MOSFETs as Amplifiers

- In saturation, the MOSFET acts as a voltage controlled current source

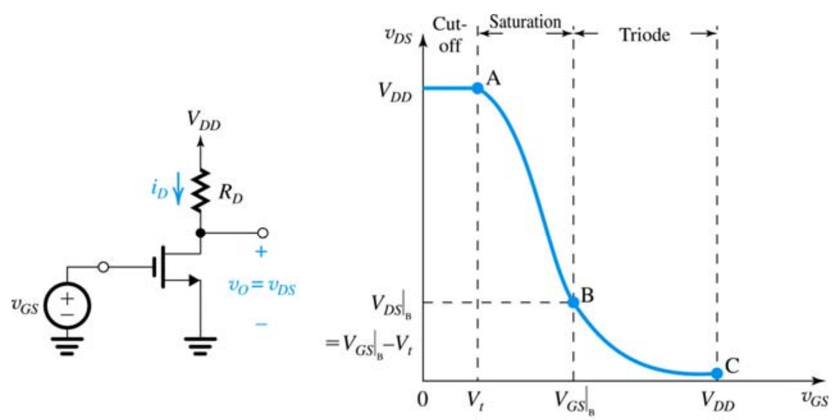
$$i_D = \frac{1}{2}k_n^{'}\left(\frac{W}{L}\right)V_{ov}^2(1+\lambda v_{DS})$$

- Non-linear V_{ov}^2
- If the current (i_D) flows in a resistive load, output voltage is proportional to i_D.

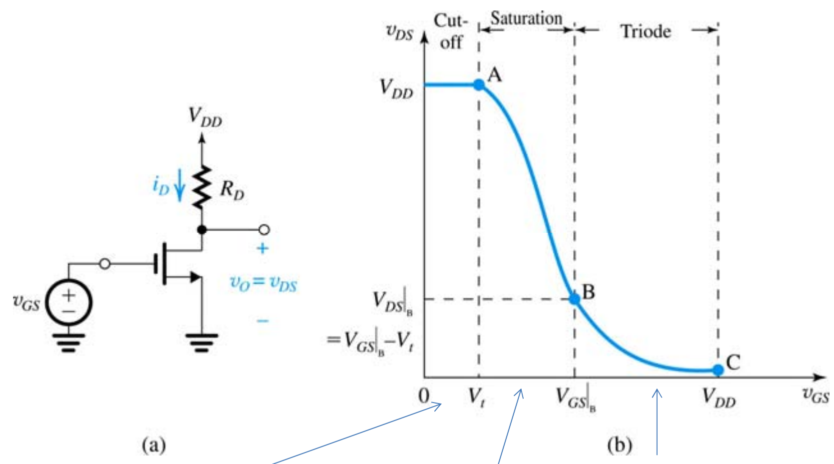
MOSFET as an amplifier

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

Later, we will discuss small signal equivalent circuit



(a) (b)

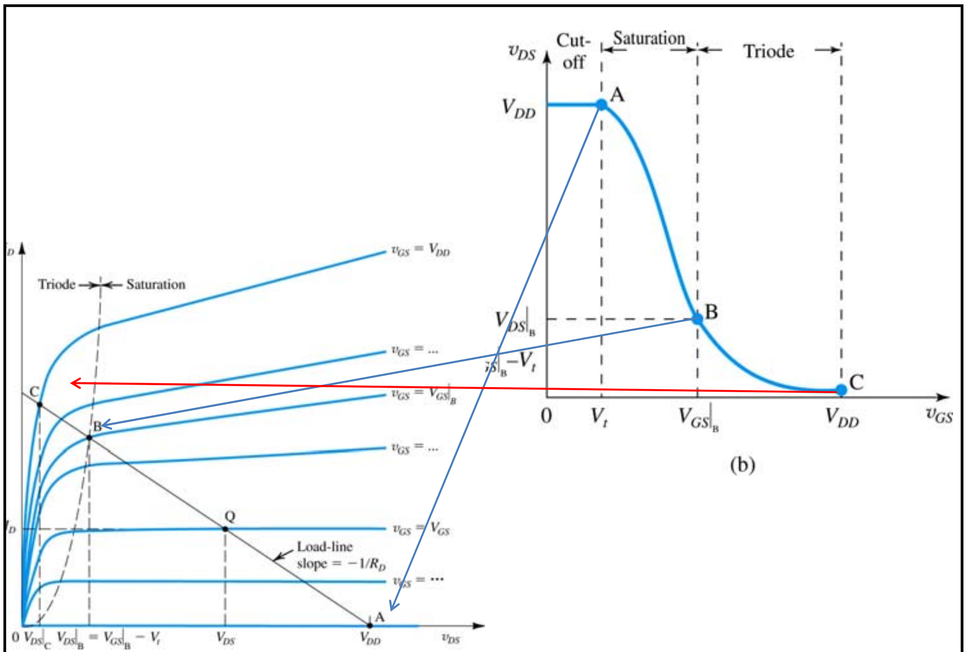


(a) (b)

$v_{gs} < V_t$ cut off

v_{gs} increases when $v_{DS} = V_{GS} - V_t$ →Triode

v_{gs} increases when reaches V_t MOSFET is ON
Since initially v_{DS} is high (no drop on R_D) →Saturation



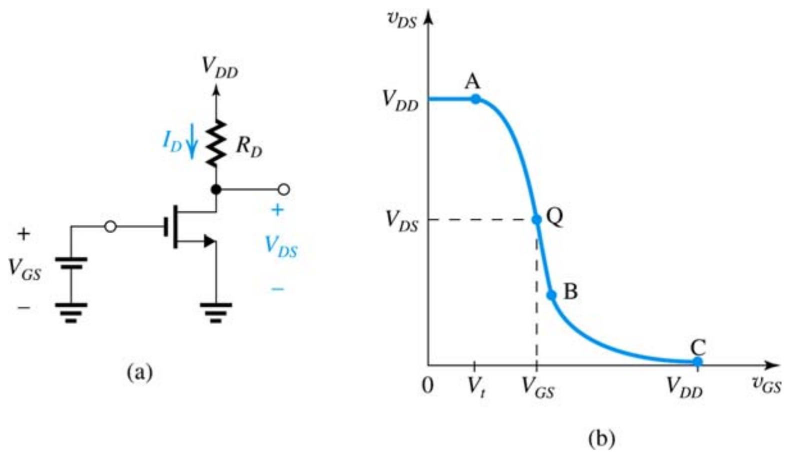


Figure 5.28 Biasing the MOSFET amplifier at a point Q located on the segment AB of the VTC.

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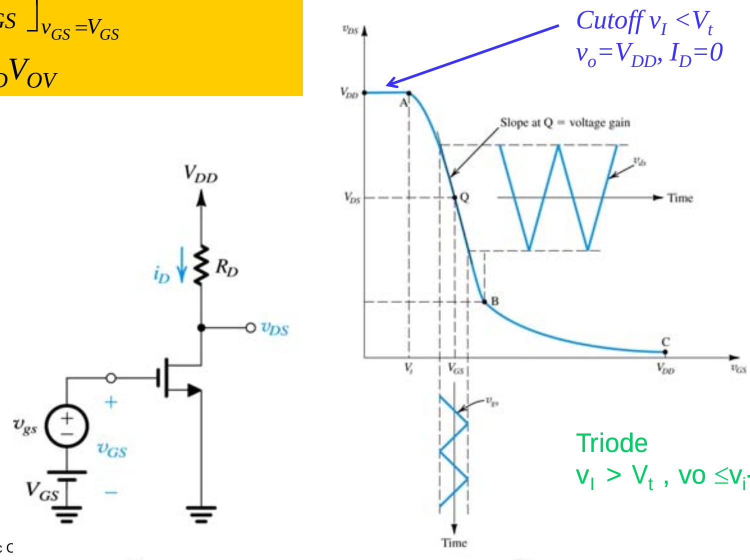
$$v_{DS} = V_{DD} - 1/2\, k_n R_D (v_{GS} - V_t)^2$$

$$A_v = \left[\frac{dv_{DS}}{dv_{GS}}\right]_{v_{GS} = V_{GS}}$$

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

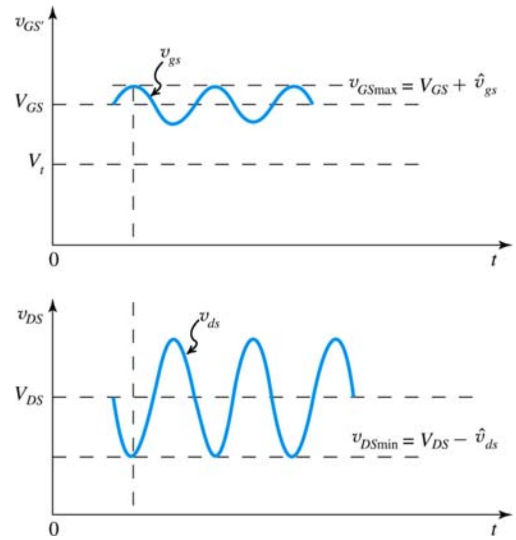
Saturation
$v_I > V_t$, $v_o \geq V_I$ - V_t

Cutoff $v_I < V_t$
$v_o = V_{DD}$, $I_D = 0$



Triode
$v_I > V_t$, vo $\leq v_i$-V_t

$$V_{DS} = V_{DD} - 1/2\, k_n R_D (v_{GS} - V_t)^2$$
$$v_{GS}(t) = V_{GS} + v_{gs}(t)$$



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VTC by Graphical Analysis

- From elementary circuit theory we have
- $V_{DD} = i_D R_D + v_{DS}$
- That represents a line with a slope of -1/RD
- The transistor operates on a point along that line.

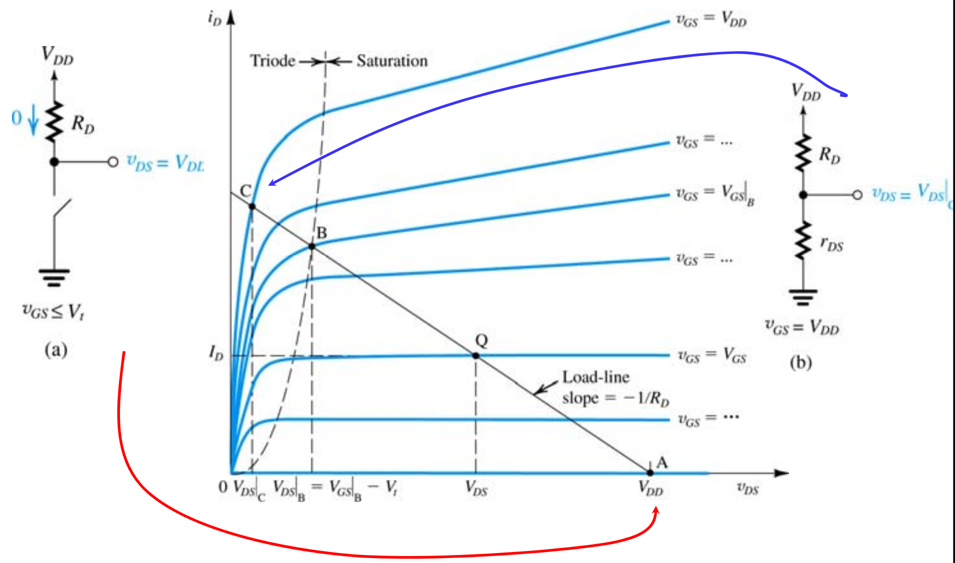

Figure 5.31 Graphical construction to determine the voltage transfer characteristic of the amplifier in Fig. 5.29(a).

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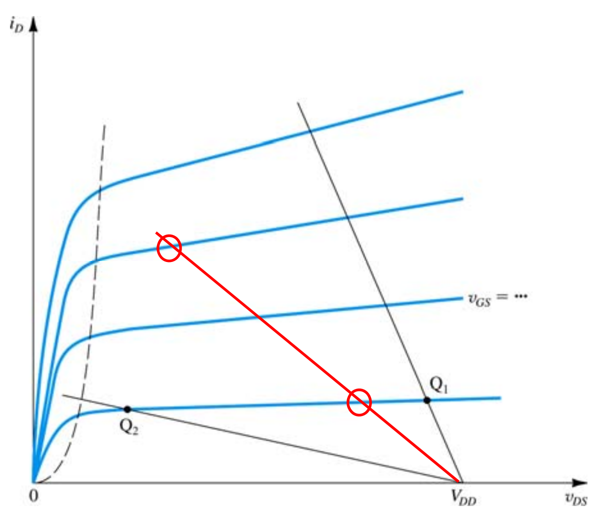

Figure 5.33 Two load lines and corresponding bias points. Bias point Q_1 does not leave sufficient room for positive signal swing at the drain (too close to V_{DD}). Bias point Q_2 is too close to the boundary of the triode region and might not allow for sufficient negative signal swing.

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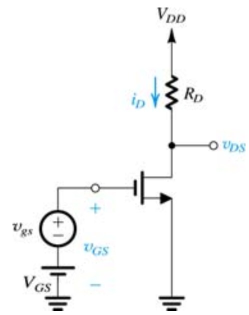
Small Signal Operations

- The signal v_{gs} is superimposed on V_{GS}
- $v_{GS}=V_{GS}+v_{gs}$
- $I_D = \frac{1}{2} k_n V_{OV}$
- $i_D = \frac{1}{2} k_n (V_{OV} + v_{gs})^2$



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

Small Signal Operation

- To minimize the nonlinear part

$$\frac{1}{2} k_n v_{gs}^2 << k_n V_{OV} v_{gs}$$
$$v_{gs} << 2V_{OV}$$

- $i_D \approx I_D + i_d$

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

Small Signal Operation

Assuming small

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

$$i_d = k_n V_{OV} v_{gs}$$

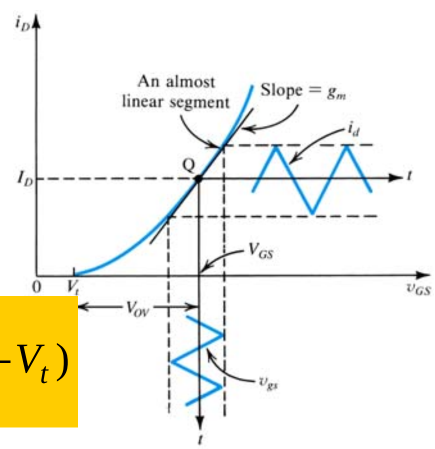
$$g_m = \frac{i_d}{v_{gs}} = k_n V_{OV}$$

$$g_m = \left. \frac{\partial i_D}{\partial v_{GS}} \right|_{v_{GS} = V_{GS}}$$

- Transconductance: relates i_d and v_{ds}

Transconductance

- The slope of the i_{DS}-v_{DS} characteristics at the Q point (DC bias point)
- As shown, almost linear.



$$g_m = \frac{i_D}{v_{GS}} = k_n' \left(\frac{W}{L} \right) (V_{GS} - V_t)$$

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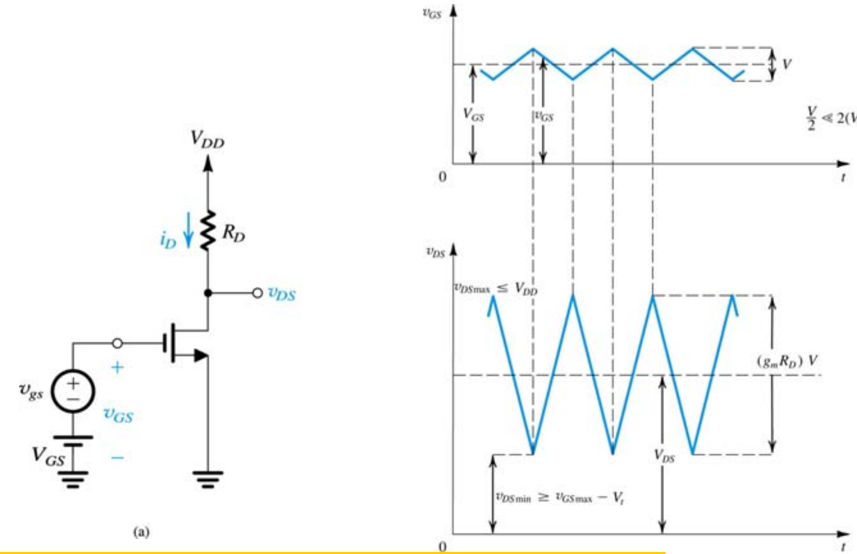


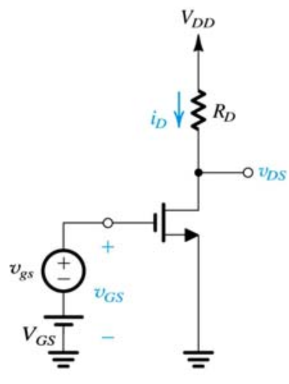
$$v_D = V_{DD} - R_D i_D = V_{DD} - R_D(I_D + i_d)$$
$$v_D = V_D - R_D i_D$$

Separating DC Analysis and Signal Analysis

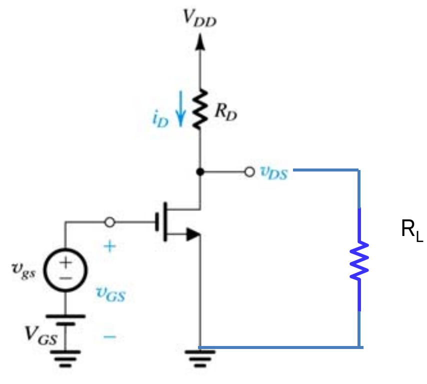
- Signal quantities are superimposed on DC quantities.
- We can separate DC and AC Analysis.
- The DC Analysis determine the Q Point
- (Bypass) Capacitors are added to prevent disturbing the DC bias (Q point). **WHY?**
- Draw the circuit from the signal point of view
  - DC voltages (current) are short (open)
  - Capacitors are short
  - MOSFET replaced by **small signal equivalent Circuit**

Why Capacotors

- Adding the load



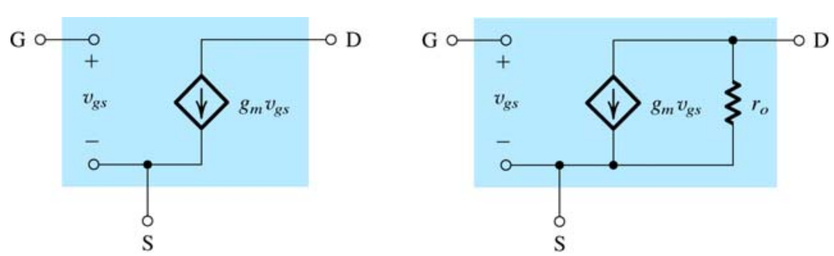
(a)



(a)

Small Signal Equivalent Circuit

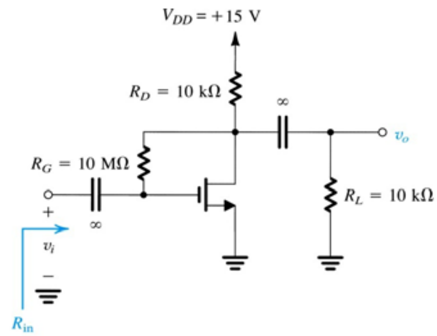
- Represents only time varying component (DC only determine the bias point)
- What is the difference between (a) and (b).



(a) (b)

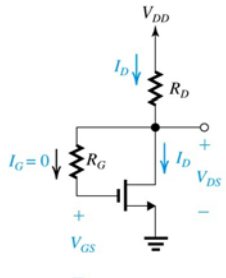
Example

- Find the small signal voltage gain, input resistance, and the largest allowable input signal. V_t=1.5V, k'_n=0.25mA/V^2, VA=50 V.



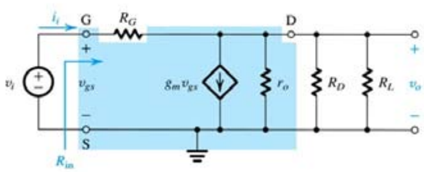
(a)

Example cont.

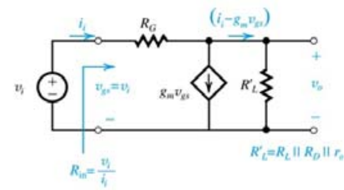


(b)

Example cont.

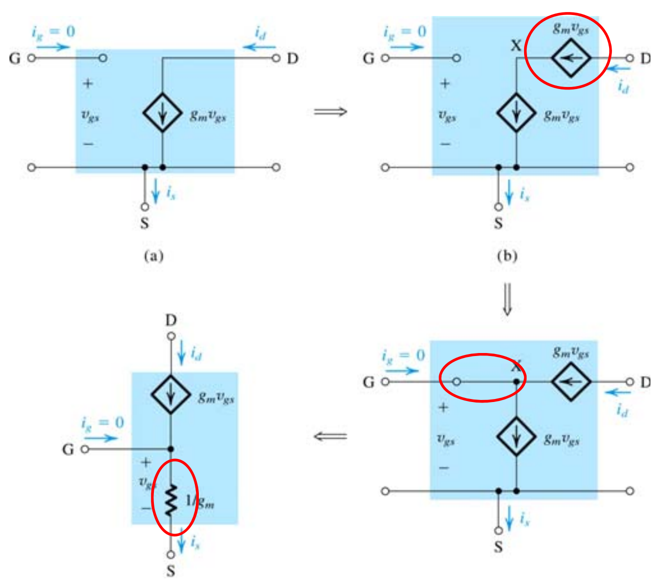


(c)



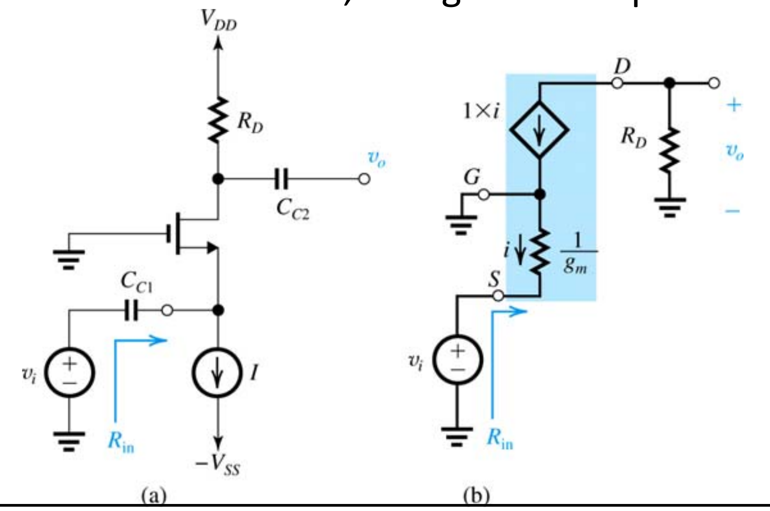
(d)

T-Equivalent-Circuit Model

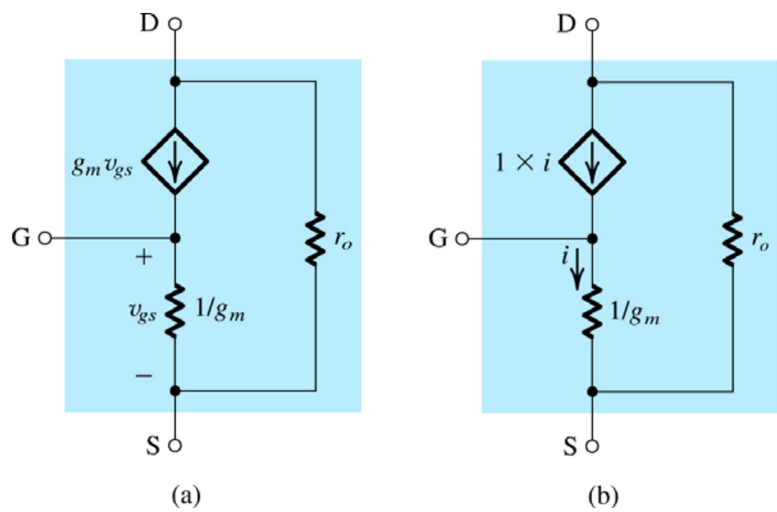


Example

- Assume saturation, find gain and input



Incorporating r_0

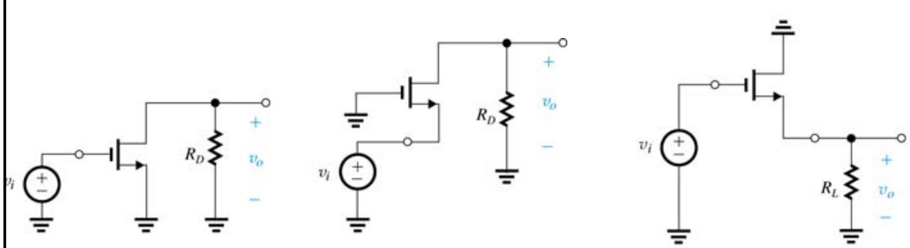


MOSFET Amplifier Configuration

- Single stage
- The signal is fed to the amplifier represented as v_{sig} with an internal resistance R_{sig}.
- MOSFET is represented by its small signal model.
- Generally interested of gain, input and output resistance (overall amplifier circuit not only the small signal model).

MOSFET Amplifier Configuration

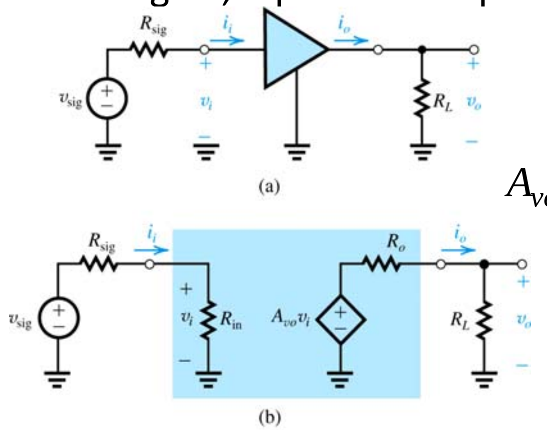
- Considering only the small signal not the bias



(a) Common Source (CS) (b) Common Gate (CG) (c) Common Drain (CD)

Characterizing Amplifiers

- Find gain, input and output resistance



$$R_{in} = \frac{v_i}{i_i}$$

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

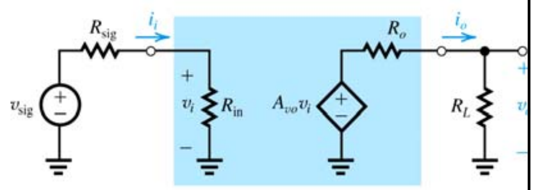
Amplifer Configuration

- Common Source
- Common Source with a source resistance
- Common gate
- Common drain or voltage follower

Amplifiers

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

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



(b)

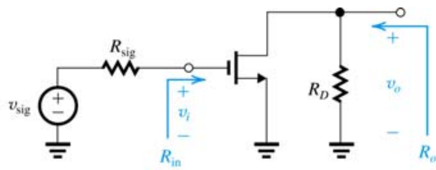
$$A_v = A_{vo} \frac{R_L}{R_L + R_o}$$

$$G_v = \frac{v_o}{v_{sig}} = \frac{R_{in}}{R_{in} + R_{sig}} A_{vo} \frac{R_L}{R_L + R_o}$$

Common Source

- Most widely used configuration
- In multistage amplifiers, the bulk of the gain is from common source.
- The source is grounded, making it common between input and output.
- We can use hybrid π model.

Common Source



$R_i = \infty$

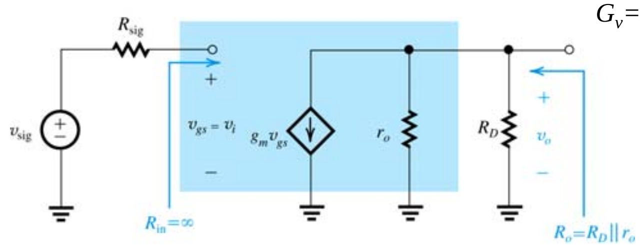
(a)

For R_o, set v_i=0

$R_o = r_0 \parallel R_D$

$A_{vo} = -g_m (r_0 \parallel R_D)$

A_V= ?
G_v=?

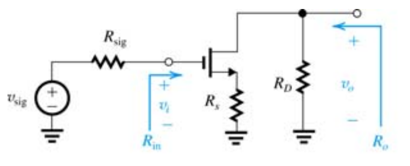


(b)

Common Source with Source R

- For simplicity, r_0 is not included.
- No effect on discrete implementation, not so for IC's
- R_s provides a negative feedback to control the magnitude of the signal to prevent nonlinear distortion.
- Also reduces the voltage gain and extends the useful bandwidth.

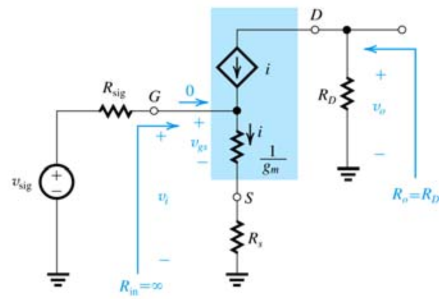
Common Source with Source R



(a)

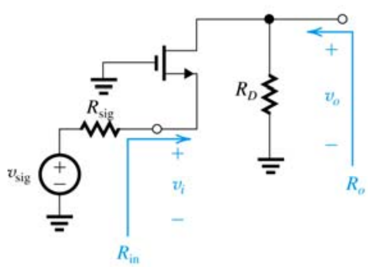
$$v_{gs} = -g_m v_i \frac{1/g_m}{1/g_m + R_S}$$

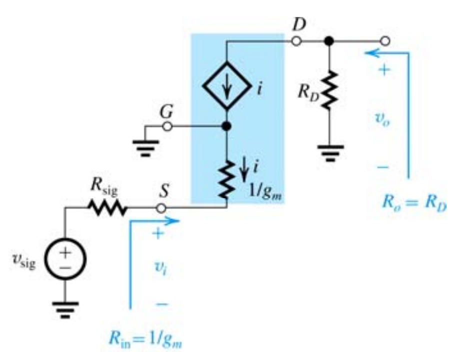
$$v_{gs} = \frac{v_i}{1 + g_m R_S}$$



(b)

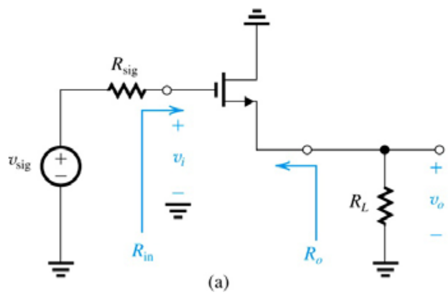
Common Gate Amplifier





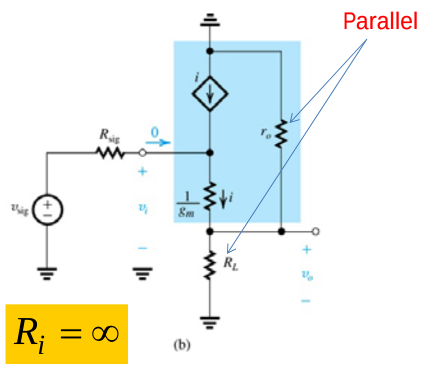
(a) (b)

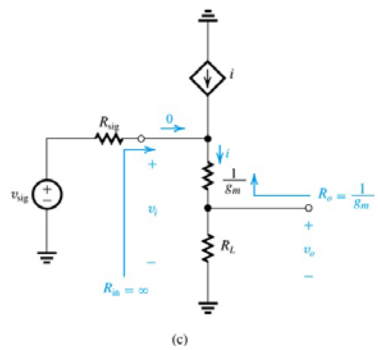
Common Drain Amplifier – Source Follower



Since there is a resistance RL connected to the source, it is easier to use the T-model

Common Source – Voltage Follower





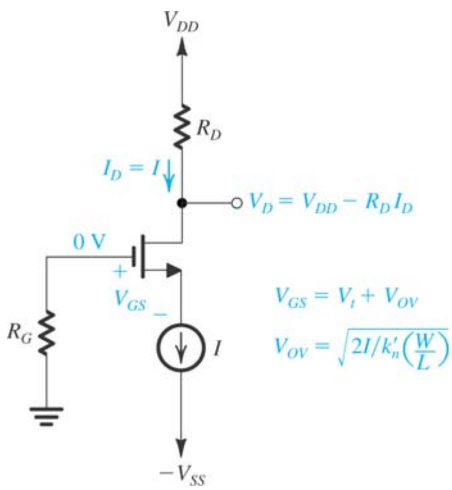
Comparison

	CS	CS+RS	CG	CD
Rin	∞	∞	$\frac{1}{g_m}$	∞
Rout	RD || ro	R_D	R_D	$1/g_m$
G	$-g_m(R_D \|\| R_L \|\| r_o)$	$A_v = \frac{g_m(R_D\|\|R_L)}{1+g_mR_s}$	$G_v = \frac{(R_D\|\|R_L)}{1/g_m+R_{sis}}$	$G_v = A_v = \frac{R_L}{1/g_m+R_L}$

Discrete CMOS Amplifiers

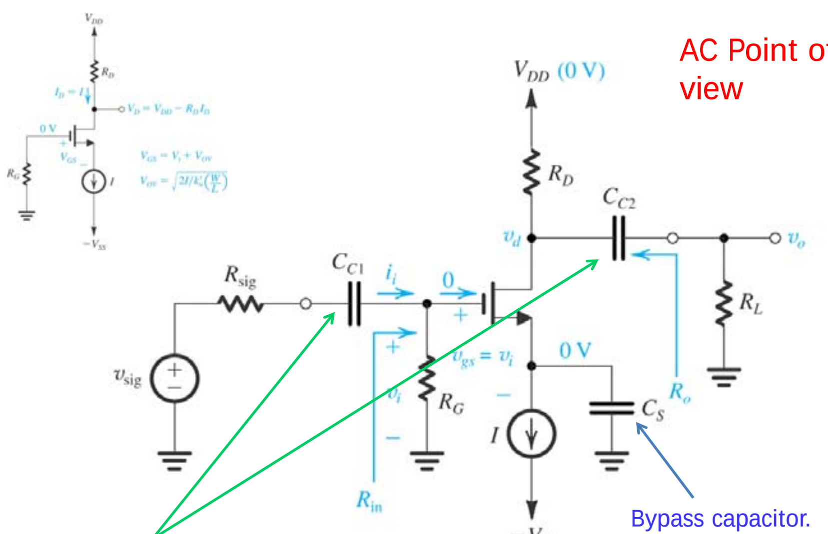
- MOS are mostly used in IC's
- However, we present practical circuits for discrete implementation.
- Good if you are building a circuit on a breadboard (in the lab).

Common Source



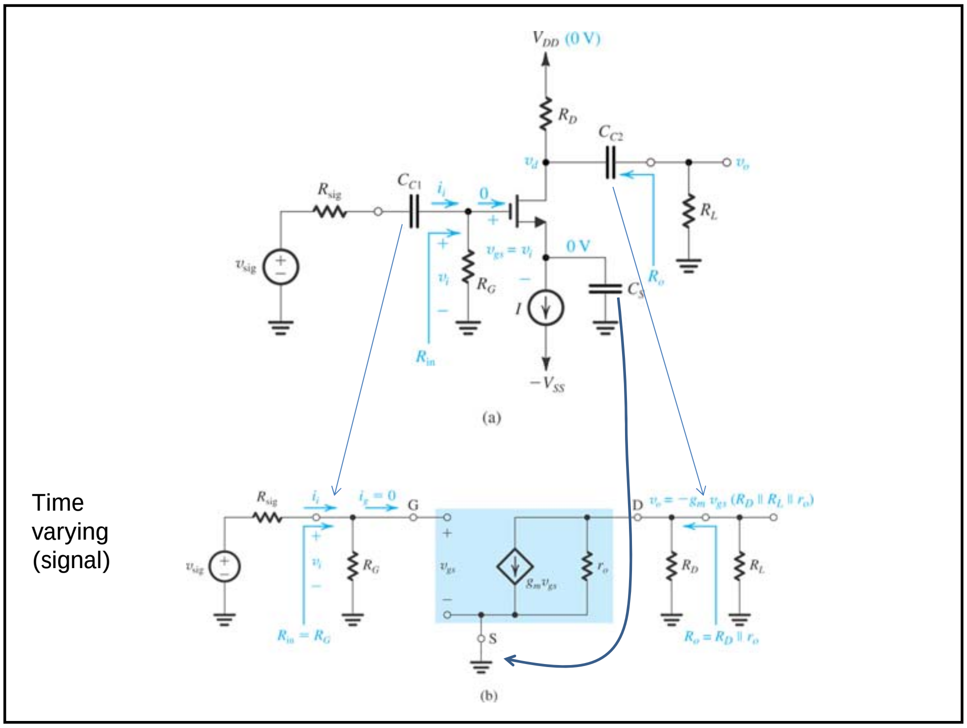
- DC Analysis
- Can use any biasing technique we studied
- Calculate the bias (Q) point

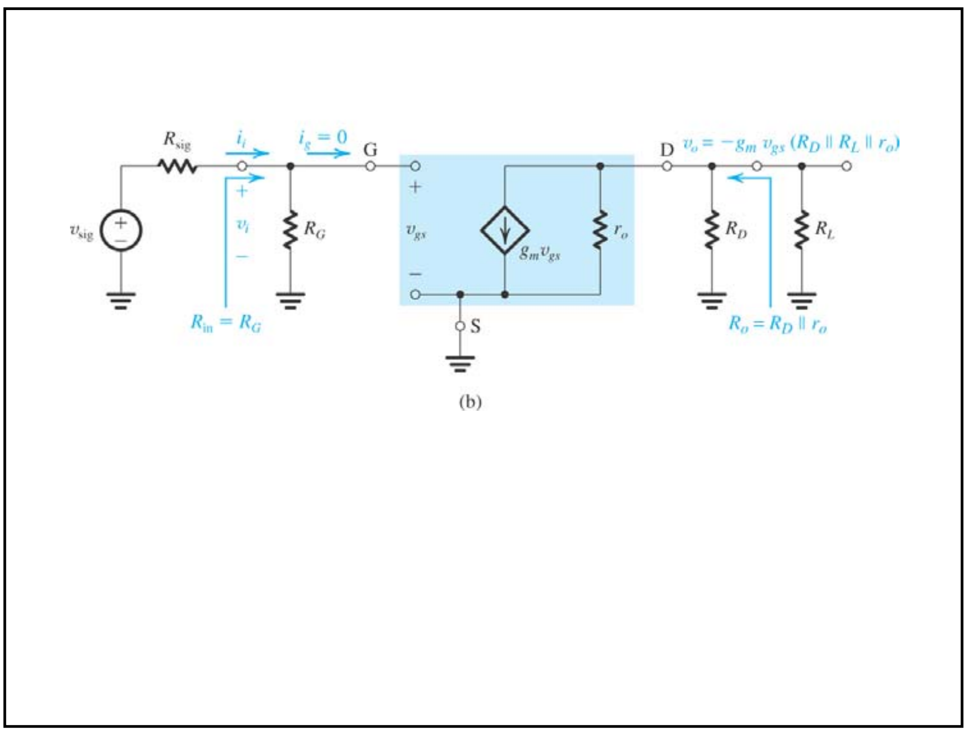
AC Point of view



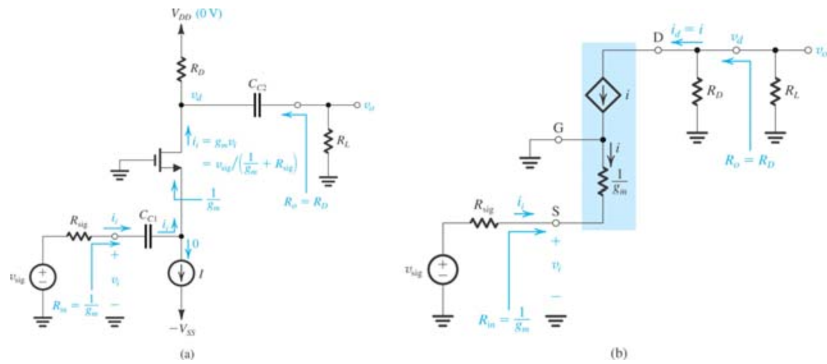
Coupling capacitors: To connect the input and output without disturbing the bias.
C is large enough to have zero impedance at signal frequency.

Bypass capacitor. Current source is an open circuit, provide a path to ground (source is ground for signal).


V_{DD} (0 V)
R_D
C_{C2}
v_d
v_o
R_{sig}
C_{C1}
i_i
0
+
$v_{gs} = v_i$
0 V
v_{sig}
v_i
R_G
R_L
C_S
R_o
I
R_{in}
$-V_{SS}$
(a)
Time
varying
(signal)
R_{sig}
i_i
$i_g = 0$
G
D
$v_o = -g_m v_{gs} (R_D \parallel R_L \parallel r_o)$
v_{sig}
v_i
R_G
v_{gs}
$g_m v_{gs}$
r_o
R_D
R_L
$R_{in} = R_G$
S
$R_o = R_D \parallel r_o$
(b)


R_{sig}
i_i
$i_g = 0$
G
D
$v_o = -g_m v_{gs} (R_D \parallel R_L \parallel r_o)$
v_{sig}
+
v_i
−
R_G
+
v_{gs}
−
$g_m v_{gs}$
r_o
R_D
R_L
$R_{in} = R_G$
S
$R_o = R_D \parallel r_o$
(b)

Common Gate



Voltage Follower

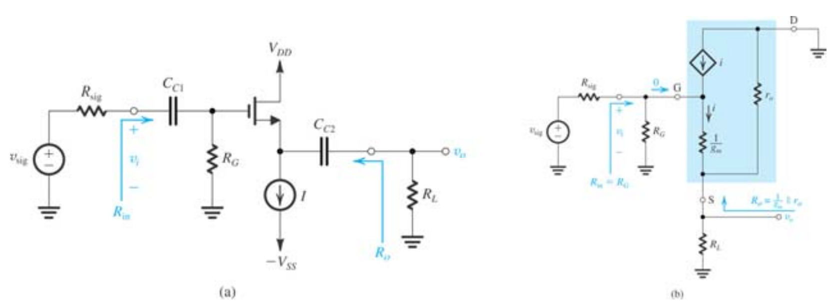


Figure 5.60 (a) A source-follower amplifier. (b) Small-signal, equivalent-circuit model.

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