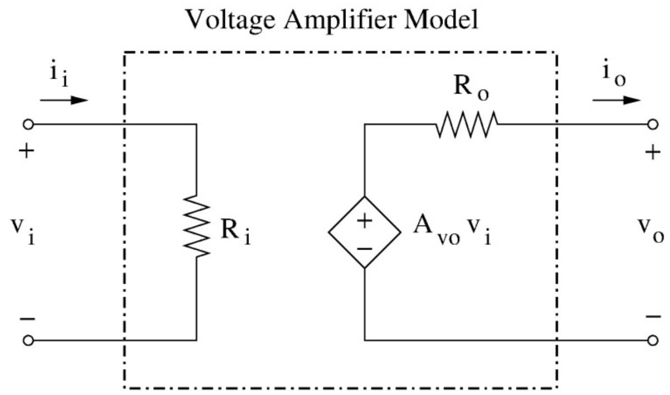
3. Fundamental amplifier configurations & Elementary R forms

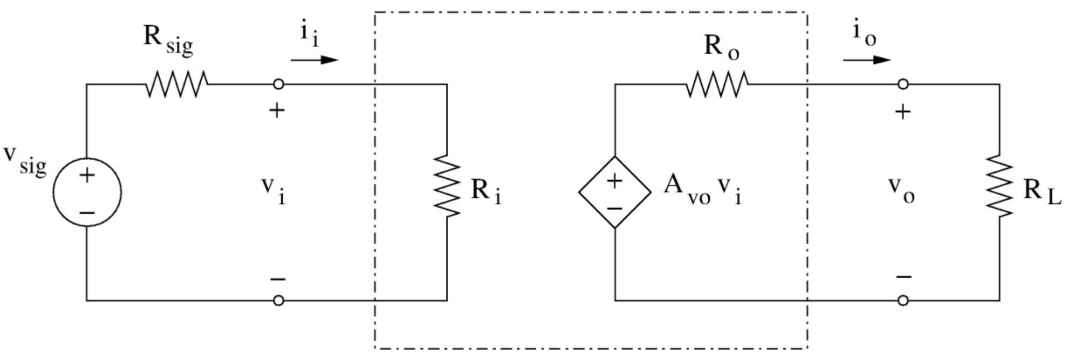
Sedra & Smith Sec. 5.6

(S&S 5th Ed: Sec. 4.7)

Voltage Amplifier Model



Input Resistance: $R_i = v_i / i_i$
Voltage gain: $A_v = v_o / v_i$ <u>with load</u>
Open-loop gain: $A_{vo} = v_o / v_i$ <u>with no load</u>
Output resistance: R_o (resistance seen between output terminals with $v_i = 0$)



$$\frac{v_i}{v_{sig}} = \frac{R_i}{R_i + R_{sig}}$$

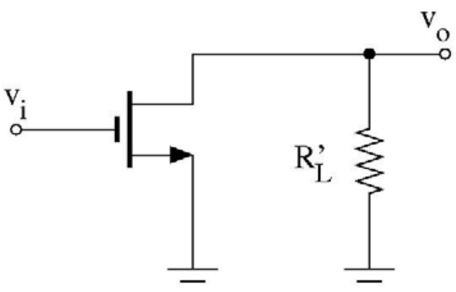
$$\frac{v_o}{v_i} = A_v = A_{vo} \cdot \frac{R_L}{R_L + R_o}$$

$$\frac{v_o}{v_{sig}} = \frac{R_i}{R_i + R_{sig}} \cdot A_{vo} \cdot \frac{R_L}{R_L + R_o}$$

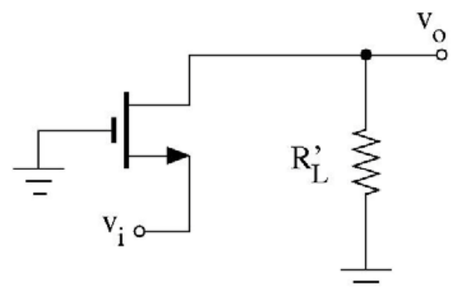
Fundamental MOS Amplifier Configurations

- **We are considering only signal circuit here!**
- **There are only <u>FOUR</u> single-transistor MOS Amplifier Configuration**

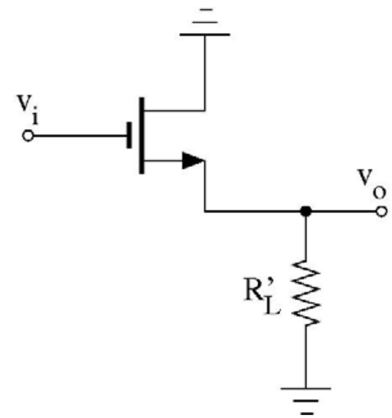
Possible MOS amplifier configurations



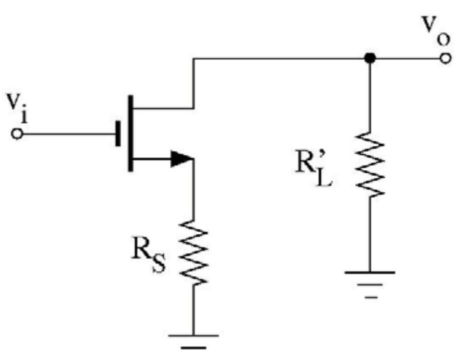
Common-Source



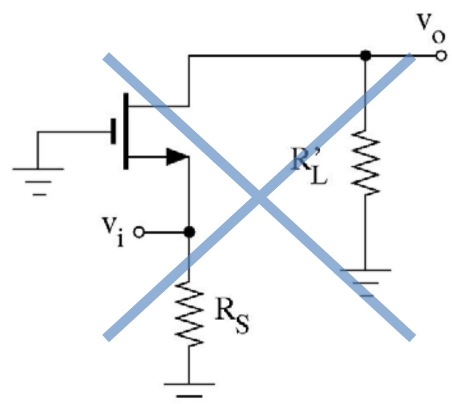
Common-Gate



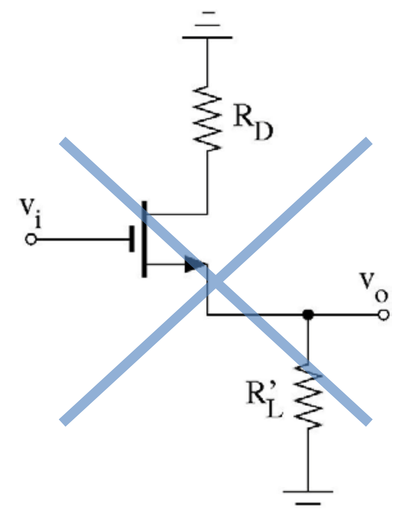
Common-Drain



Common-Source with R_s

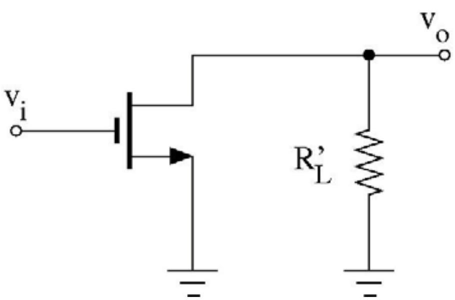


Same as Common Gate
(v_i does not change)

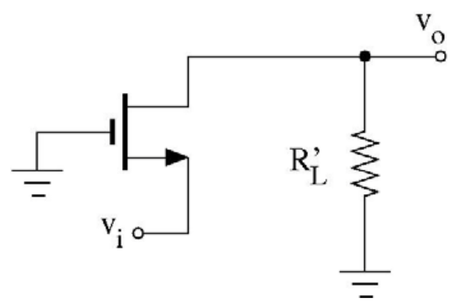


Not Useful

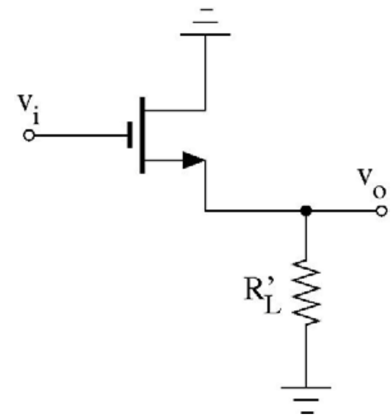
PMOS configurations are the same as NMOS



Common-Source

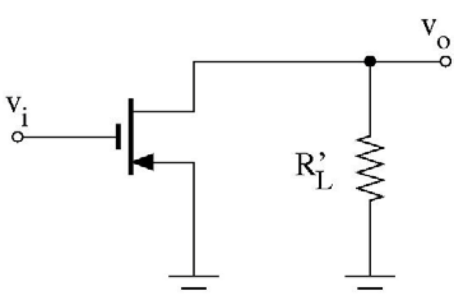


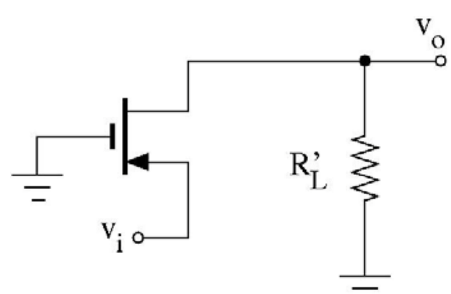
Common-Gate

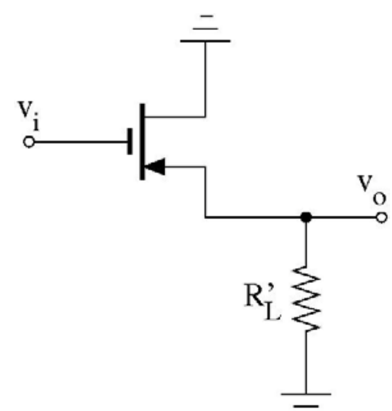


Common-Drain

Since PMOS has the same signal model, configurations and results are exactly the same



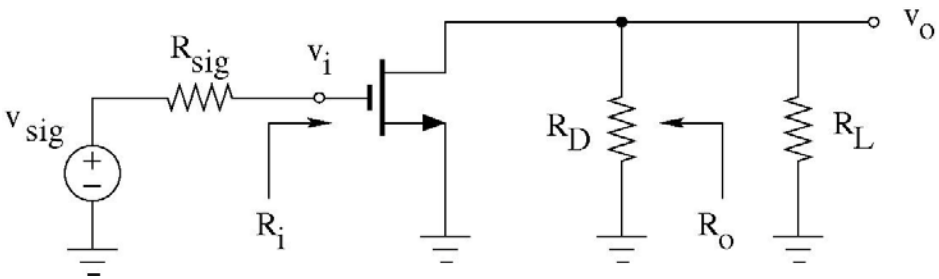




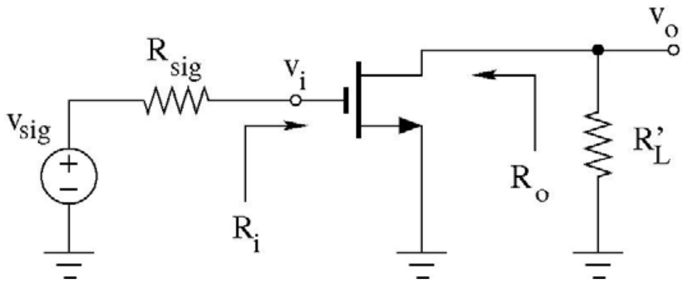
Textbook includes R_D in its analysis

Small Signal Circuit for a Common Source Amplifier

Textbook:



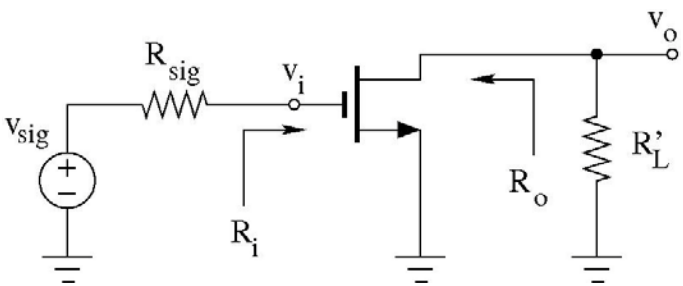
Lecture:



- Textbook is inconsistent. It includes R_D for common source and common gate but does not include R_S in common drain.
- Note R_D is parallel to R_L.
- **To avoid confusion, I am using only one resistor, R'_L,** which is the equivalent of all resistors in the drain circuit (e.g., for the above circuit, $R'_L = R_L \,||\, R_D$)

Common Source Configuration (Gain)

Signal Circuit:

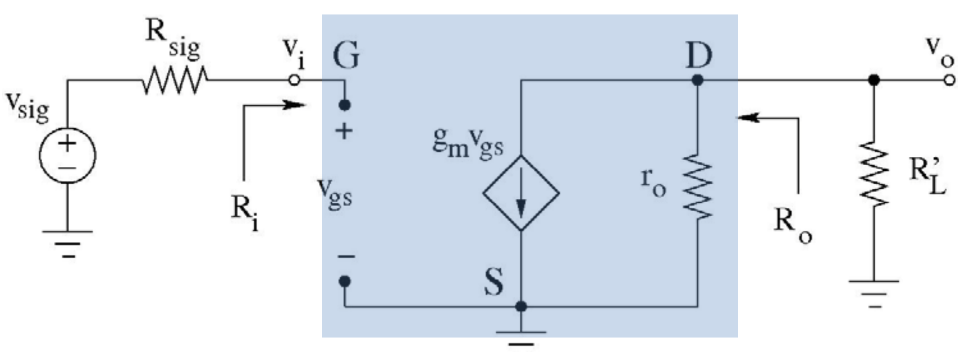


$$v_o = -g_m v_{gs} (r_o \parallel R'_L)$$

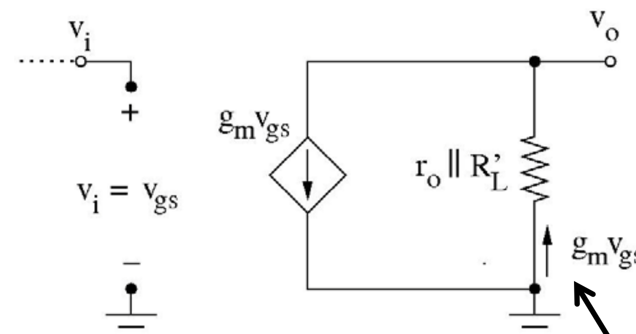
$$A_v = \frac{v_o}{v_i} = -g_m (r_o \parallel R'_L)$$

$$A_{vo} = -g_m r_o$$

Small Signal Circuit with MOS SSM



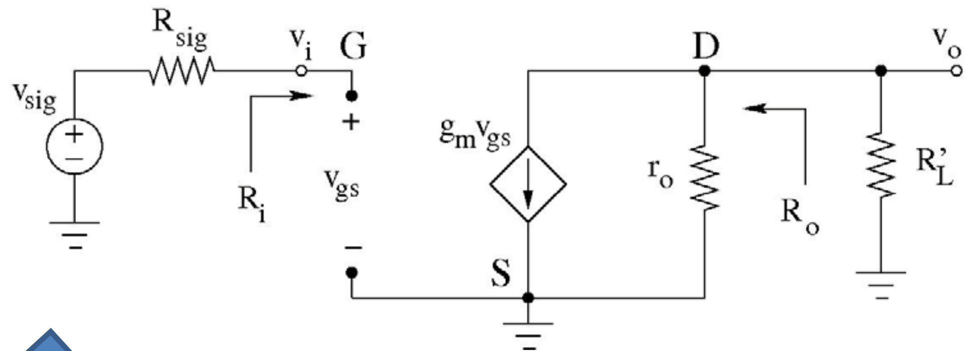
Relevant circuit for Gain calculation



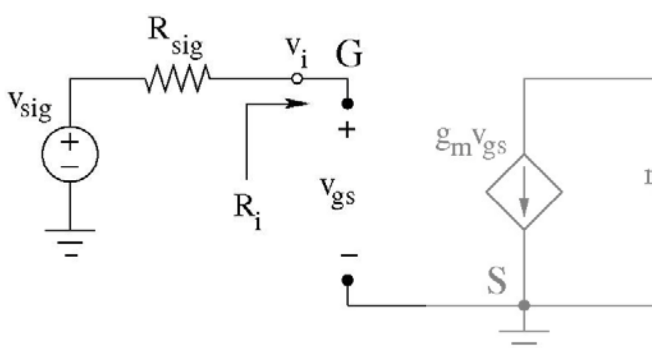
By KCL

Common Source Configuration (R_i)

Small Signal Circuit with MOS SSM



Relevant circuit for R_i calculation

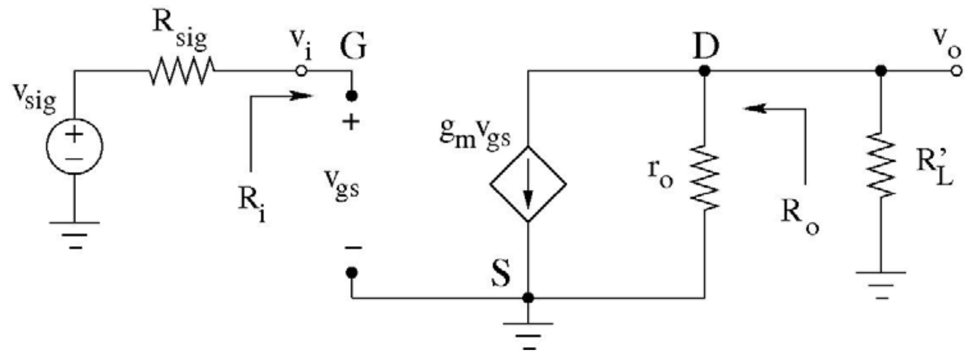


$$i_i = 0$$

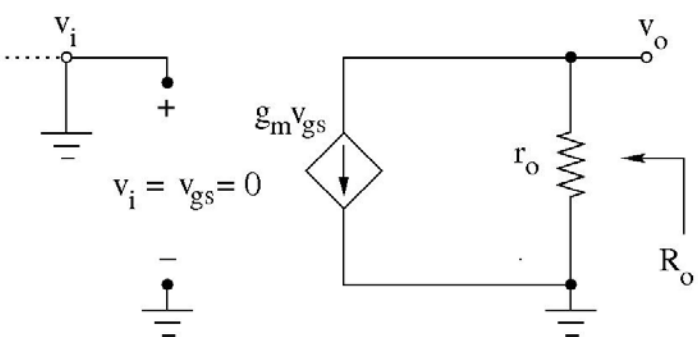
$$R_i = \frac{v_i}{i_i} = \infty$$

Common Source Configuration (R_o)

Small Signal Circuit with MOS SSM



Relevant circuit for R_o calculation (set $v_i = 0$)

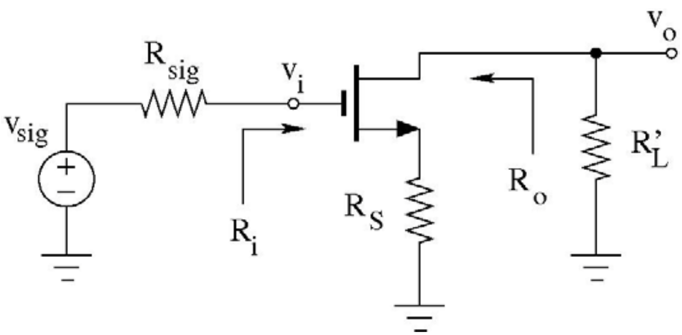


Current source becomes open circuit

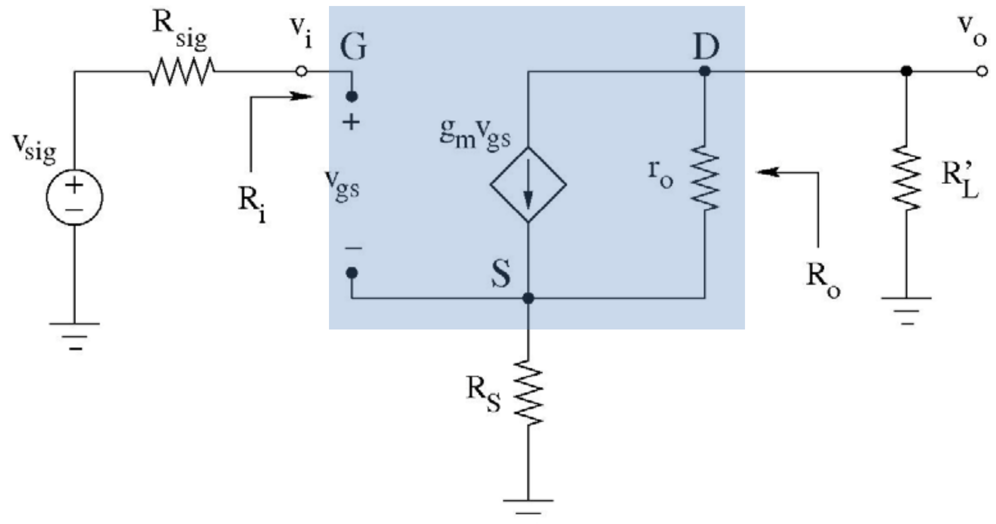
$$R_o = r_o$$

Common Source with Source Resistor

Signal Circuit:



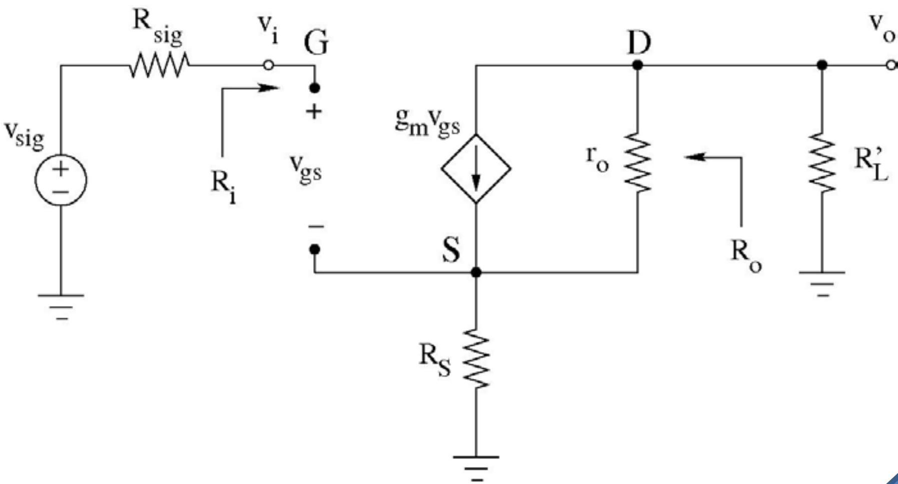
Small Signal Circuit with MOS SSM

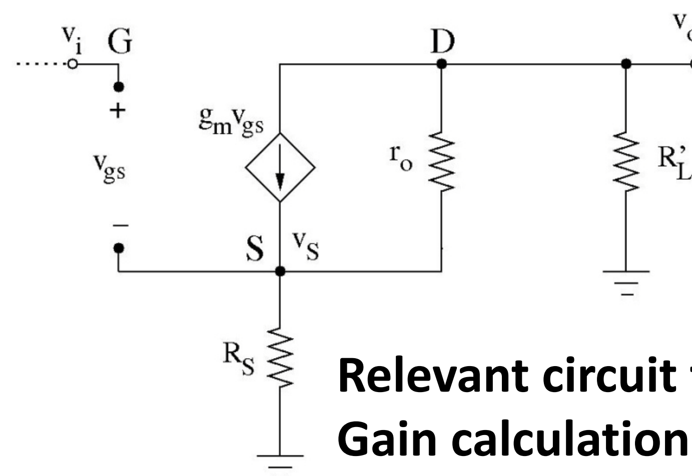


Input Resistance

$$\boxed{i_i = 0 \Rightarrow R_i = \frac{v_i}{i_i} = \infty}$$

Common Source with Source Resistor (Gain*)





Relevant circuit for Gain calculation

Node voltage method:

$$v_{gs} = v_i - v_S$$

Node v_S $\quad \frac{v_S}{R_S} + \frac{v_S - v_o}{r_o} - g_m(v_i - v_S) = 0$

Node v_o $\quad \frac{v_o}{R'_L} + \frac{v_o - v_S}{r_o} + g_m(v_i - v_S) = 0$

$$A_v = \frac{v_o}{v_i} = -\frac{g_m r_o R'_L}{r_o + (1 + g_m r_o) R_S + R'_L}$$

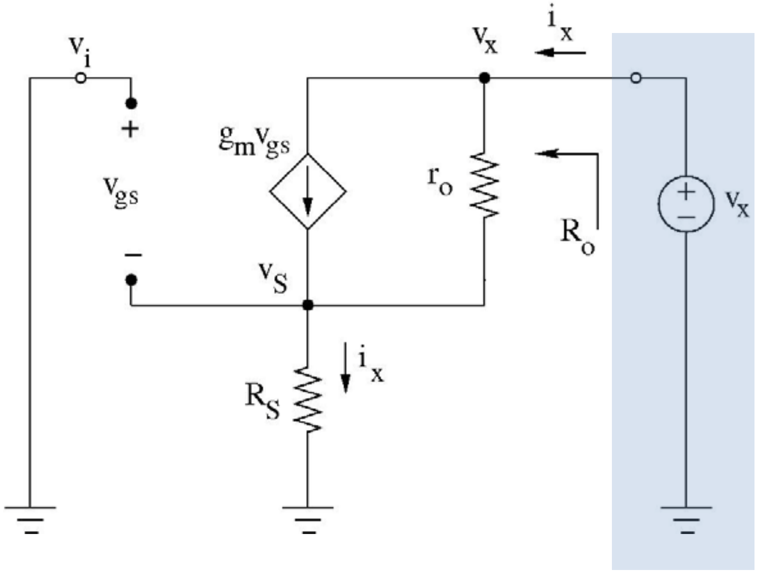
$$A_v \approx -\frac{g_m R'_L}{1 + g_m R_S + R'_L / r_o}$$

$$A_{vo} = -g_m r_o$$

* Text book ignore r_o

Common Source with Source Resistor (R_o*)

- set $v_i = 0$
- Attach v_x and compute i_x
- $R_o = v_x / i_x$



Node voltage method:

$$v_{gs} = -v_S$$

Node v_S $\quad \dfrac{v_S}{R_S} + \dfrac{v_S - v_x}{r_o} - g_m(-v_S) = 0$

$$\frac{v_S}{R_S} = \frac{v_x}{r_o + (1 + g_m r_o) R_S}$$

$$i_x = \frac{v_S}{R_S} = \frac{v_x}{r_o + (1 + g_m r_o) R_S}$$

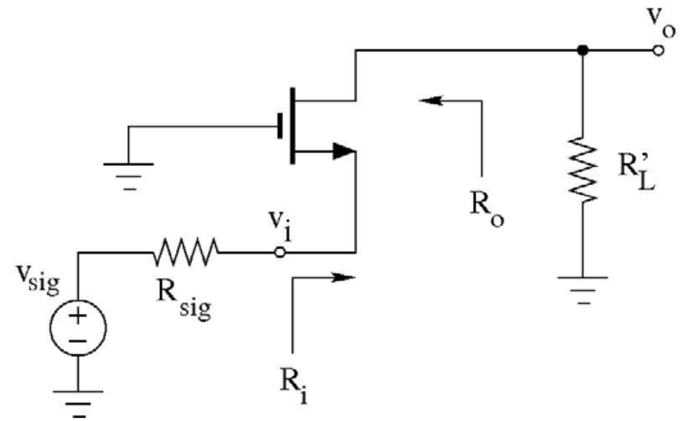
$$\frac{1}{R_o} \equiv \frac{i_x}{v_x} = \frac{1}{r_o + (1 + g_m r_o) R_S}$$

$$\boxed{R_o = r_o + (1 + g_m r_o) R_S}$$

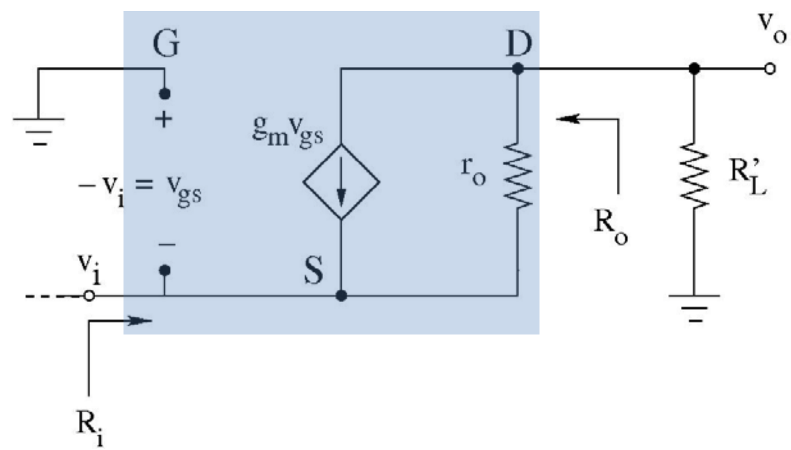
* Text book ignore r_o

Common Gate Configuration

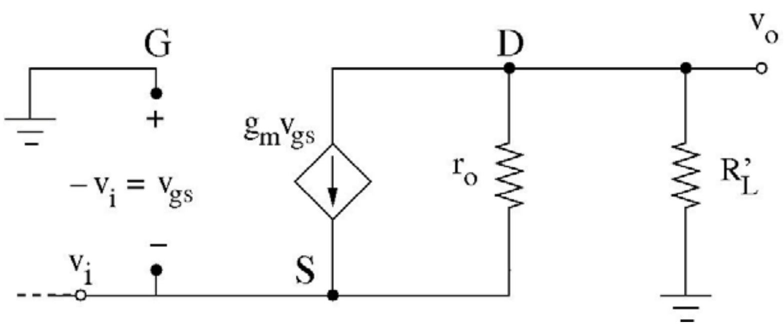
Signal Circuit:



Small Signal Circuit with MOS SSM



Common Gate Configuration (Gain*)



Node voltage method:

$$v_{gs} = -v_i$$

Node v_o $$\frac{v_o}{R_L'} + \frac{v_o - v_i}{r_o} + g_m(-v_i) = 0$$

$$\frac{v_o}{r_o \parallel R_L'} = \frac{1 + g_m r_o}{r_o} v_i$$

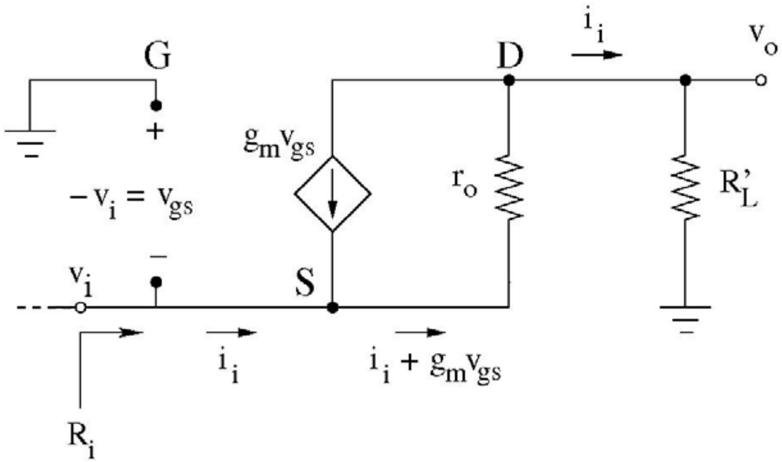
$$A_v = \frac{v_o}{v_i} = \frac{1 + g_m r_o}{r_o}(r_o \parallel R_L')$$

$$A_v \approx g_m(r_o \parallel R_L')$$

$$A_{vo} \approx g_m r_o$$

Common Gate Configuration (R_i and R_o*)

Input Resistance

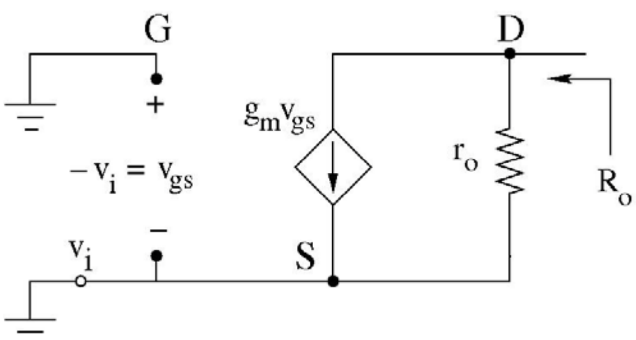


KVL: $v_i = (i_i + g_m v_{gs}) r_o + i_i R'_L$

$v_i (1 + g_m r_o) = i_i (r_o + R'_L)$

$$\boxed{R_i = \frac{v_i}{i_i} = \frac{r_o + R'_L}{1 + g_m r_o} \qquad R_i \approx \frac{1}{g_m} + \frac{R'_L}{g_m r_o}}$$

Output Resistance (set $v_i = 0$)

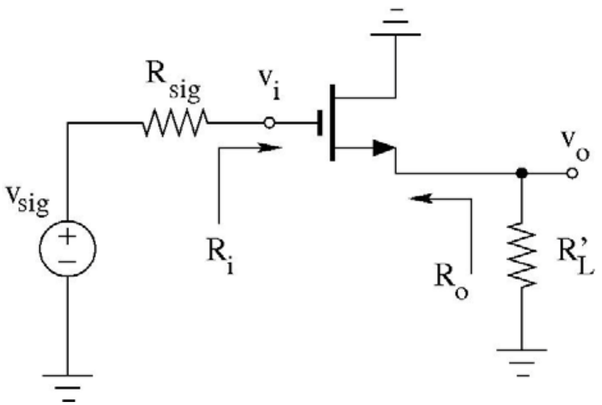


Current source becomes open circuit

$$\boxed{R_o = r_o}$$

* Text book ignore r_o

Common Drain Configuration (Source Follower)



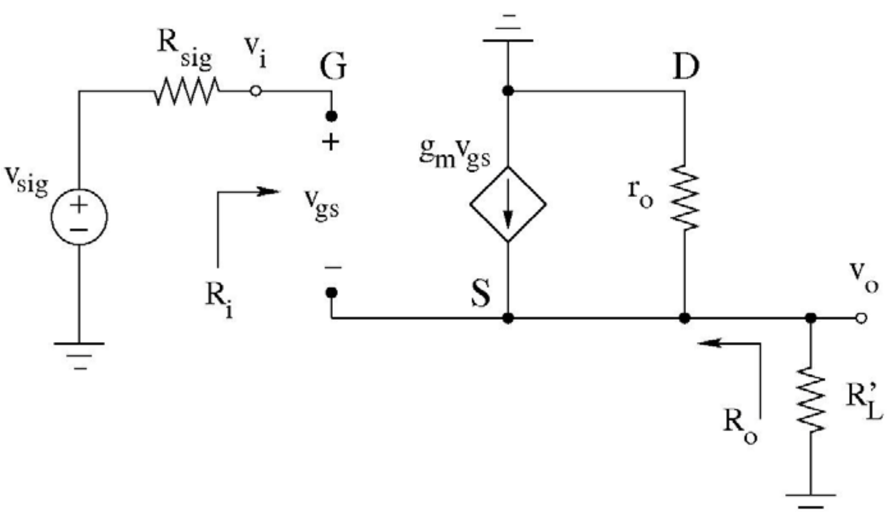
Gain

Node voltage method:

$$v_{gs} = v_i - v_o$$

Node v_o $$\frac{v_o}{R'_L} + \frac{v_o}{r_o} - g_m(v_i - v_o) = 0$$

$$g_m v_i = \frac{v_o}{r_o \parallel R'_L} + g_m v_o$$

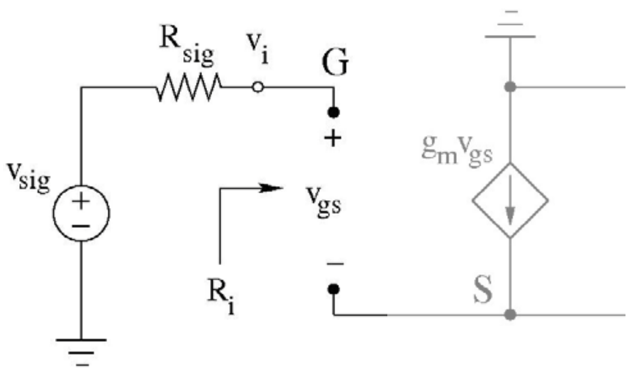


$$A_v = \frac{g_m(r_o \parallel R'_L)}{1 + g_m(r_o \parallel R'_L)}$$

$$A_{vo} = \frac{g_m r_o}{1 + g_m r_o} \approx 1$$

Common Drain Configuration (Source Follower)

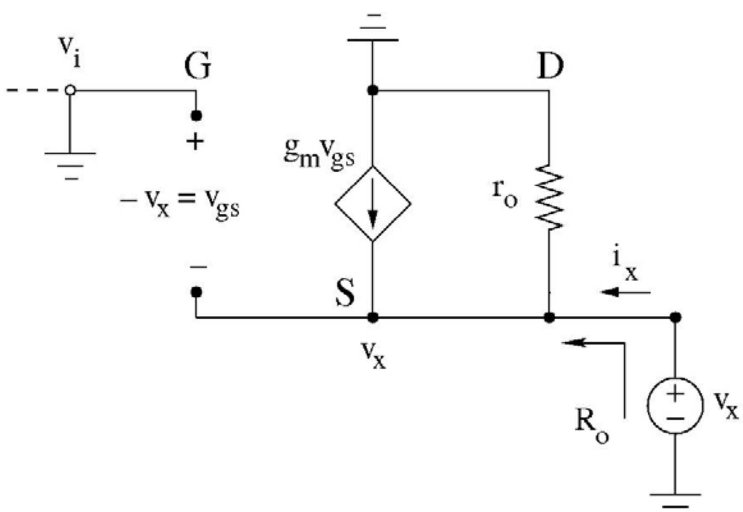
Input Resistance



$$i_i = 0$$

$$\boxed{R_i = \frac{v_i}{i_i} = \infty}$$

Output Resistance (set $v_i = 0$)

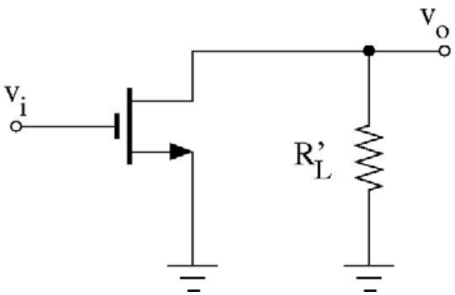


$$i_x = \frac{v_x}{r_o} - g_m v_{gs} = \frac{v_x}{r_o} + \frac{v_x}{1/g_m}$$

$$\boxed{R_o = \frac{1}{g_m} \| r_o \approx \frac{1}{g_m}}$$

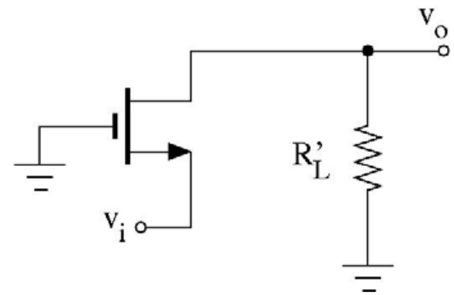
MOS Fundamental Amplifier Configurations
(PMOS circuits are identical)

Common Source



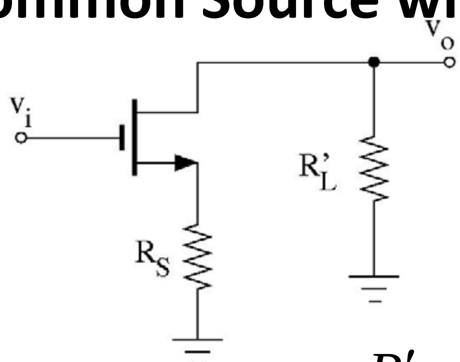
$$A_v = -g_m (r_o \parallel R'_L)$$

Common Gate



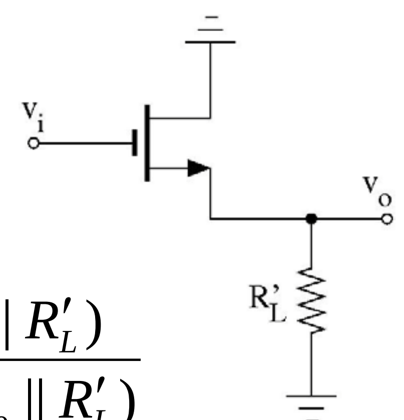
$$A_v = g_m (r_o \parallel R'_L)$$

Common Source with RS



$$A_v = -\frac{g_m R'_L}{1 + g_m R_S + R'_L / r_o}$$

Common Drain/Source Follower

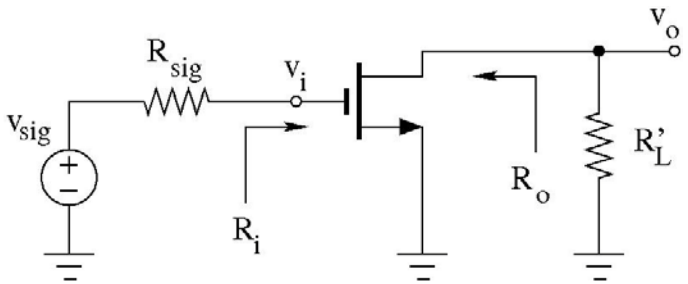


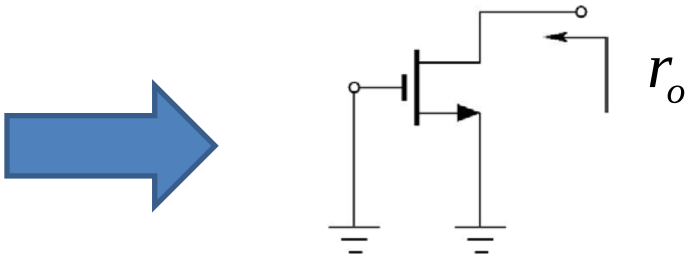
$$A_v = \frac{g_m (r_o \parallel R'_L)}{1 + g_m (r_o \parallel R'_L)}$$

Elementary R Forms

A Transistor can be configured to act as a resistor for small signals!

Ex: Output resistance of a CS Amplifier





Set $v_i = 0$, current source becomes open circuit

$$R_o = r_o$$

Notation:
r_o is the small-signal resistance between the point and ground

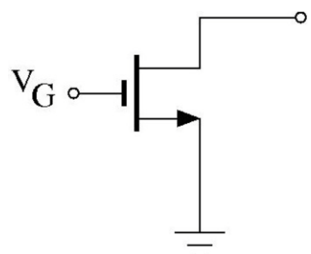
- If we connect any two terminals of a MOS, we get a two-terminal device.
  - For Small Signals, this two terminal device can be replaced with its Thevenin equivalent circuit.
  - As there is NO independent sources present, the Thevenin equivalent circuit is reduced to a resistor.

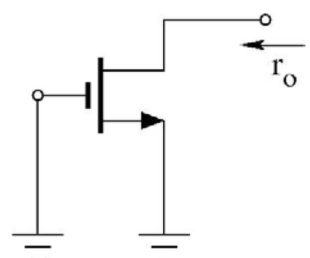
A Transistor can be configured to act as a resistor <u>for small signals</u>!

- But, MOS should be in saturation for small signal model to work!
  - Connection between MOS terminals are, therefore, made through <u>ground for signals</u>.
  - In fact, one or two MOS terminals have to be connected to bias power supply to ensure that MOS is in saturation (there is an exception, see next page)

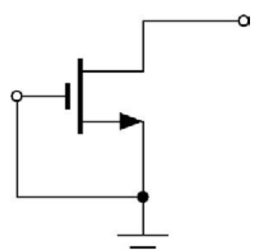
Real Circuit **Signal Circuit**

A)





B)



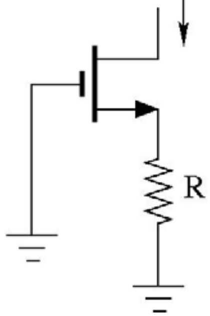
No Signal circuit

MOS is NOT in saturation

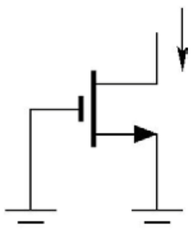
MOS Elementary R Forms

(PMOS circuits are identical)

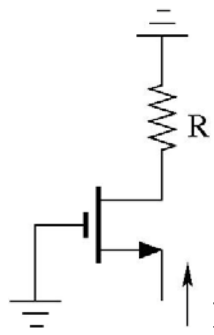
$$r_o(1+g_m R)+R \approx r_o(1+g_m R)$$



Output resistance of CS Amp with R_s

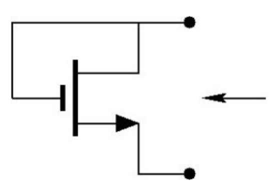


$$r_o$$



$$\frac{r_o+R}{1+g_m r_o} \approx \frac{1}{g_m} + \frac{R}{g_m r_o}$$

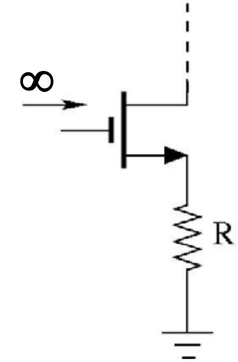
Input resistance of CG Amp



$$\frac{1}{g_m} \| r_o \approx \frac{1}{g_m}$$

Diode-connected Transistor
Always in saturation!

$$\infty$$



Input resistance of CS Amp

Above configurations are for <u>Small Signal</u>. Typically one or both grounds are connected to bias voltage sources to ensure that MOS is in saturation!

Gain, input, and output resistances of MOS amplifiers can be found using fundamental amplifiers configurations and elementary R forms