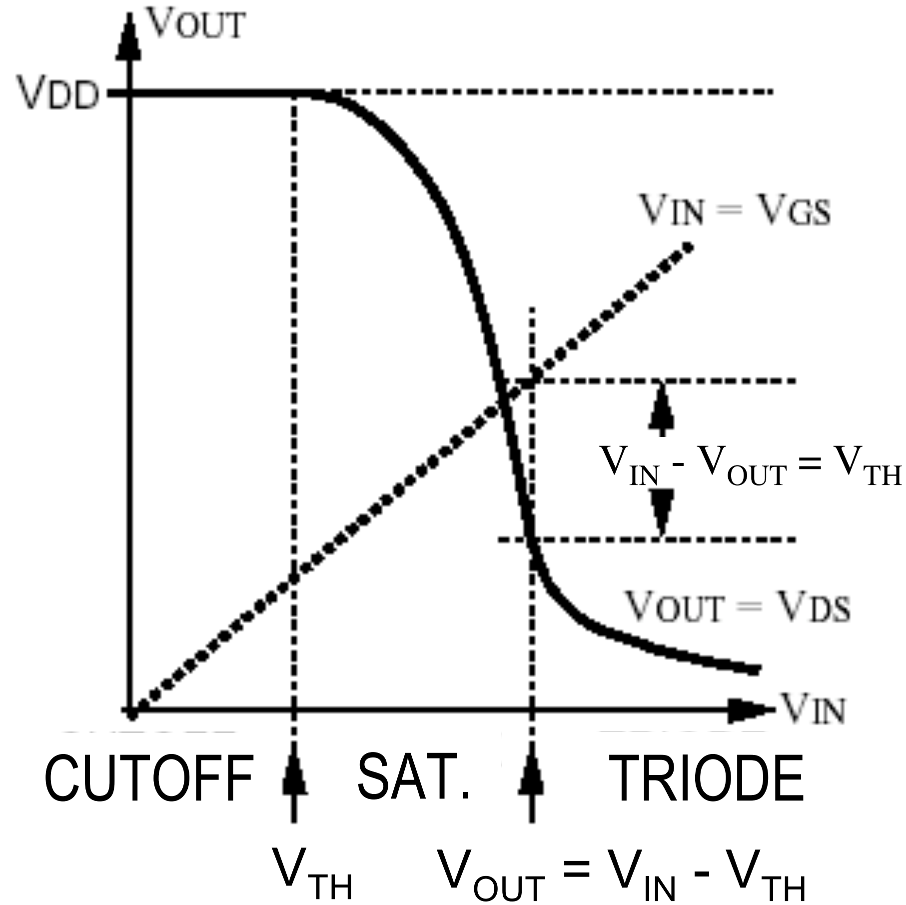




Condition for saturation-triode boundary

- V_{DS} V_{GS} - $V_{TH} \Rightarrow$
- **On boundary, both triode, saturation equations apply**





Condition for saturation-triode boundary

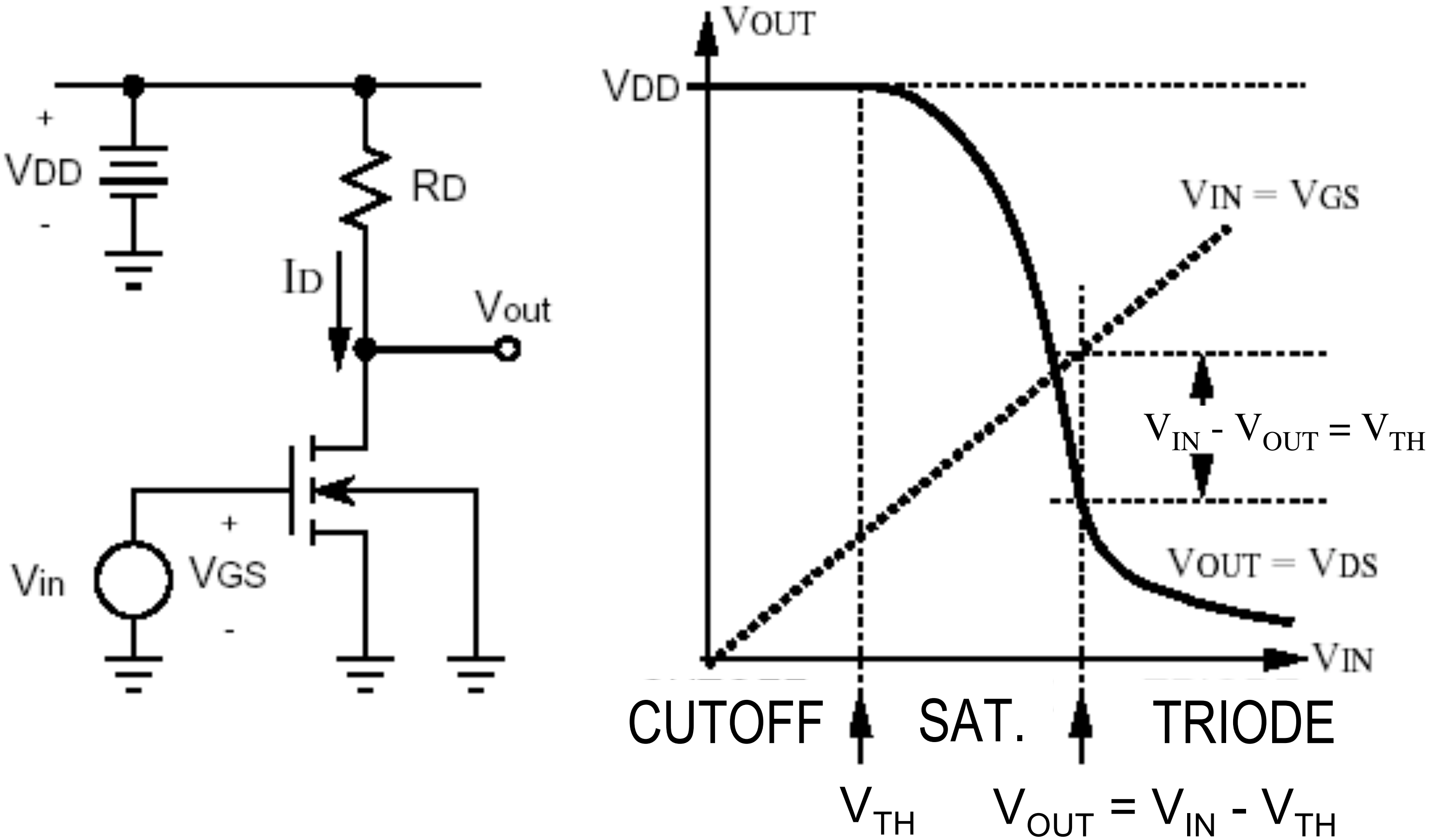
- **Expression for V_{out} on boundary (use square law)**

$$\underbrace{V_{DD} - \frac{\mu_n C_{ox}}{2}\frac{W}{L}\left(V_{in} - V_{TH}\right)^2 R_D}_{V_{OUT}} = V_{in} - V_{TH}$$

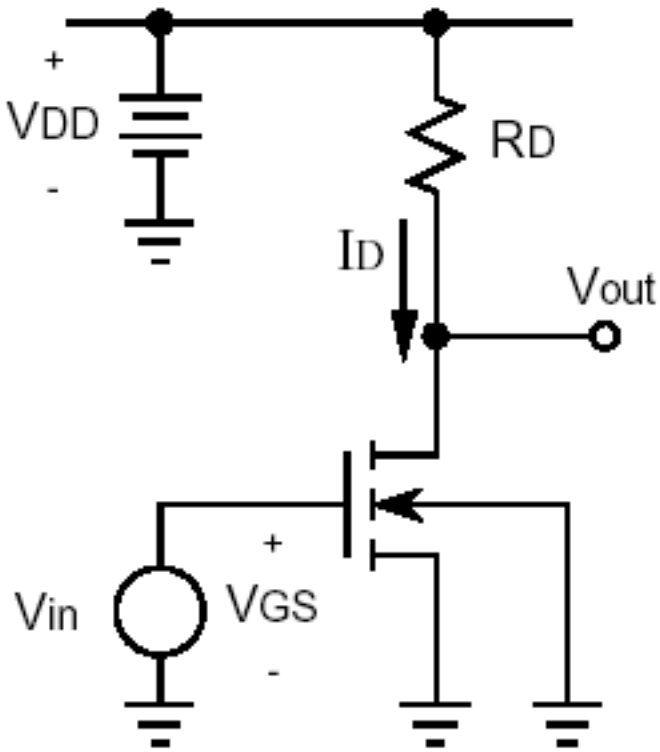
- **Ugly quadratic: solve numerically or let SPICE do it**

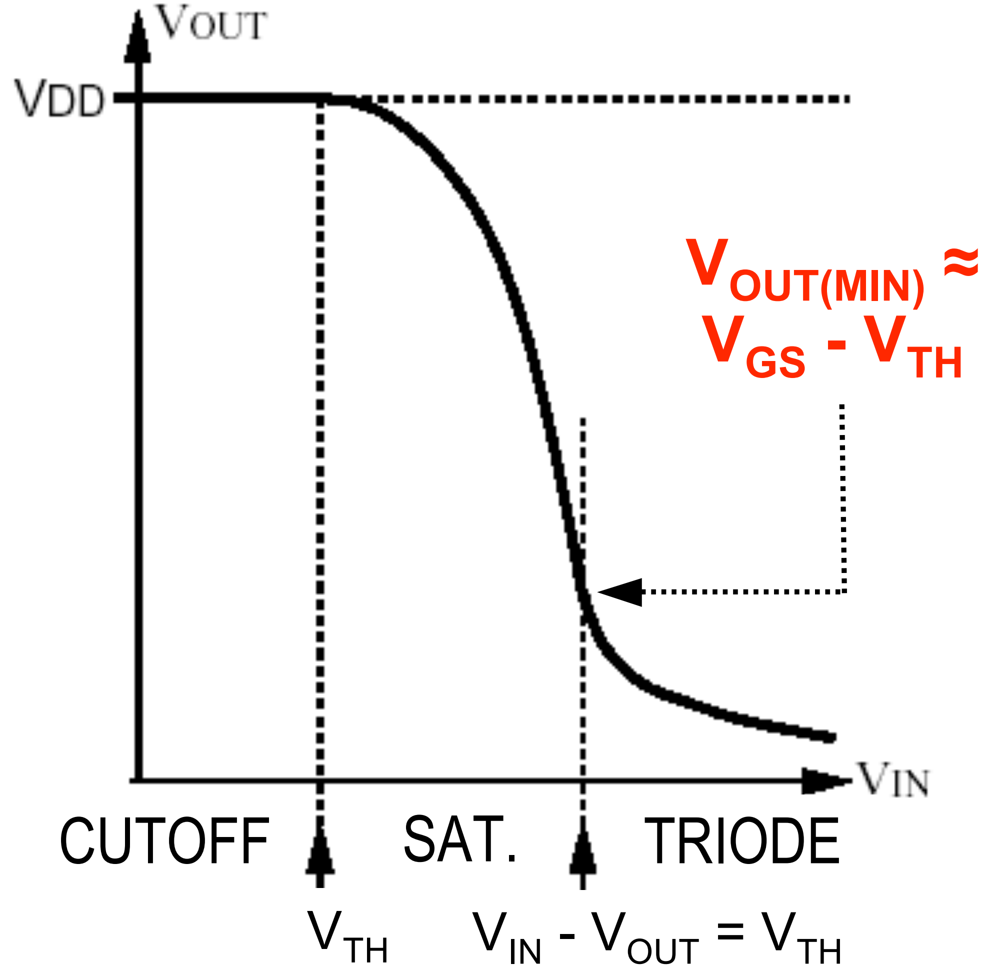
Triode

- **Ugly math: let SPICE do the work**



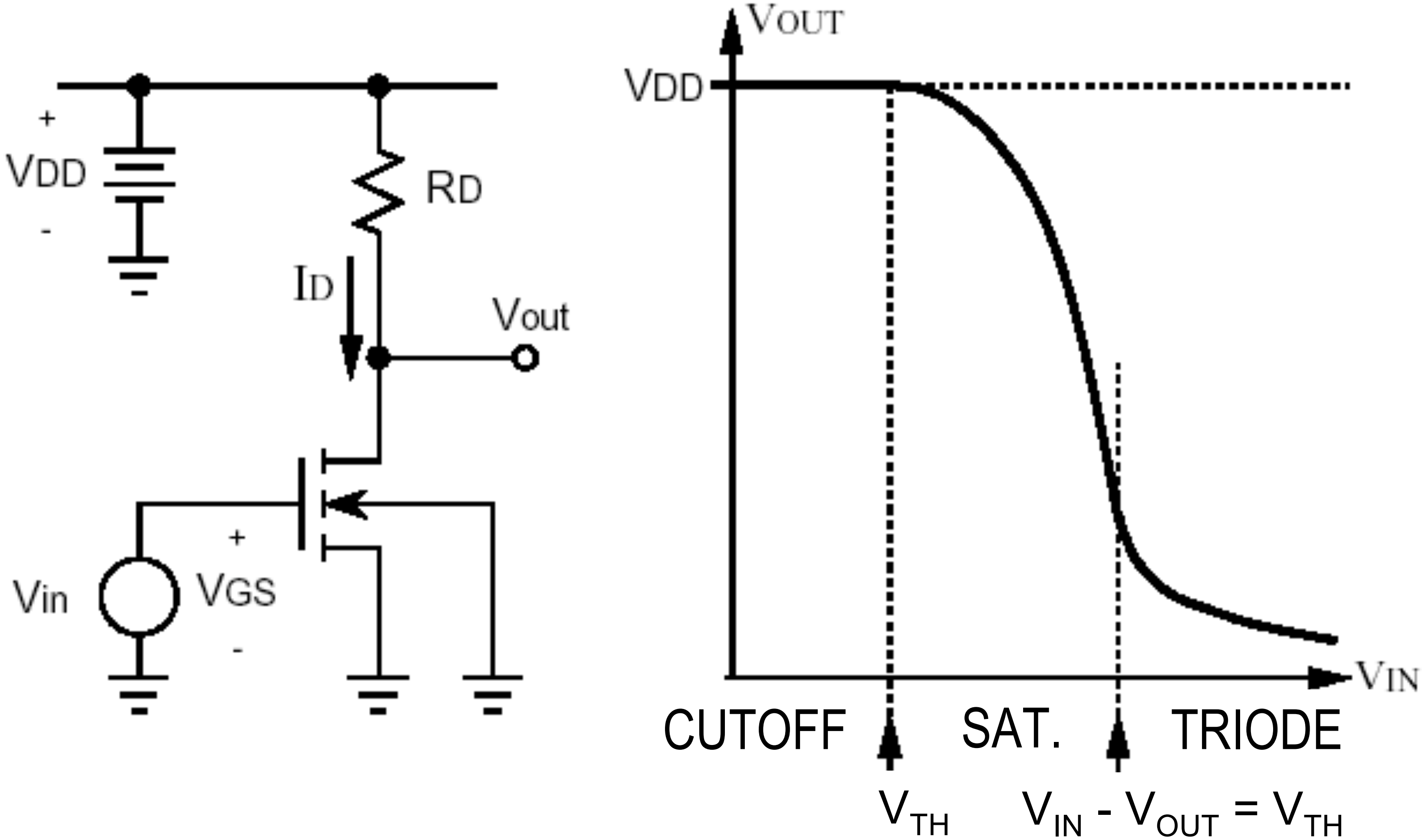
Input-output characteristic





- **Minimum output ≈ V_{GS} - V_{TH} (gate overdrive!)**
- **Maximize output swing ⇔ minimize overdrive**

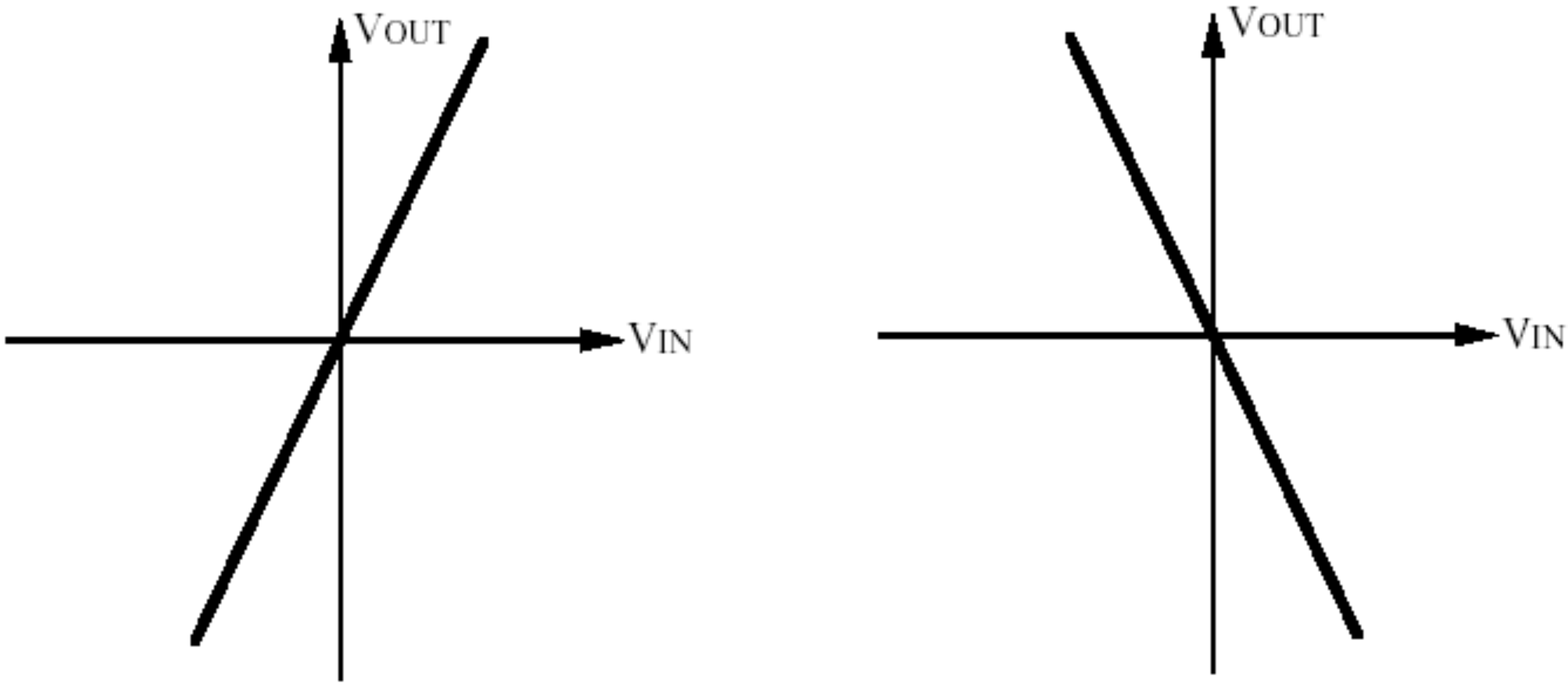
Input-output characteristic



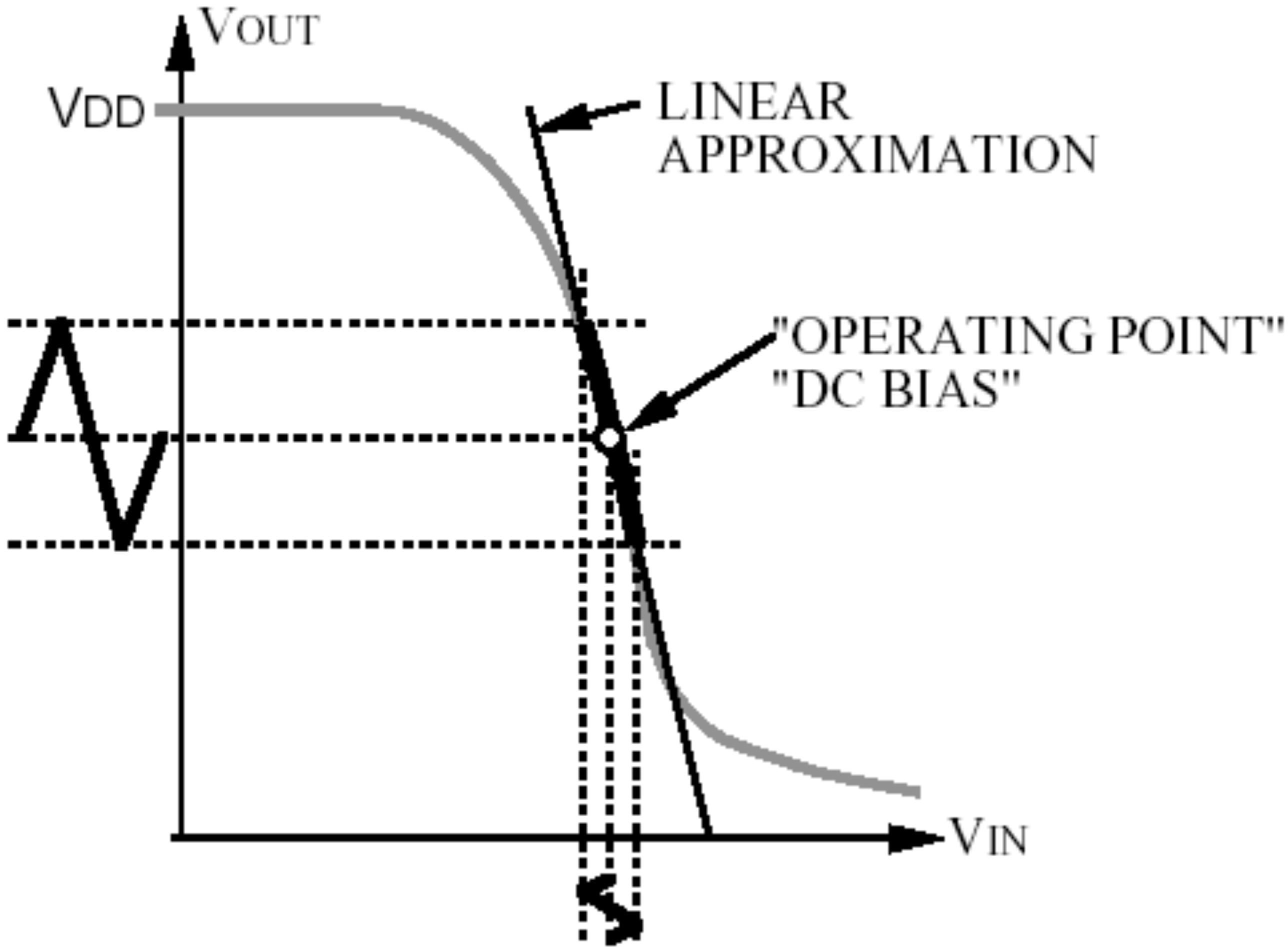
- **Compare to desired amplifier characteristic …**

Desired linear amplifier characteristic

$v_{out} = a_v\, v_{in}$ (negative slope OK - but should be linear!)



Linear (sort of) part of input-output characteristic



- **Key: Small signal ⇒ Slope = Derivative**

Slope: derivative

- **Find slope (small signal gain)**

$$\frac{dV_{OUT}}{dV_{in}} = \frac{d}{dV_{in}}\left[V_{DD} - \frac{\mu_n C_{ox}}{2}\frac{W}{L}\left(V_{in} - V_{TH}\right)^2 R_D\right]$$

$$\frac{dV_{OUT}}{dV_{in}} = -\mu_n C_{ox}\frac{W}{L}\left(V_{in} - V_{TH}\right)R_D$$

- **Constant terms (such as supply V_{DD}) drop out**
- **Why carry constant terms through equations if they're just going to drop out when we take derivative? ...**

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.**
  - **"Take derivative first"**

Small Signal Analysis: Why you do it

- **Linear signal analysis : powerful tool**
- **Use it to analyze systems that aren't linear.**
- **<u>Anything</u> (even a nonlinear circuit element) <u>looks</u> linear if you look at small enough changes from an operating point.**

Small Signal Analysis: Procedure:

1. **First, find the DC (large signal) operating point for each element in the nonlinear circuit.**
2. **Redraw the circuit: replace each circuit element with its small-signal model**
3. **Solve the small-signal circuit model using all the linear analysis tools you know and love**
4. **Total behavior is sum of**
   DC (large signal) operating point
   + small signal component "riding on" DC bias from large signal operating point solution

Small Signal Analysis: 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 saturation region MOSFET square-law model)
     - Iteratively solve nonlinear equations (e.g. SPICE)
     - Approximate analysis (e.g. for diode, assume V_D = 0.7V when forward biased)
     - Graphical technique
   - Small signal solution will "ride on" bias levels provided by large signal operating point solution

Small Signal Analysis: Procedure:

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

Small Signal Analysis: Procedure:

- Nonlinear element: Replace with small-signal model
  - For each type of device, small-signal model is obtained from derivative of appropriate terminal characteristic 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).

Small Signal Analysis: Procedure:

3. Solve the small-signal circuit model using all the linear analysis tools you know and love:
   - Good Old Ohm's Law
   - Can use Thevenin's theorem to simplify large circuits
   - Can use superposition to calculate response to different inputs
   - Can use transfer functions to express frequency-dependent behavior
   - Can always use KVL, KCL, nodal analysis (these don't require linearity)

Small Signal Analysis: Procedure:

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

Small Signal Analysis: Limitations

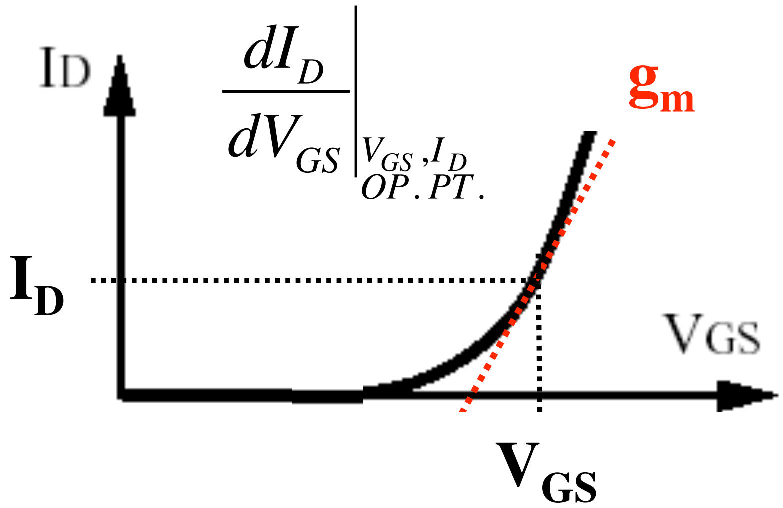
- **If actual signal isn't "small", then "solution" won't be valid!**
- **How small is "small"? Depends on accuracy required. Need to look at derivation of model for individual devices used.**
- **ALWAYS check output waveform max/min to be sure assumptions for linear model are valid (for example, output not clipped at supply rails)**

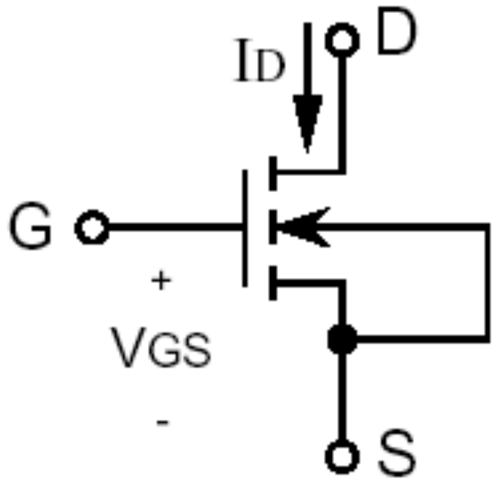
Simplest MOSFET Small Signal Model

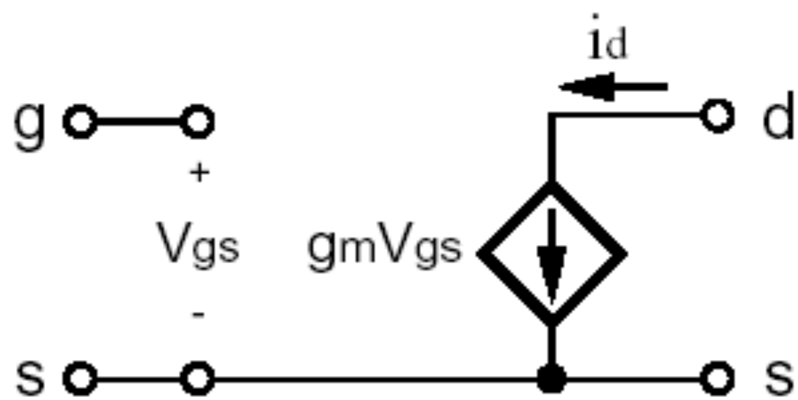
- **Saturation Region: Transconductance g_m**

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

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







Summary

- **MOSFET operating regions**
- **Common source amplifier**
- **Large signal input-output characteristic**
- **Small-signal concept**

Lab exercise

- **Plot Large Signal input-output characteristic**
- **Measure small-signal gain**