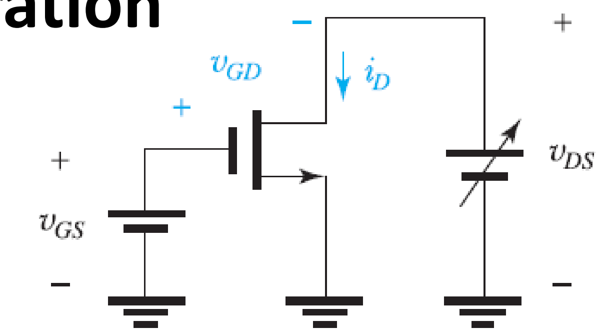
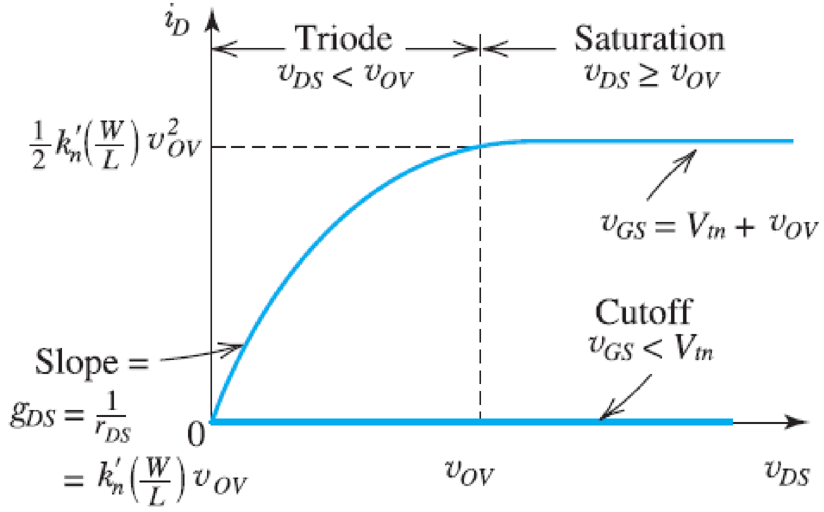
Modes of Operation
NMOS





- $v_{GS} < V_{tn}$: no channel; transistor in cutoff; $i_D = 0$
- $v_{GS} = V_{tn} + v_{OV}$: a channel is induced; transistor operates in the triode region or the saturation region depending on whether the channel is continuous or pinched off at the drain end;

Triode Region

Continuous channel, obtained by:

$$v_{GD} > V_{tn}$$

or equivalently:

$$v_{DS} < v_{OV}$$

Then,

$$i_D = k_n'\left(\frac{W}{L}\right)\left[(v_{GS} - V_{tn})v_{DS} - \frac{1}{2}v_{DS}^2\right]$$

or equivalently,

$$i_D = k_n'\left(\frac{W}{L}\right)\left(v_{OV} - \frac{1}{2}v_{DS}\right)v_{DS}$$

Saturation Region

Pinched-off channel, obtained by:

$$v_{GD} \leq V_{tn}$$

or equivalently:

$$v_{DS} \geq v_{OV}$$

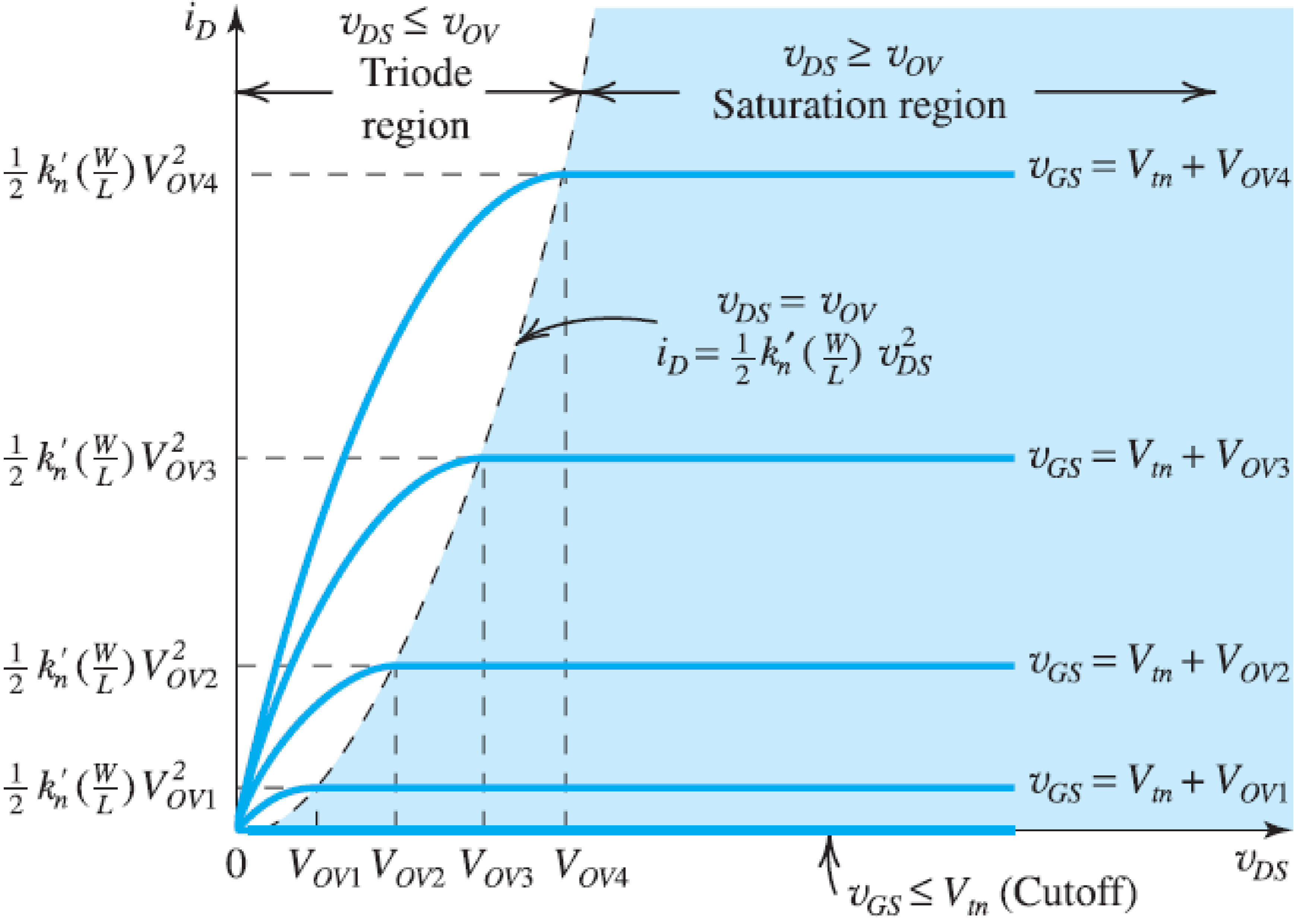
Then

$$i_D = \frac{1}{2}k_n'\left(\frac{W}{L}\right)(v_{GS} - V_{tn})^2$$

or equivalently,

$$i_D = \frac{1}{2}k_n'\left(\frac{W}{L}\right)v_{OV}^2$$

i_D vs v_{DS} curves



The i_D–v_{GS} Characteristic

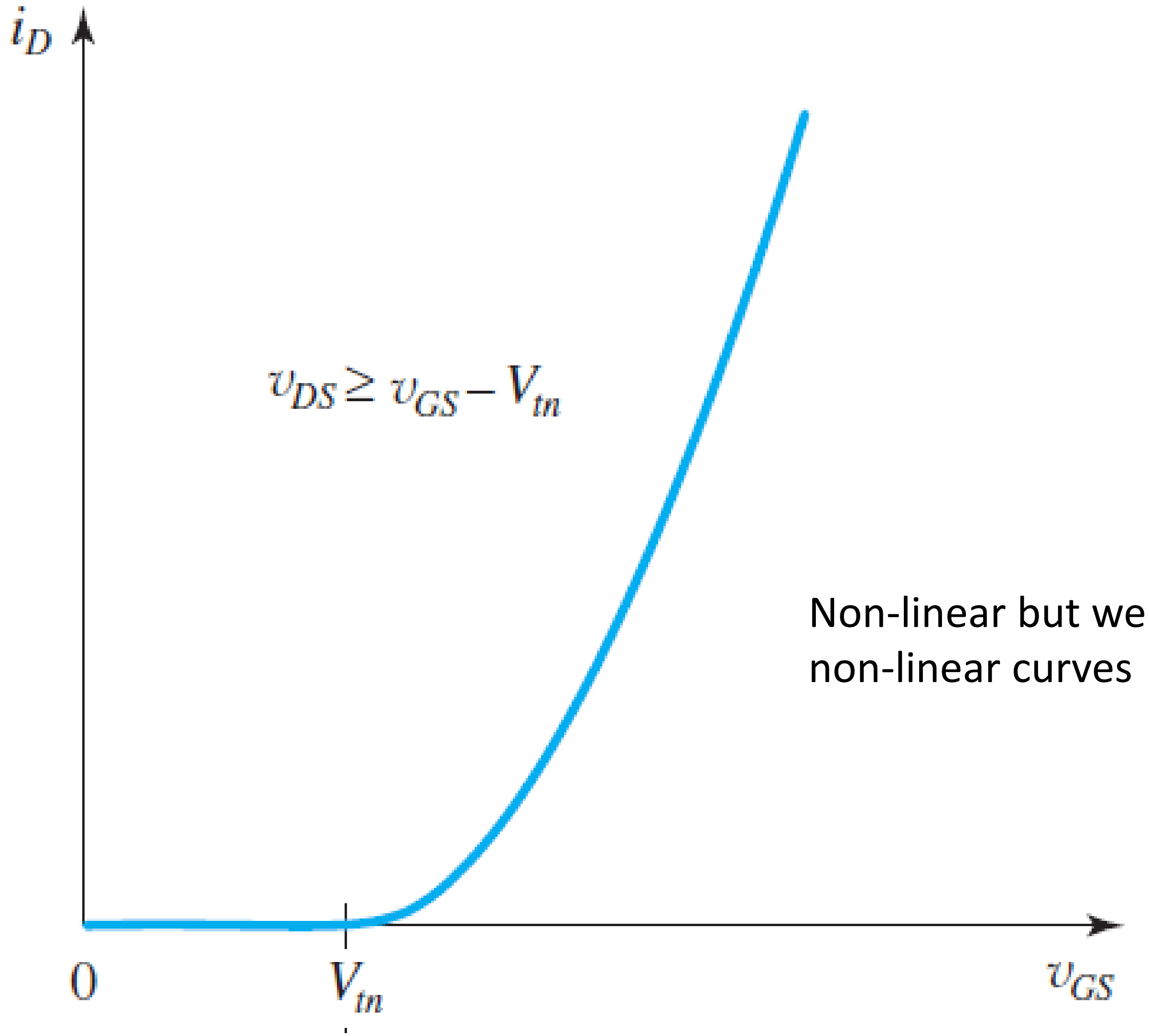
Voltage-controlled current source

Saturation current

$$i_D = \frac{1}{2} k_n' \left(\frac{W}{L} \right) (v_{GS} - V_{tn})^2$$

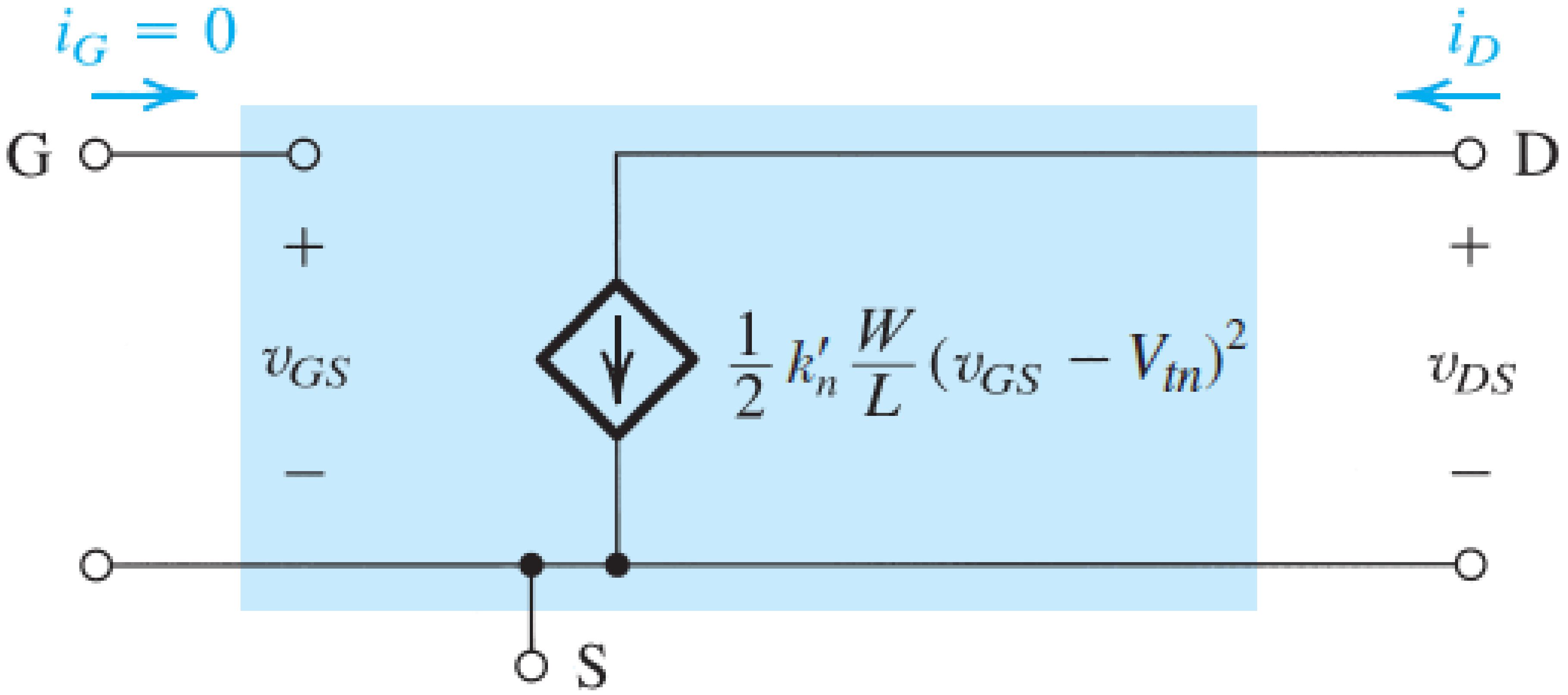
$$i_D = \frac{1}{2} k_n' \left(\frac{W}{L} \right) v_{OV}^2$$

i_D vs v_{GS} curve



Non-linear but we know what to do with non-linear curves

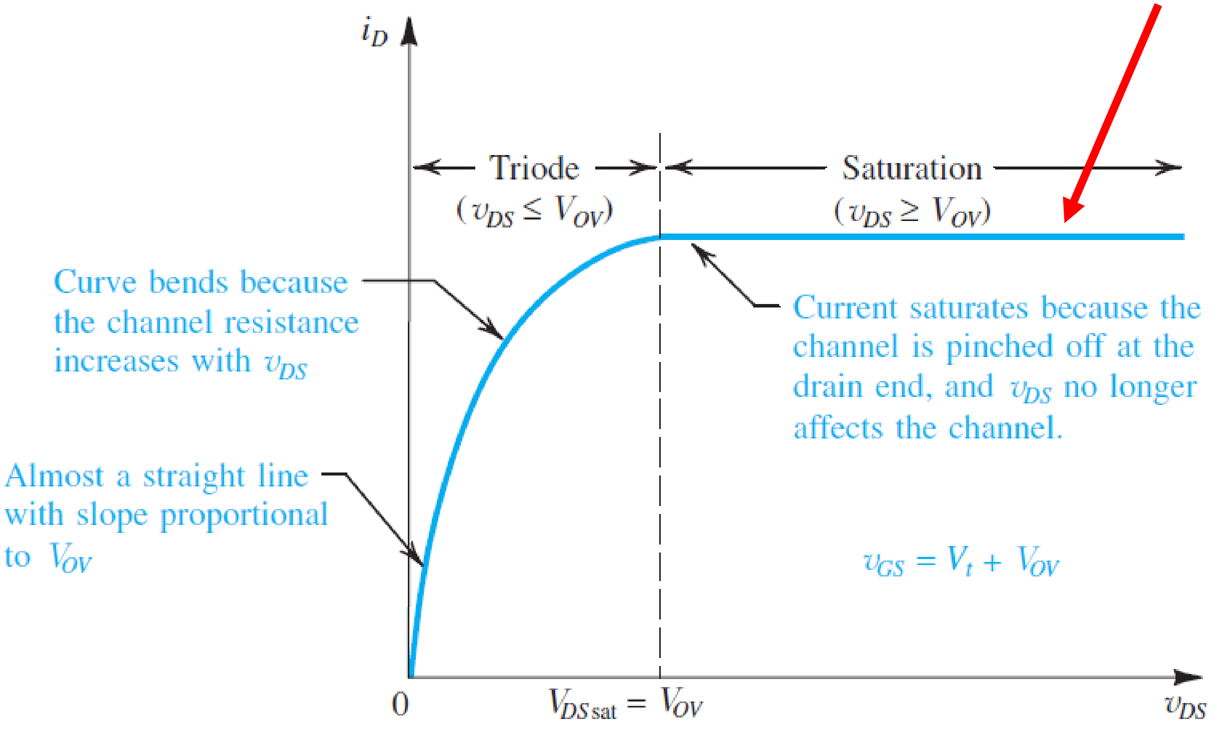
Large-Signal Model



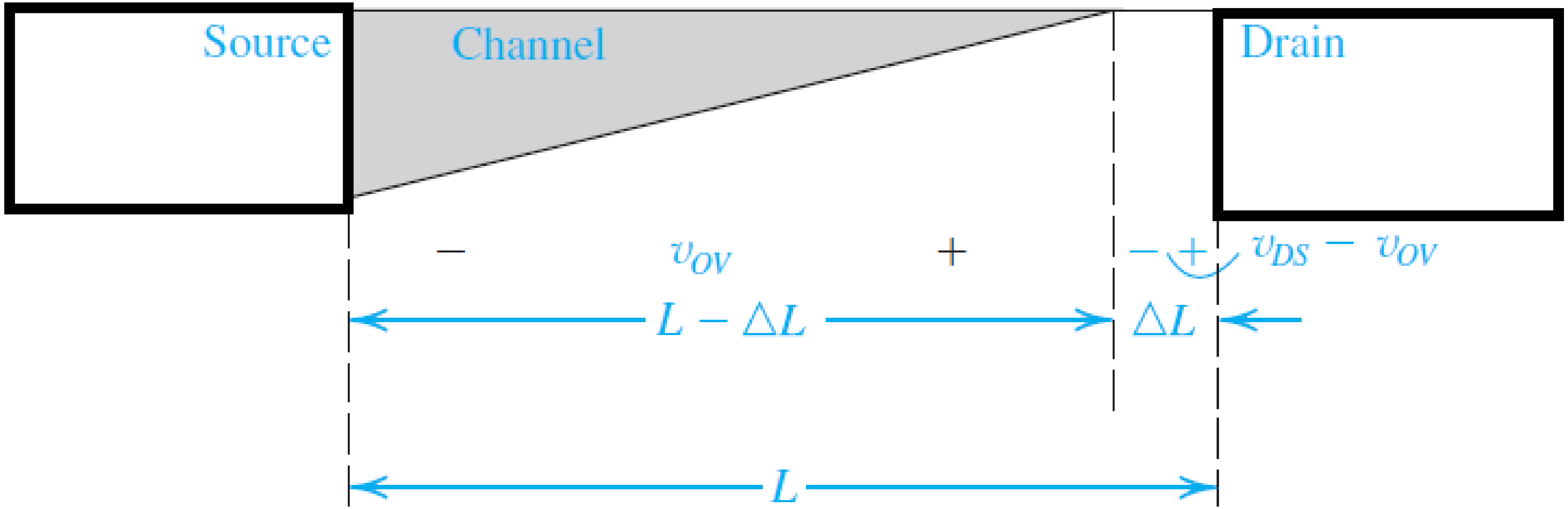
However

Finite Output Resistance in Saturation

ideal infinite output resistance



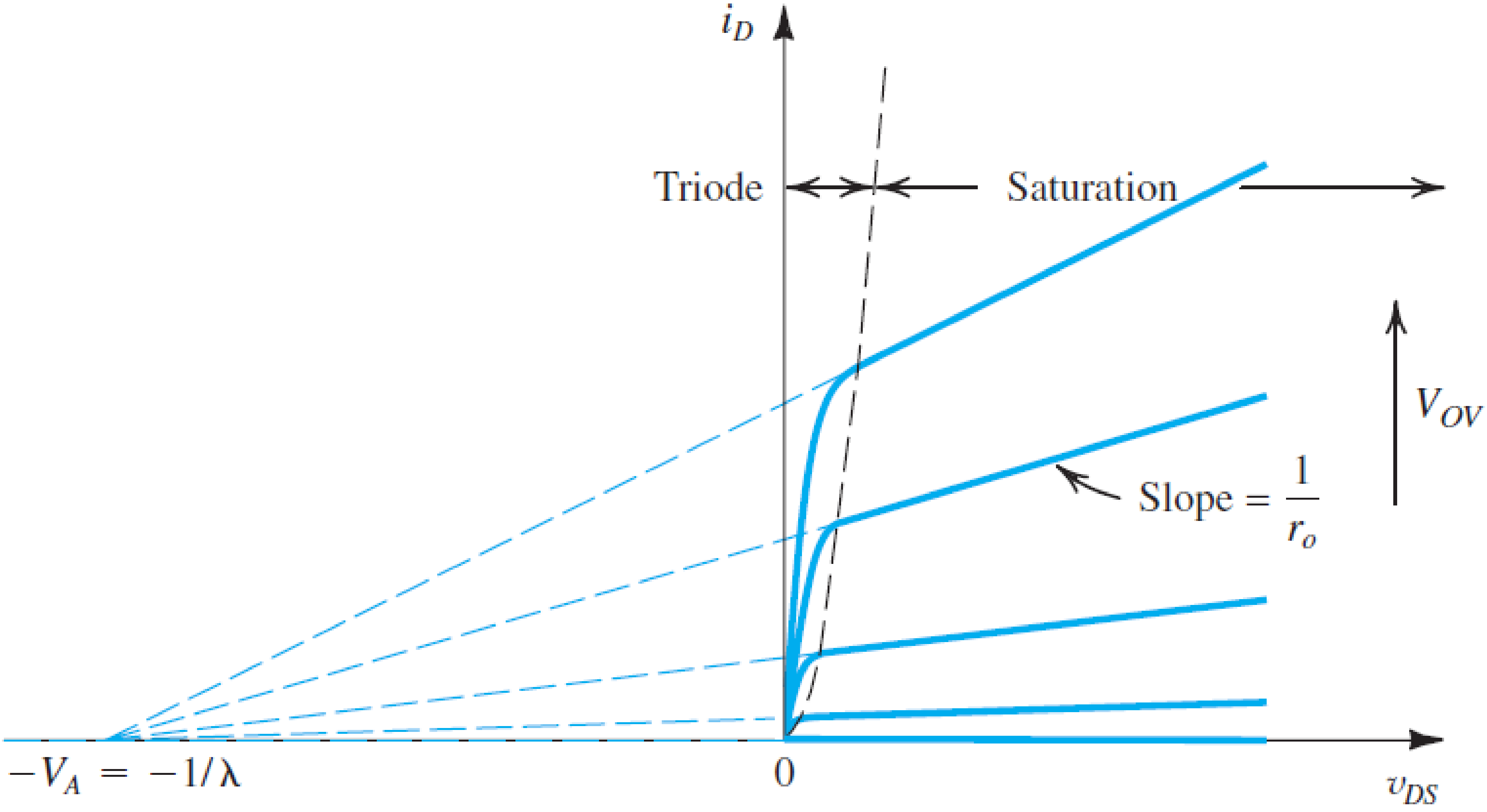
Channel-length modulation



$$i_D = \frac{1}{2} k_n' \left(\frac{W}{L} \right) (v_{GS} - V_{tn})^2 (1 + \lambda v_{DS})$$

(V^{-1})

“lamda” parameter
channel-length modulation parameter
ideal λ = 0



Early voltage

$$i_D = \frac{1}{2} k_n' \left(\frac{W}{L} \right) (v_{GS} - V_{tn})^2 (1 + \lambda v_{DS})$$

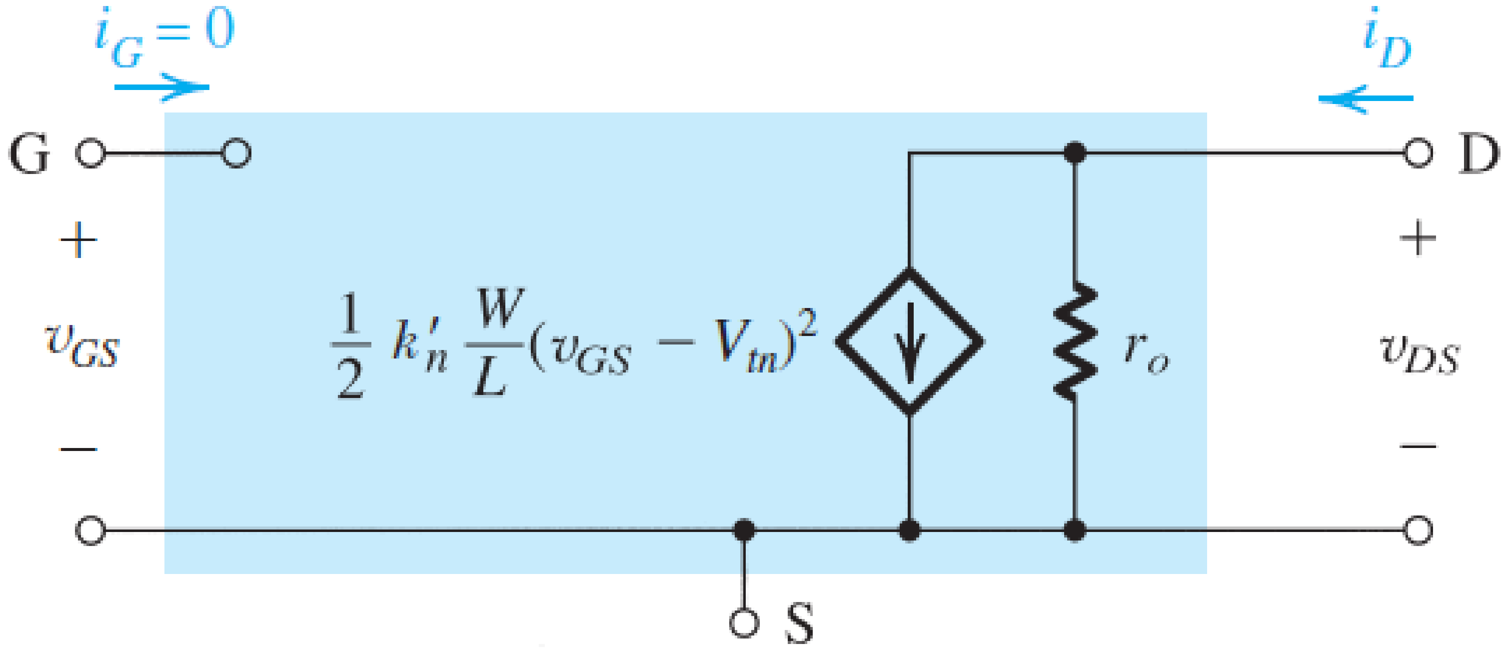
$$r_o \equiv \left[\frac{\partial i_D}{\partial v_{DS}} \right]^{-1}_{v_{GS}\ \text{constant}}$$

$$r_o = \left[\lambda \frac{k_n'}{2} \frac{W}{L} (V_{GS} - V_{tn})^2 \right]^{-1}$$

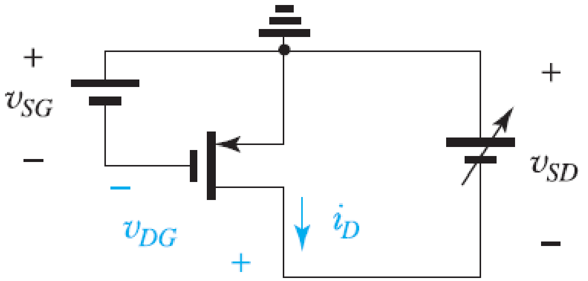
$$r_o = \frac{1}{\lambda I_D}$$

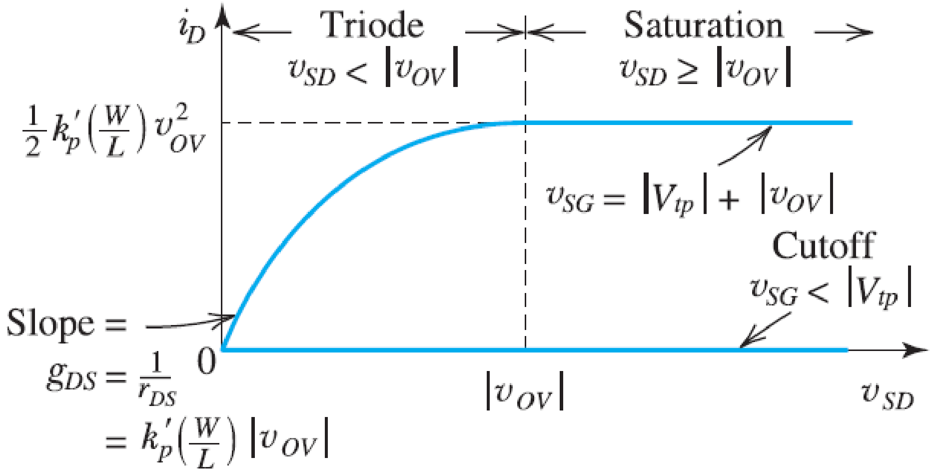
Transistor model with output resistance

$$r_o = \frac{V_A}{I'_D} \qquad I'_D = \frac{1}{2} k'_n \frac{W}{L} (V_{GS} - V_{tn})^2$$



Modes of Operation
PMOS





As you study, note voltage polarities and use of absolute values

- $v_{SG} < |V_{tp}|$: no channel; transistor in cutoff; $i_D = 0$
- $v_{SG} = |V_{tp}| + |v_{OV}|$: a channel is induced; transistor operates in the triode region or in the saturation region depending on whether the channel is continuous or pinched off at the drain end;

Triode Region

Continuous channel, obtained by:

$$v_{DG} > |V_{tp}|$$

or equivalently

$$v_{SD} < |v_{OV}|$$

Then

$$i_D = k_p'\left(\frac{W}{L}\right)\left[(v_{SG} - |V_{tp}|)v_{SD} - \frac{1}{2}v_{SD}^2\right]$$

or equivalently

$$i_D = k_p'\left(\frac{W}{L}\right)\left(|v_{OV}| - \frac{1}{2}v_{SD}\right)v_{SD}$$

Saturation Region

Pinched-off channel, obtained by:

$$v_{DG} \leq |V_{tp}|$$

or equivalently

$$v_{SD} \geq |v_{OV}|$$

Then

$$i_D = \frac{1}{2}k_p'\left(\frac{W}{L}\right)(v_{SG} - |V_{tp}|)^2$$

or equivalently

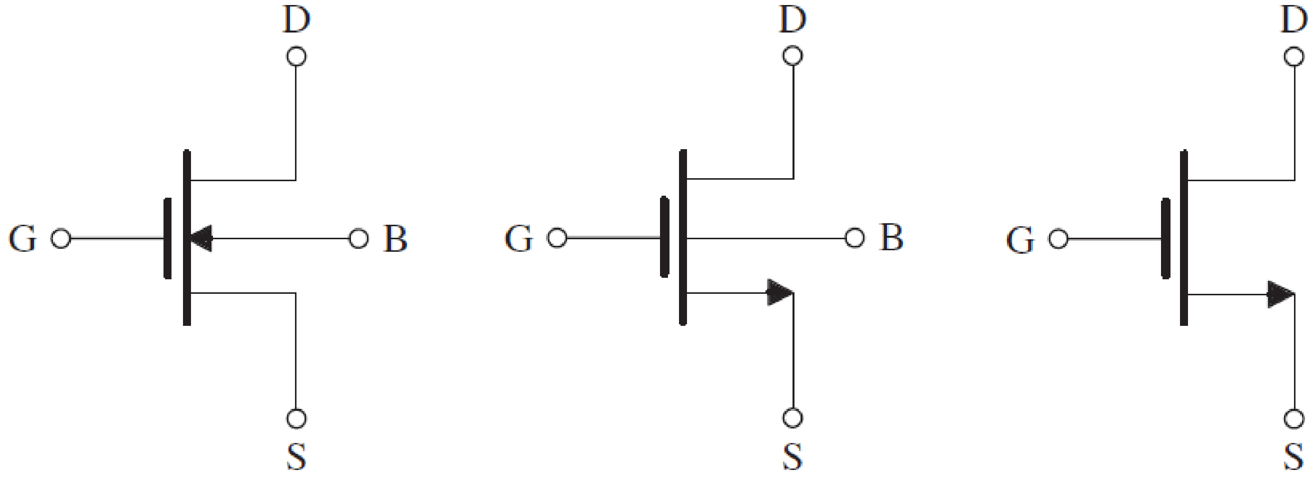
$$i_D = \frac{1}{2}k_p'\left(\frac{W}{L}\right)v_{OV}^2$$

Channel-length modulation (PMOS)

$$i_D = \frac{1}{2} k_p' \left(\frac{W}{L} \right) (v_{SG} - |V_{tp}|)^2 (1 + |\lambda| v_{SD})$$

$$i_D = \frac{1}{2} k_p' \left(\frac{W}{L} \right) (v_{SG} - |V_{tp}|)^2 \left(1 + \frac{v_{SD}}{|V_A|} \right)$$

NMOS



PMOS