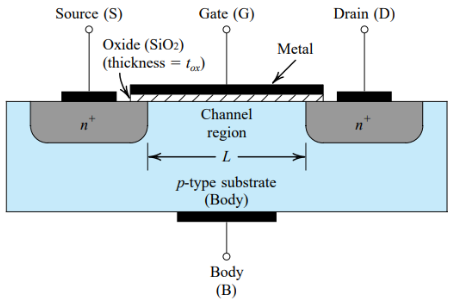


The size of the "process" indicates the minimum possible channel length.
Magnitude of the electron charge in the channel [Q]:

$$|Q| = C_{OX}(WL)v_{OV}$$

C_{OX} is the oxide capacitance, [F/m^2]

$$C_{OX} = \frac{\epsilon_{OX}}{t_{OX}}$$

ϵ_{OX} is the permittivity of the SiO$_2$.
t_{OX} is the oxide thickness.
For C_{OX} per micron squared, use
$C = C_{OX}WL$ [fF]

$$i_D = \left[(\mu_n C_{OX})\left(\frac{W}{L}\right)(v_{GS} - V_t)\right]v_{DS}$$

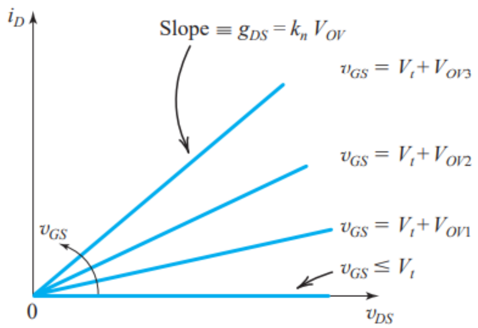
$$i_D = [g_{DS}]\, v_{DS}$$

$$k_n' = \mu_n C_{OX}$$

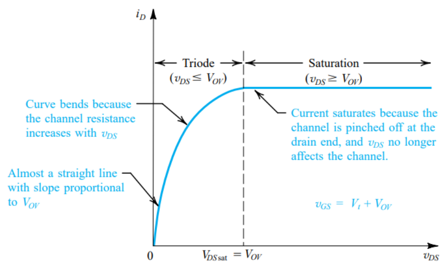
$$k_n = k_n'(W/L)$$

k_n' is **process transconductance paramter**.
k_n is **device transconductance paramter**.
When V_{DS} is small, the MOSFET behaves as a linear resistance r_{DS} whose value is controlled by the gate voltage v_{GS}.

$$r_{DS} = \frac{1}{g_{DS}}$$



Triode vs Saturation



Triode ($v_{DS} \le V_{OV}$)

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

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

Saturation ($v_{DS} \ge V_{OV}$)

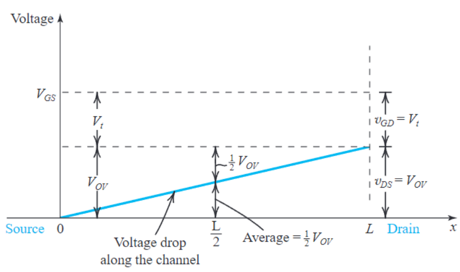
$$i_D = \frac{1}{2}k_n'\left(\frac{W}{L}\right)V_{OV}^2$$

$k_n = k_n'$, so

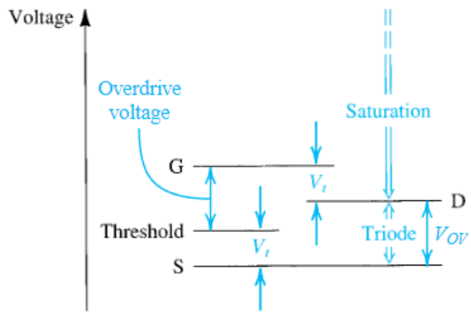
$$i_D = \frac{1}{2}k_n V_{OV}^2$$

Or,

$$i_D = \frac{1}{2}k_n(V_{GS} - V_{th})^2$$



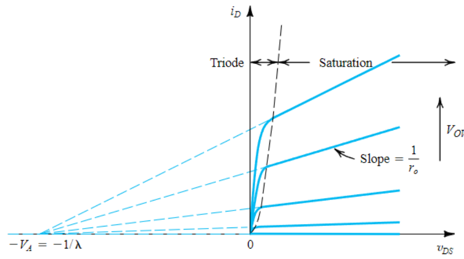
Constant V_{OV} can be replaced by variable v_{OV}. PMOS transistors operate similarly but the polarity is reversed, so v_{GS} must be negative and larger than a negative v_{tp}, as is v_{DS} negative.



If you care about **channel-length modulation**, then use the expression:

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

$v_{DS} = -\frac{1}{\lambda}$ | $V_A = \frac{1}{\lambda}$ | $V_A = V_A'L$
V_A (Early Voltage) has units of volts.
V_A' has units of volts per micron.



Expression for r_o:

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

I_D is the drain current without channel-length modulation taken into account.

$$I_D = \frac{1}{2}k_n'\frac{W}{L}(V_{GS} - V_{tn})^2$$

For a p-Channel MOSFET, everything is backwards, here is an equation showing the voltages without negative signs, everything here is considered in terms of positive voltages or magnitudes.

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

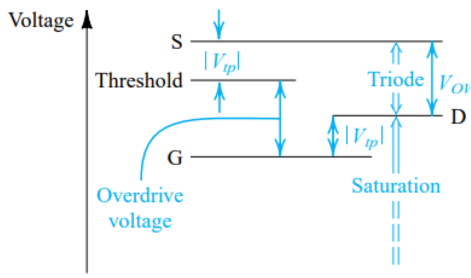
Also,

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

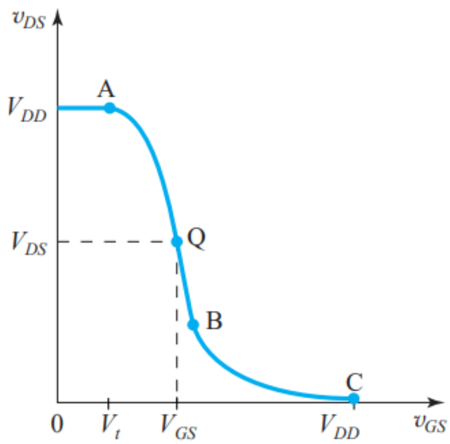
Kinda useful:

$$R_D = \frac{V_{DD} - V_D}{I_D}$$

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



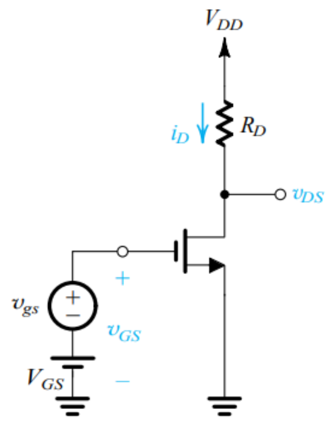
MOSFETs biased for linear amplification



Note **bias point Q**. Voltages V_{GS} and V_{DS} are related at the bias point by

$$v_{DS} = V_{DD} - \frac{1}{2}k_n R_D(v_{GS} - V_t)^2$$

$$v_{GS} = V_{GS} + v_{gs}$$



A_v is expressed in terms of V_{OV} at the bias point by

$$A_v = -k_n V_{OV} R_D$$

$$A_v = -\frac{2I_D R_D}{V_{OV}} = -\frac{I_D R_D}{V_{OV}/2}$$

To prevent *nonlinear distortion*, v_{gs} must be sufficiently small.

$$v_{gs} \ll 2(V_{GS} - Vt)$$

$$v_{gs} \ll 2V_{OV}$$

When this condition is met, we can express i_D as:

$$i_D \simeq I_D + i_d$$

Of course, $I_D = \frac{1}{2}k_n V_{OV}^2$
and $i_d = k_n(V_{GS} - V_t)v_{gs}$

$$g_m \equiv \frac{i_d}{v_{gs}} = k_n(V_{GS} - V_t)$$

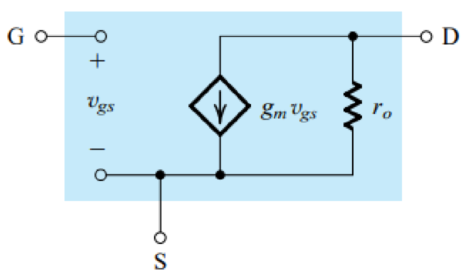
$$g_m = k_n V_{OV} = \mu_n C_{ox}\frac{W}{L}V_{OV}$$

$$g_m = k_n'(W/L)(V_{GS} - V_t) = k_n'(W/L)V_{OV}$$

$$g_m = \sqrt{2k_n'}\sqrt{W/L}\sqrt{I_D}$$

$$g_m = \frac{2I_D}{V_{GS} - V_t} = \frac{2I_D}{V_{OV}} = \sqrt{2\mu_n C_{ox}\frac{W}{L}I_D}$$

Small Signal Model



$r_o = \frac{|V_A|}{I_D} = \frac{1}{\lambda I_D}$ | $A_v = \frac{v_{ds}}{v_{gs}} = -g_m(R_D \parallel r_o)$

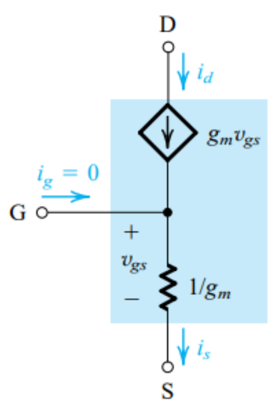
$$v_{DS} = V_{DD} - R_D i_D$$

$$v_{DS} = V_{DD} - R_D(I_D + i_d) = V_{DS} - R_D i_d$$

$$v_{DS} = -i_d R_D = -g_m v_{gs} R_D$$

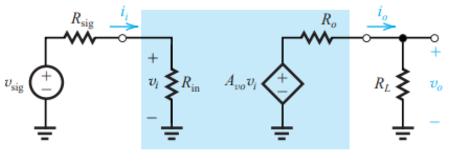
$$A_v \equiv \frac{v_{ds}}{v_{gs}} = -g_m R_D$$

T Equivalent-Circuit Model



$i_d = i_s = g_m v_{gs}$

Characterizing Amplifiers



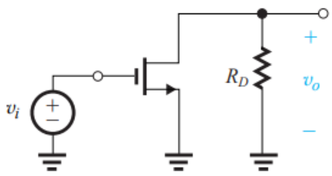
(b)

$$A_{vo} \equiv \left.\frac{v_o}{v_i}\right|_{R_L=\infty}$$

$$A_v \equiv \frac{v_o}{v_i} = A_{vo}\frac{R_L}{R_L + R_o}$$

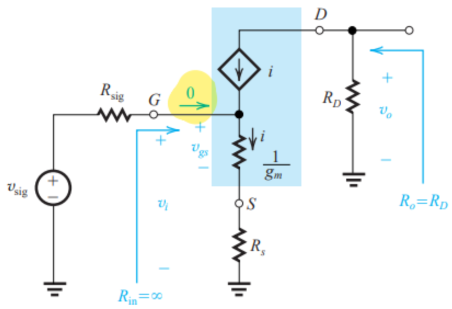
$$G_v \equiv \frac{v_o}{v_{\text{sig}}}$$

Basic circuit configurations



(a) Common Source (CS)

$R_{\text{in}} = \infty \mid v_o = -(g_m v_{gs})(R_D \parallel r_o)$
$A_{vo} = -g_m(R_D \parallel r_o)$
$A_v = G_v = -g_m(R_D \parallel R_L \parallel r_o)$
v_{sig} must be much smaller than $2V_{OV}$



(b)

$$v_{gs} = \frac{v_i}{1 + g_m R_s}$$

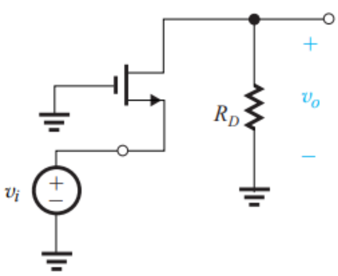
$$v_o = -iR_D$$

$$i = \frac{v_i}{1/g_m + R_s} = \left(\frac{g_m}{1 + g_m R_s}\right) v_i$$

Those two together make:

$$A_{vo} = \frac{v_o}{v_i} = -\frac{R_D}{1/g_m + R_s}$$

$$A_v = -\frac{R_D \parallel R_L}{1/g_m + R_s}$$

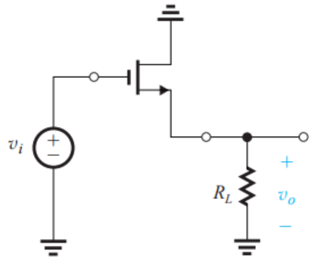


(b) Common Gate (CG)

$R_{\text{in}} = \frac{1}{g_m} \mid i = -\frac{v_i}{1/g_m} \mid v_o = -iR_D$

$$A_{vo} \equiv \frac{v_o}{v_i} = g_m R_D$$

$$G_v = \frac{(R_D \parallel R_L)}{R_{\text{sig}} + 1/g_m}$$



(c) Common Drain (CD) / Source

Often used as a voltage buffer so that the signal isn't attenuated at the output.
$R_{\text{in}} = \infty \mid A_{vo} = 1 \mid R_o = 1/g_m$

$$G_v = A_v = \frac{R_L}{R_L + 1/g_m}$$

Biasing amplifier circuits

Fixing V_G and using R_s, use
$V_G = V_{GS} + R_s I_D$

Depletion-type MOSFET is the same as normal mosfet but it has a negative V_t (positive for PMOS).