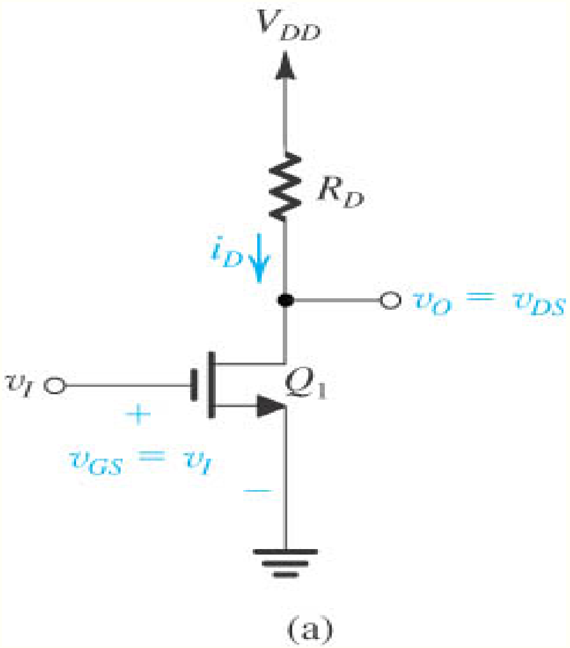
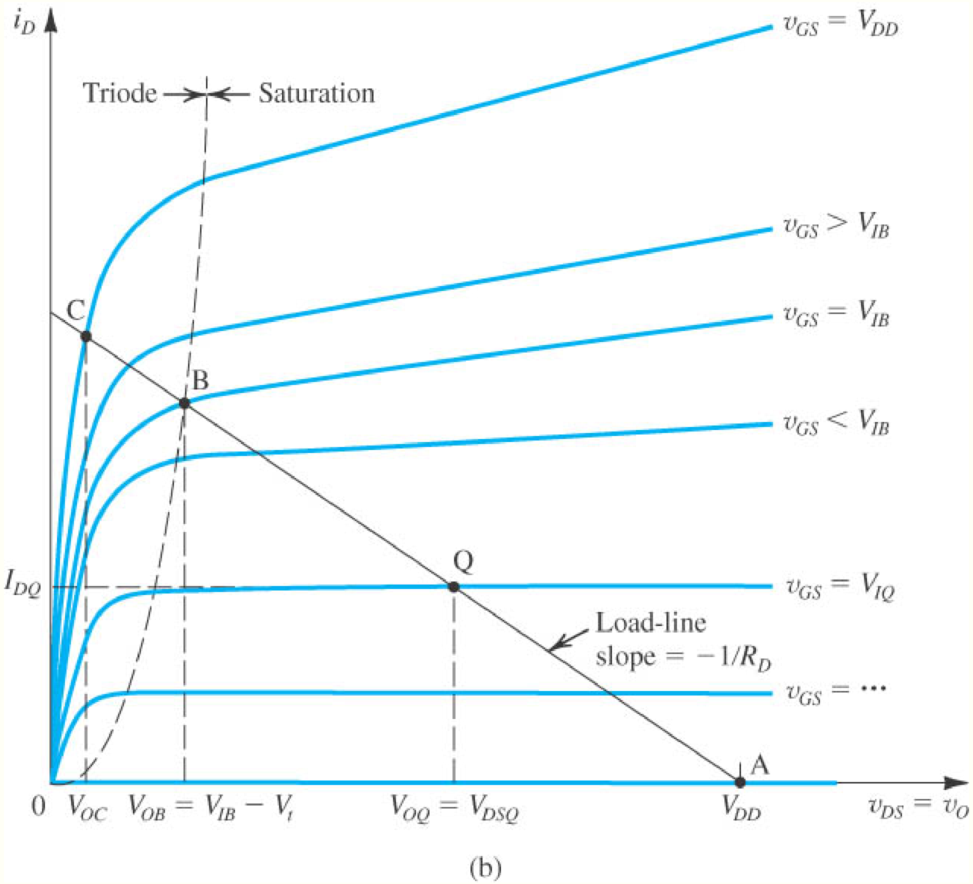
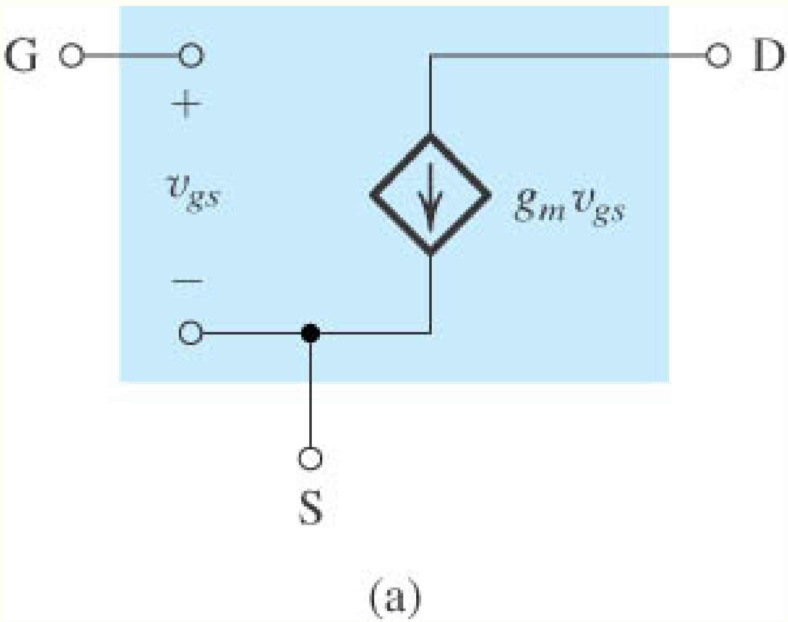
The MOSFET as an Amplifier

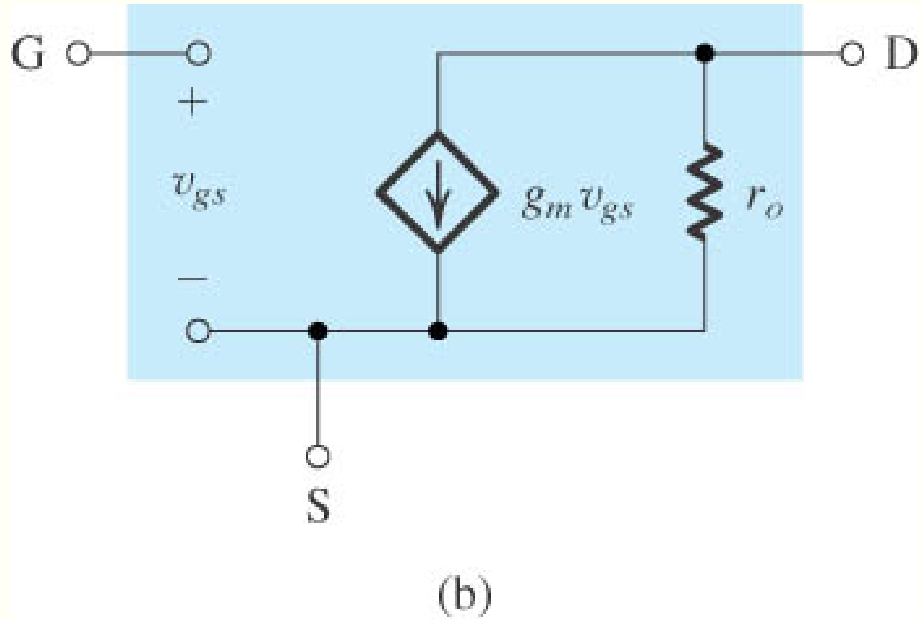




➢Basic structure of the common-source amplifier.

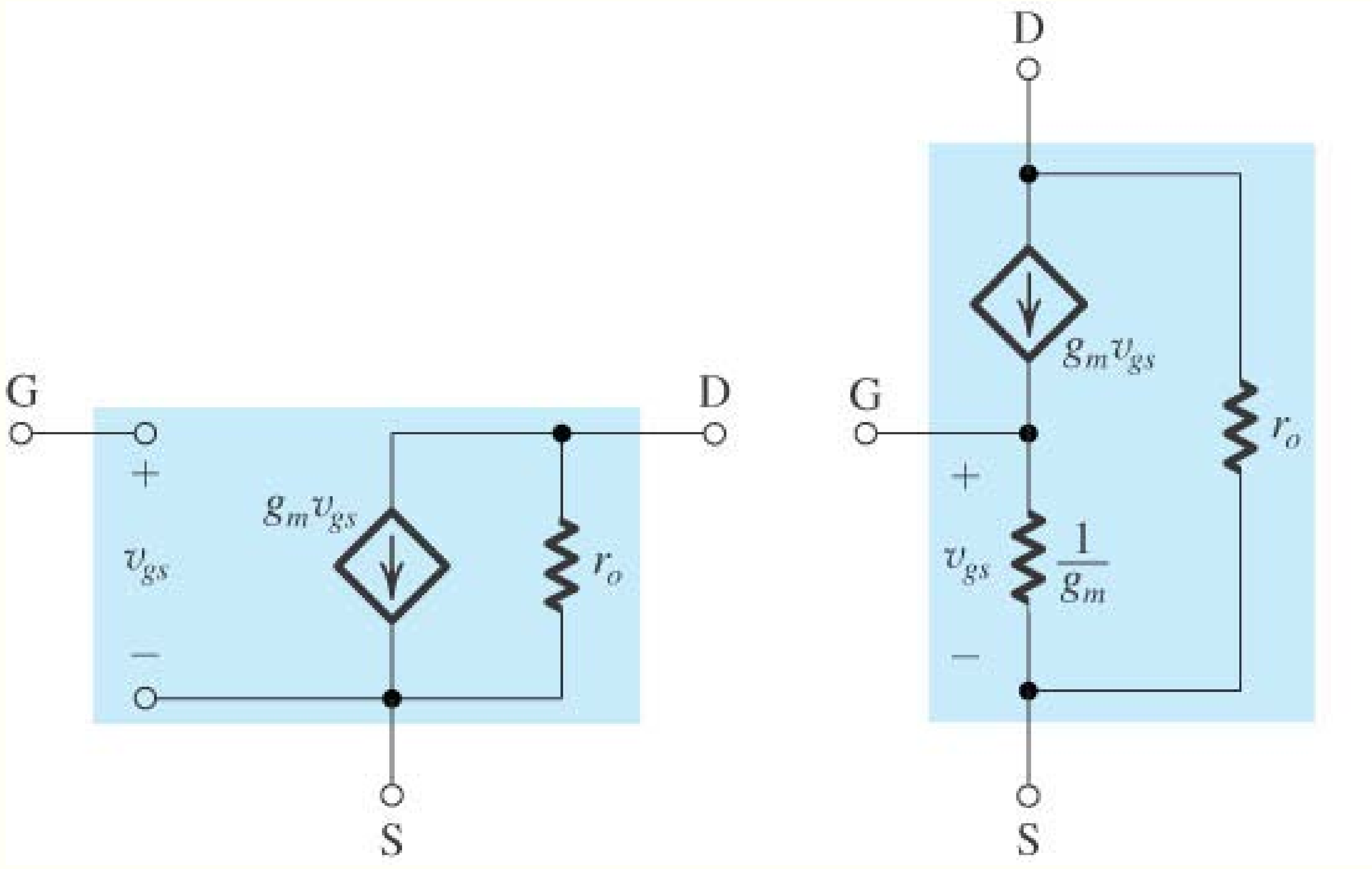
The Small-Signal Models





(a) neglecting the the channel-length modulation effect

(b) including the effect of channel-length modulation, modeled by output resistance $r_o = |V_A| / I_D$.


G
D
S
+
v_{gs}
−
$g_m v_{gs}$
r_o
$\frac{1}{g_m}$

The ac Characteristics

Transconductance $$g_m \equiv \left.\frac{\partial i_D}{\partial v_{GS}}\right|_{v_{GS}=V_{GS}} = k_n' \frac{W}{L}\left(V_{GS} - V_T\right)$$

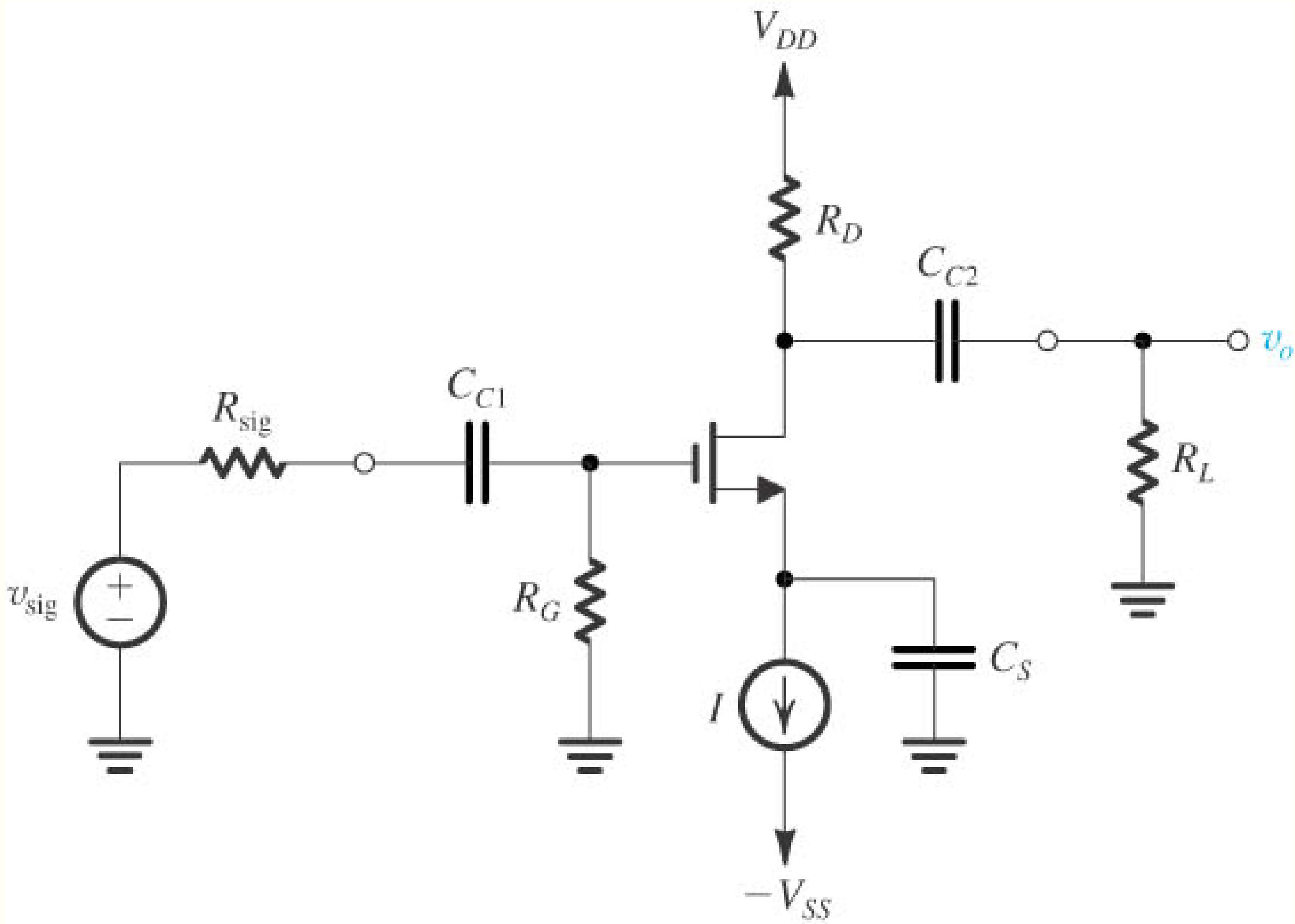
Output Resistance $$r_o \equiv \left.\frac{\partial v_{DS}}{\partial i_D}\right|_{i_D=I_D} = \frac{V_A}{I_D}$$

V_A is MOSFET parameter used to determine r_0

Voltage gain

$$A_v \equiv \frac{v_o}{v_i}$$

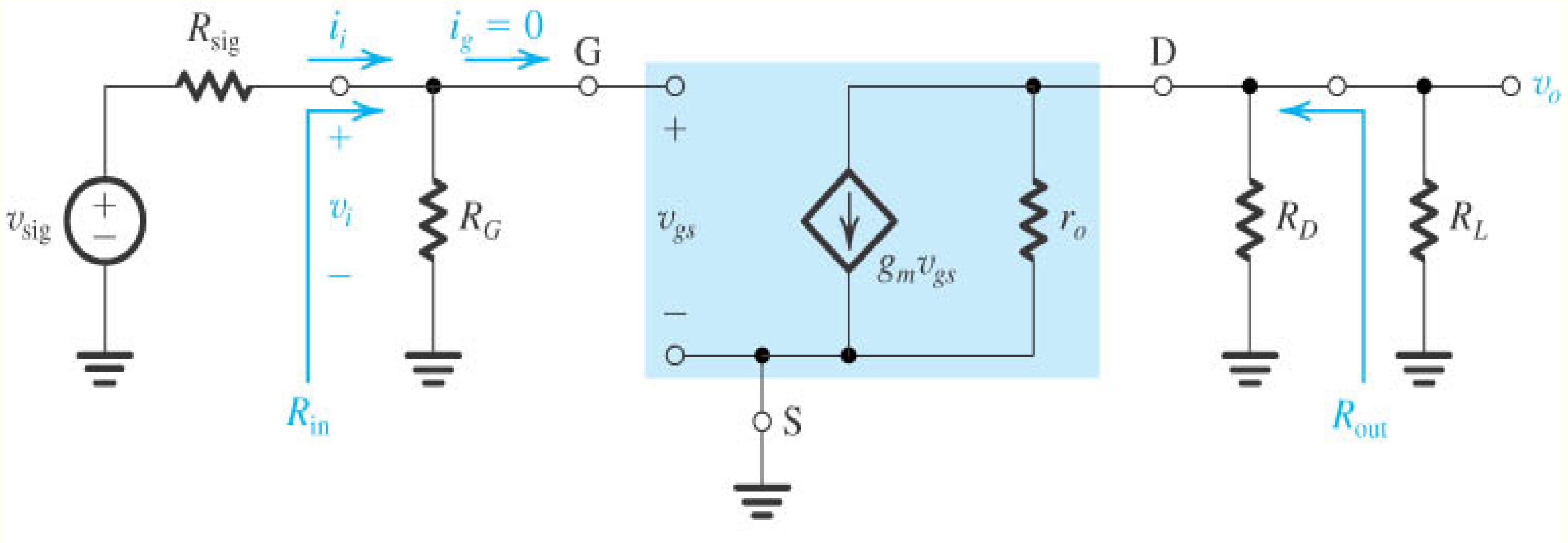
The Common-Source Amplifier



(a)

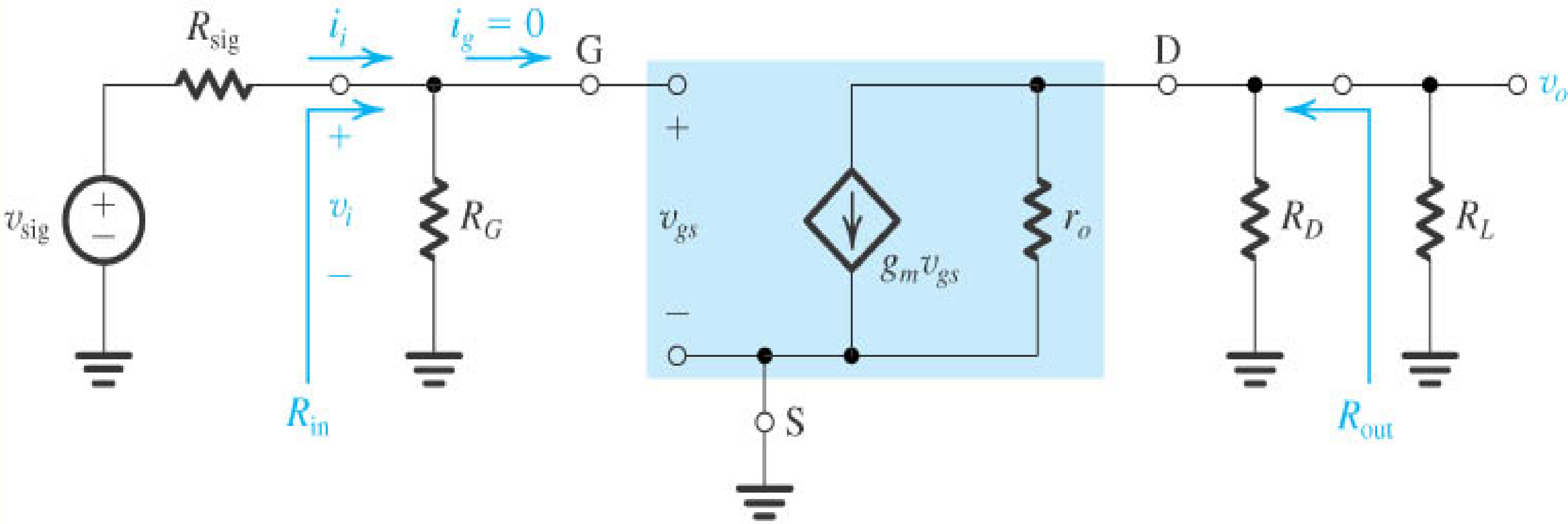
- Very high input resistance
- Moderately high voltage gain
- Relatively high output resistance

Equivalent Circuit of the CS Amplifier



(b)

Characteristics of CS Amplifier



Input resistance $R_{in} = R_G$

Voltage gain $A_v = \frac{v_o}{v_{gs}} = -g_m(r_o // R_D // R_L)$

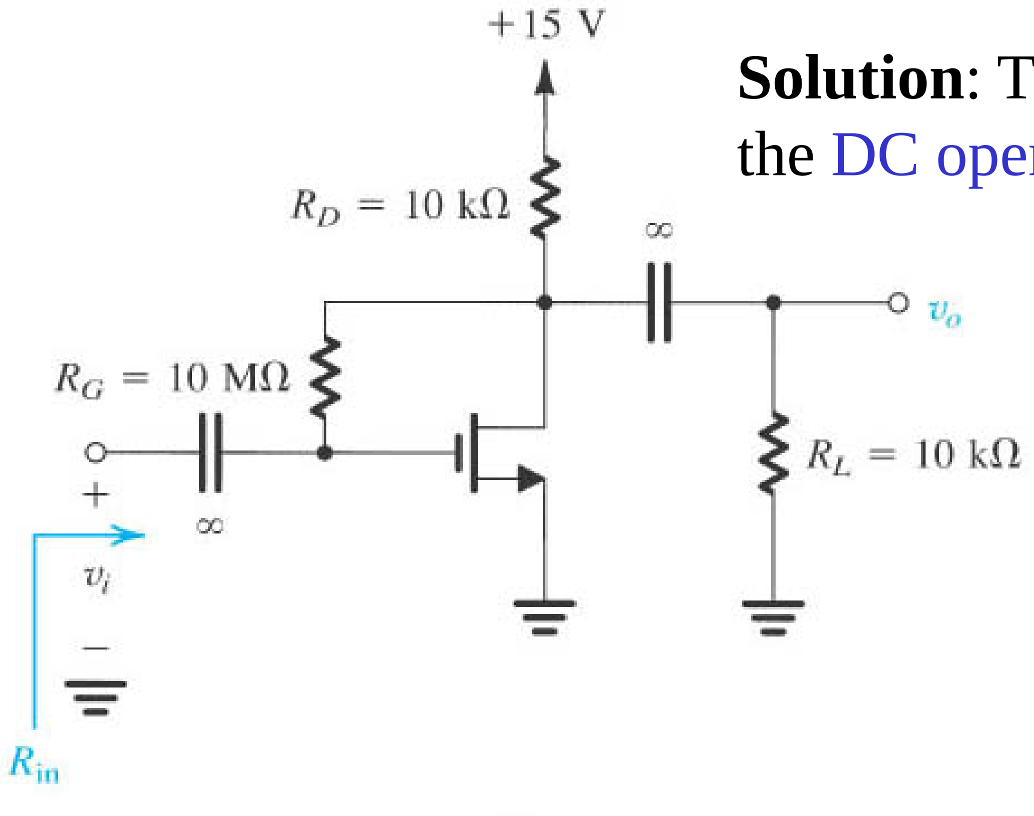
Overall voltage gain $G_v = \frac{v_o}{v_{sig}} = -\frac{R_G}{R_G + R_{sig}} g_m(R_D // R_L // r_o)$

Output resistance $R_{out} = r_o // R_D$

Example-9: Small signal analysis of MOSFET Amplifiers

Determine A_v (neglecting the effects of R_G), R_{in} , and R_{out} for the circuit shown in Fig.. given that $V_t = 1.5$ V, $V_A = 50$ V and

$$k'_n W/L = 0.25\,\text{mA/V}^2$$



(a)

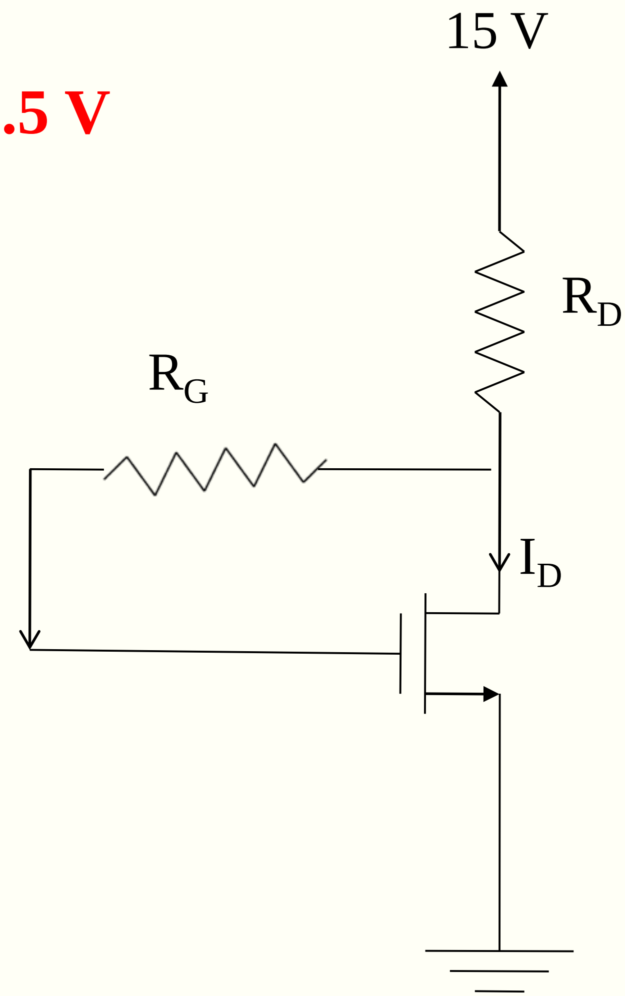
Solution: The first step is to determine the DC operating point.

The DC equivalent circuit:

$$v_{GS} > V_T$$

$$v_{DS} > v_{GS} - V_T$$

$V_T = 1.5$ V



$$I_G = 0$$

Since $I_G = 0$, $V_G = V_D$

$$V_T > (v_{GS} - v_{DS})$$

$$V_T > 0$$

$$I_D = \frac{1}{2} \cdot 0.25 \times 10^{-3} (V_{GS} - 1.5)^2 = 1.25 \times 10^{-4} (V_{GS} - 1.5)^2$$

Since, $V_{GS} = V_{DS}$

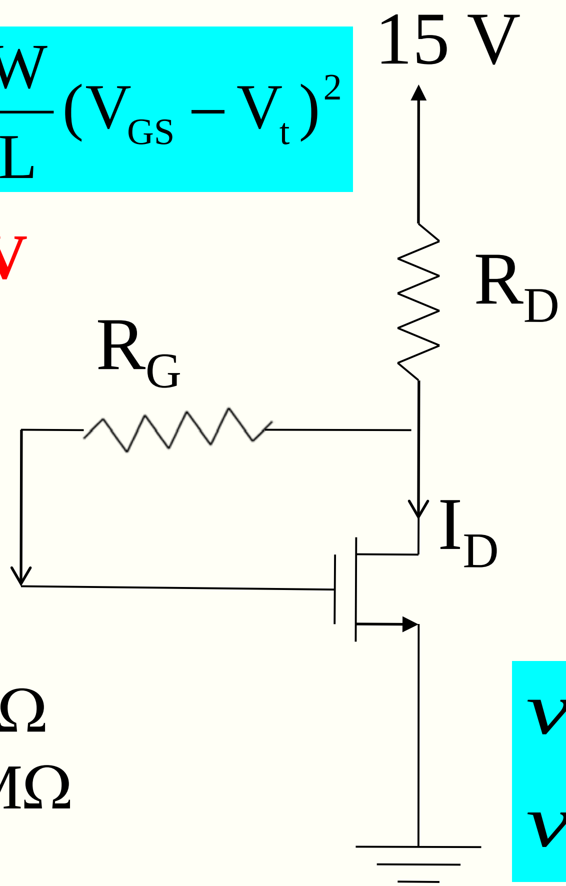
$$I_D = 0.125 (V_{DS} - 1.5)^2 \ \text{mA}$$

$$V_{DS} = 15 - R_D I_D = 15 - 10 I_D$$

$$I_D = 0.125 (15 - 10 I_D - 1.5)^2$$

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

V_T = 1.5 V



$I_G = 0$

R_D = 10 kΩ

R_G = 10 MΩ

$$I_D = 1.06 \text{ mA}$$

$$\boxed{\Rightarrow \ V_{DS} = 4.4 \text{ V} \ (= V_{GS})}$$

$$I_D = 1.72 \text{ mA}$$

$$\Rightarrow \ V_{DS} = -2.2 \text{ V} \ (= V_{GS})$$

$$v_{GS} > V_T$$

$$v_{DS} > v_{GS} - V_T$$

MOSFET is in saturation

For small signal analysis:

Transconductance

$$g_m = k'_n \frac{W}{L}(V_{GS} - V_t)$$

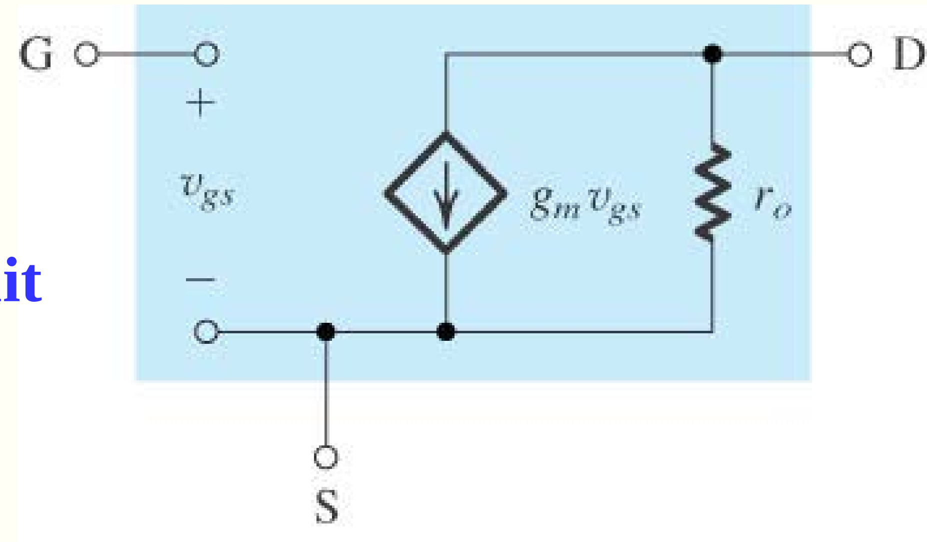
$$g_m = 0.25 \times 10^{-3}(4.4 - 1.5) = 0.725 \text{ mS}$$

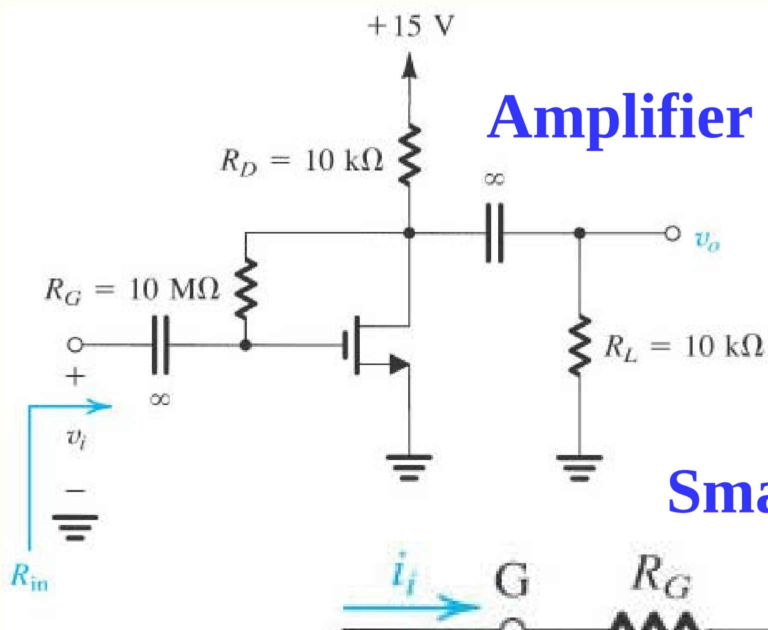
Output Resistance

$$r_0 = \frac{V_A}{I_D}$$

$$r_0 = \frac{V_A}{I_D} = \frac{50}{1.06 \text{ mA}} = 47.2 \text{ k}\Omega$$

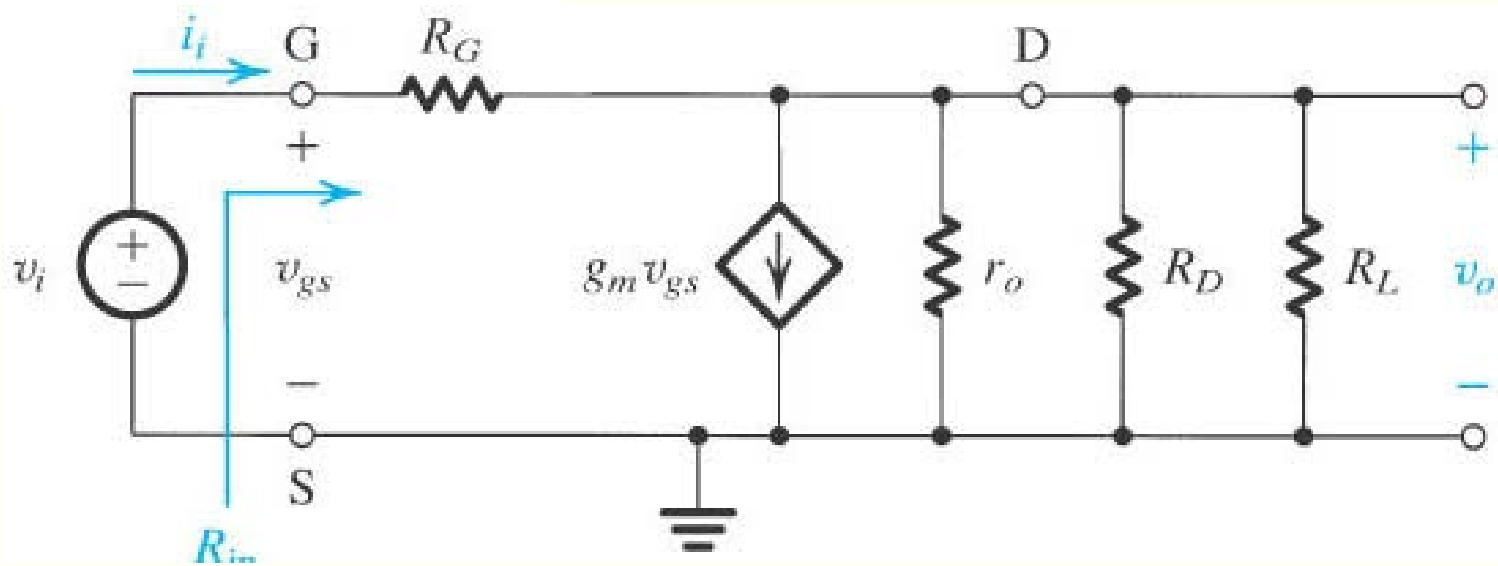
For small signal analysis:





Amplifier Circuit

Small signal Equivalent circuit model



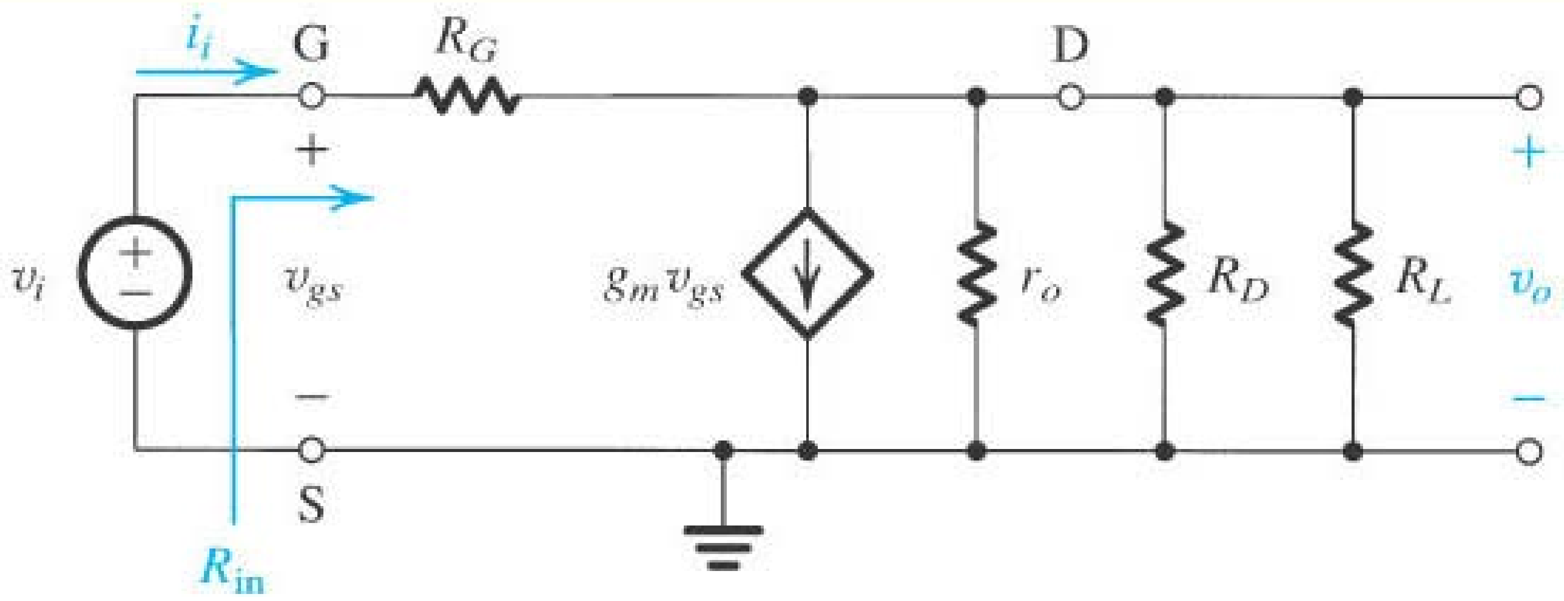
For small-signal voltage gain,

R_G is extremely large $\quad R_G >> r_0 \,||\, R_D \,||\, R_L$

$$v_0 \approx -g_m v_{gs}(r_0 \,||\, R_D \,||\, R_L)$$

$v_{gs} = v_i$

$$A_v = \frac{v_0}{v_i} \approx -g_m(r_0 \,||\, R_D \,||\, R_L) = -3.3$$



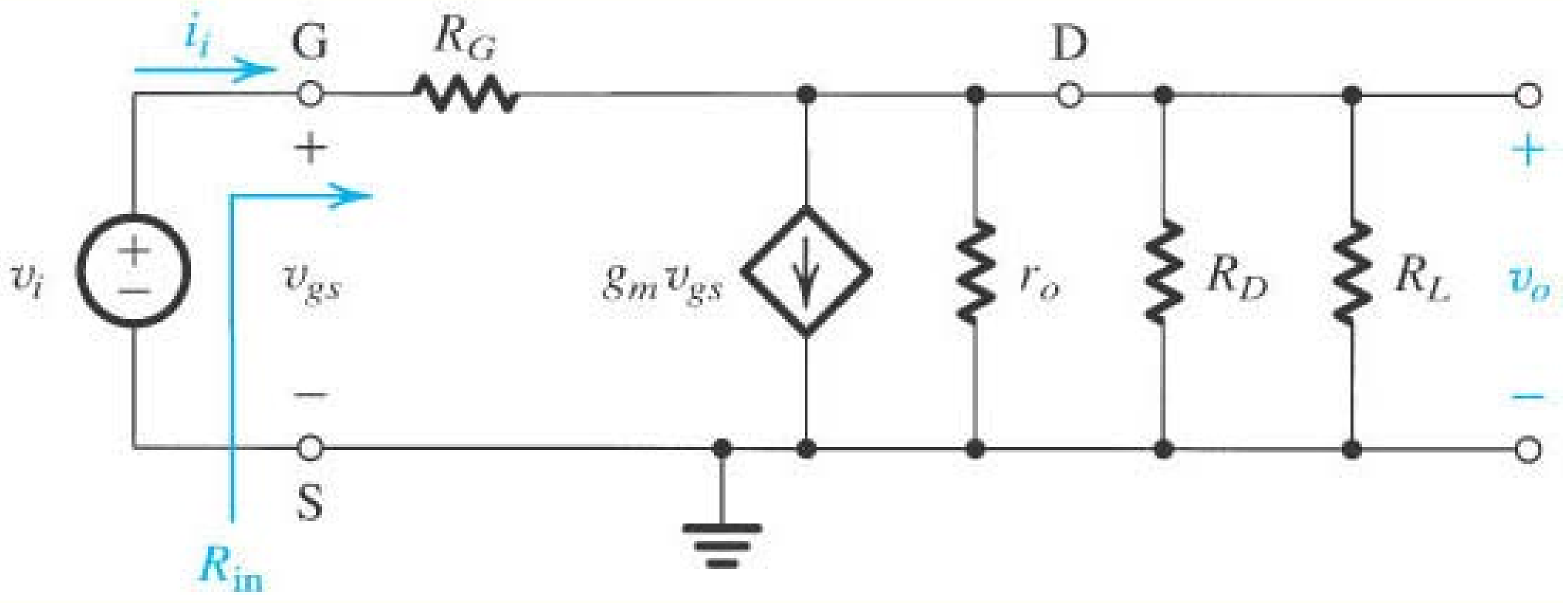
Input resistance

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

$$i_i = \frac{v_i - v_0}{R_G} = \frac{v_i}{R_G}\left(1 - \frac{v_0}{v_i}\right) = \frac{v_i}{R_G}(1 - A_v)$$

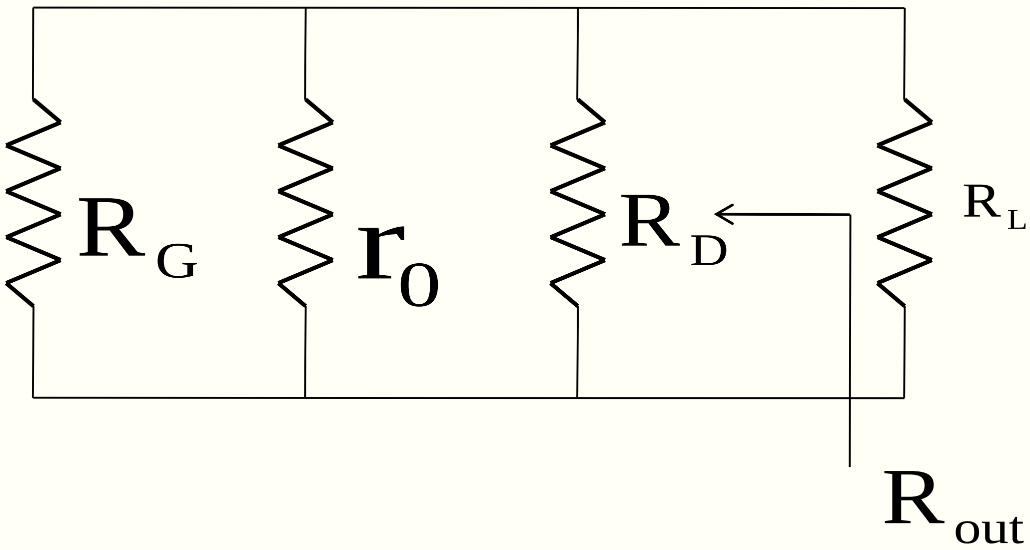
$$i_i = \frac{v_i}{R_G}(1 + 3.28)$$

$$R_{in} = \frac{v_i}{i_i} = \frac{R_G}{4.28} = 2.34 \ \mathrm{M\Omega}$$



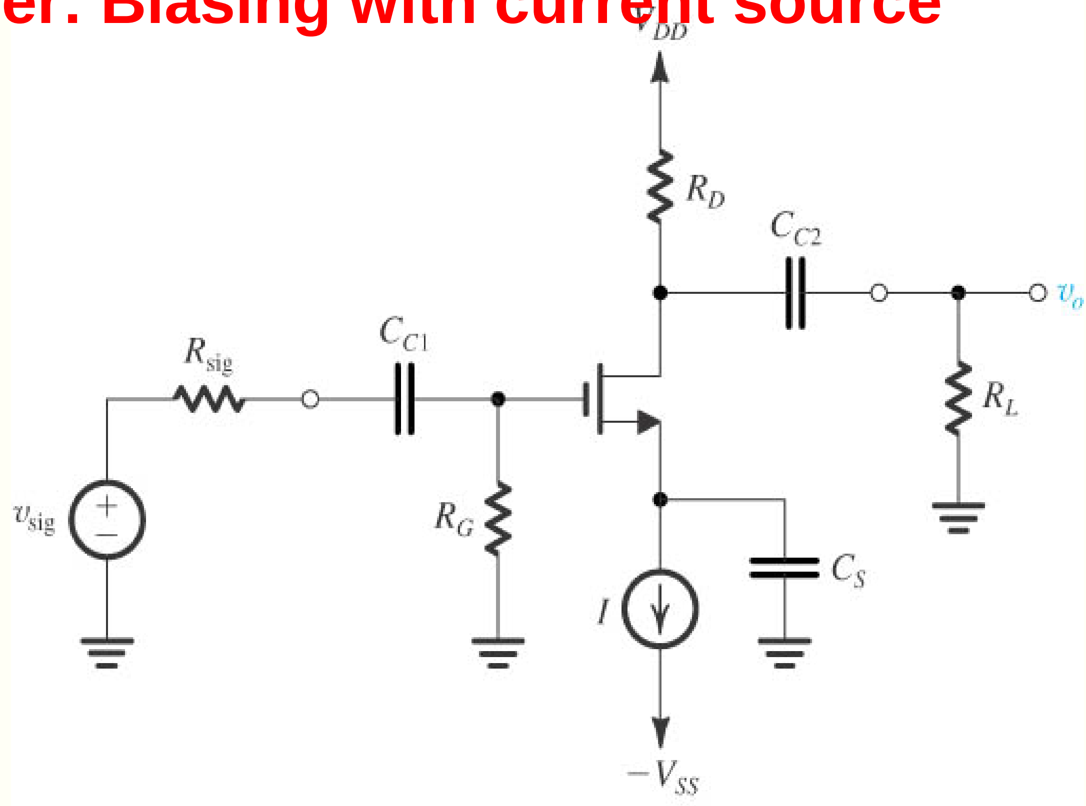
Output Resistance,

- To compute this we set $v_{gs} = 0$ in the small scale equivalent circuit, which will open circuit the dependent current source leading to equivalent circuit as shown below.
- From the figure we can compute R_{out} as



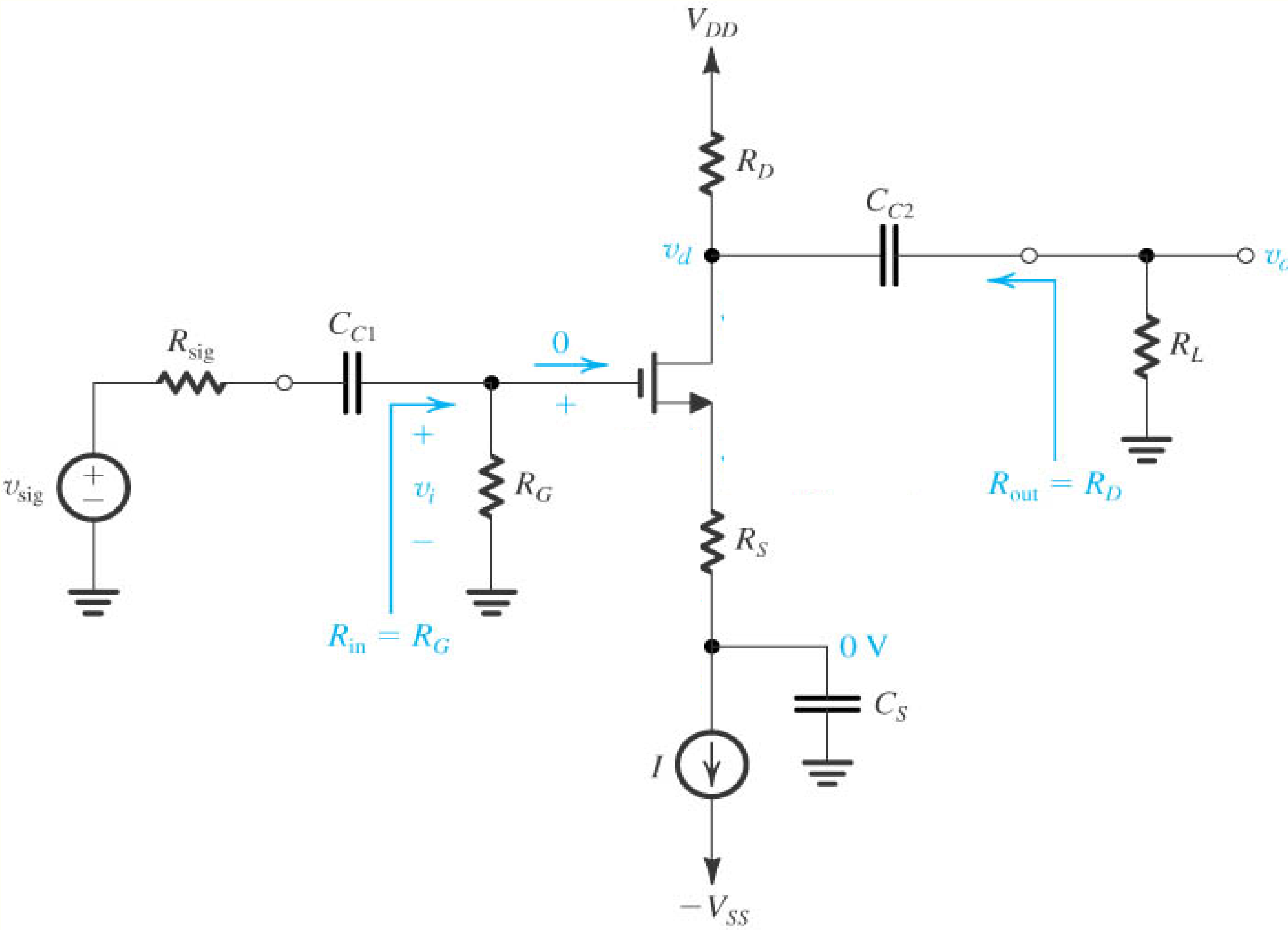
$$R_{out} = R_G \,||\, r_0 \,||\, R_D = 8.24\ \text{k}\Omega$$

Common-Source Amplifier: Biasing with current source



- Biasing with constant-current source.
- C_{C1} And C_{C2} are coupling capacitors.
- C_S is the bypass capacitor.

The Common-Source Amplifier with a Source Resistance



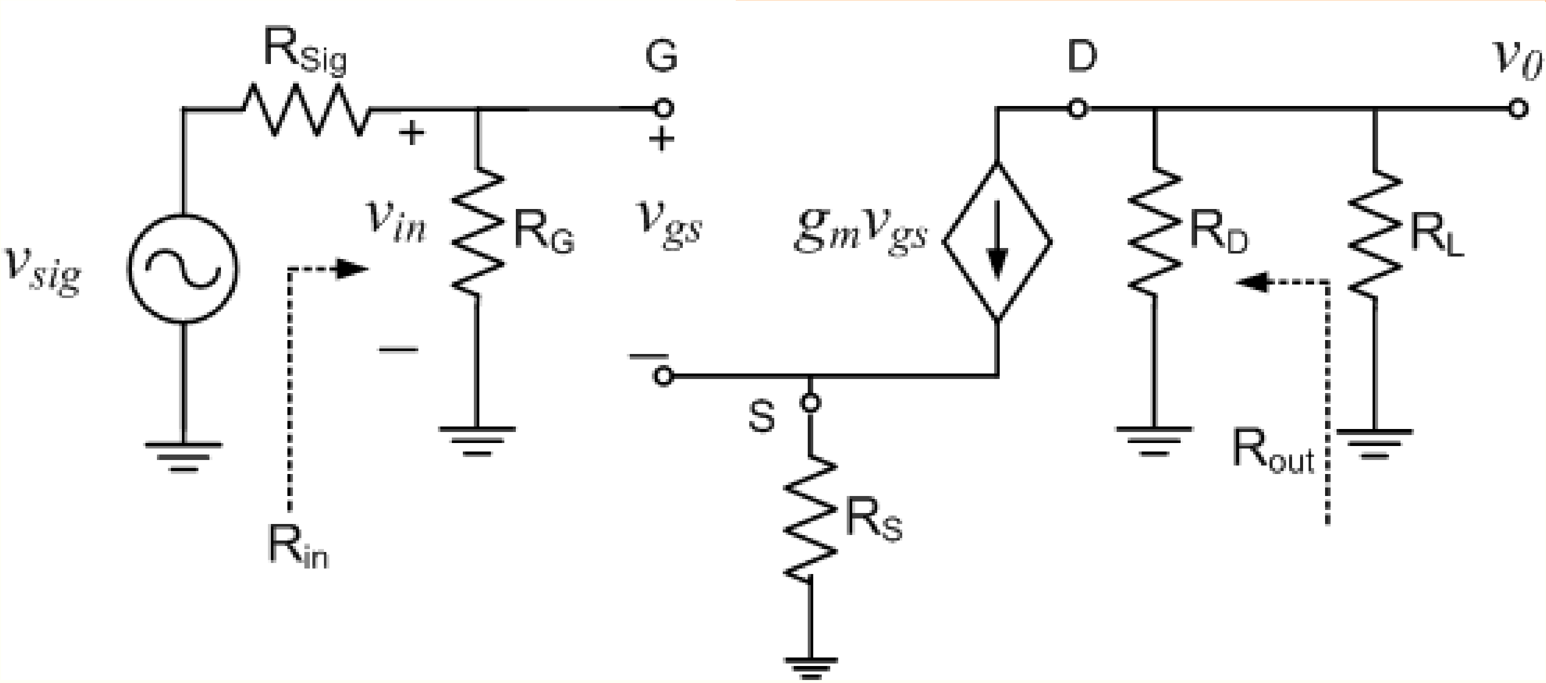
(a)

Small-signal Equivalent Circuit: Neglecting r_o

$$v_{in} = v_{gs} + g_m v_{gs} R_s$$

$$v_o = -g_m v_{gs} \left(R_D \parallel R_L \right)$$

Voltage gain $$A_v = \frac{v_o}{v_{in}} = -\frac{g_m \left(R_D \parallel R_L \right)}{1 + g_m R_s}$$



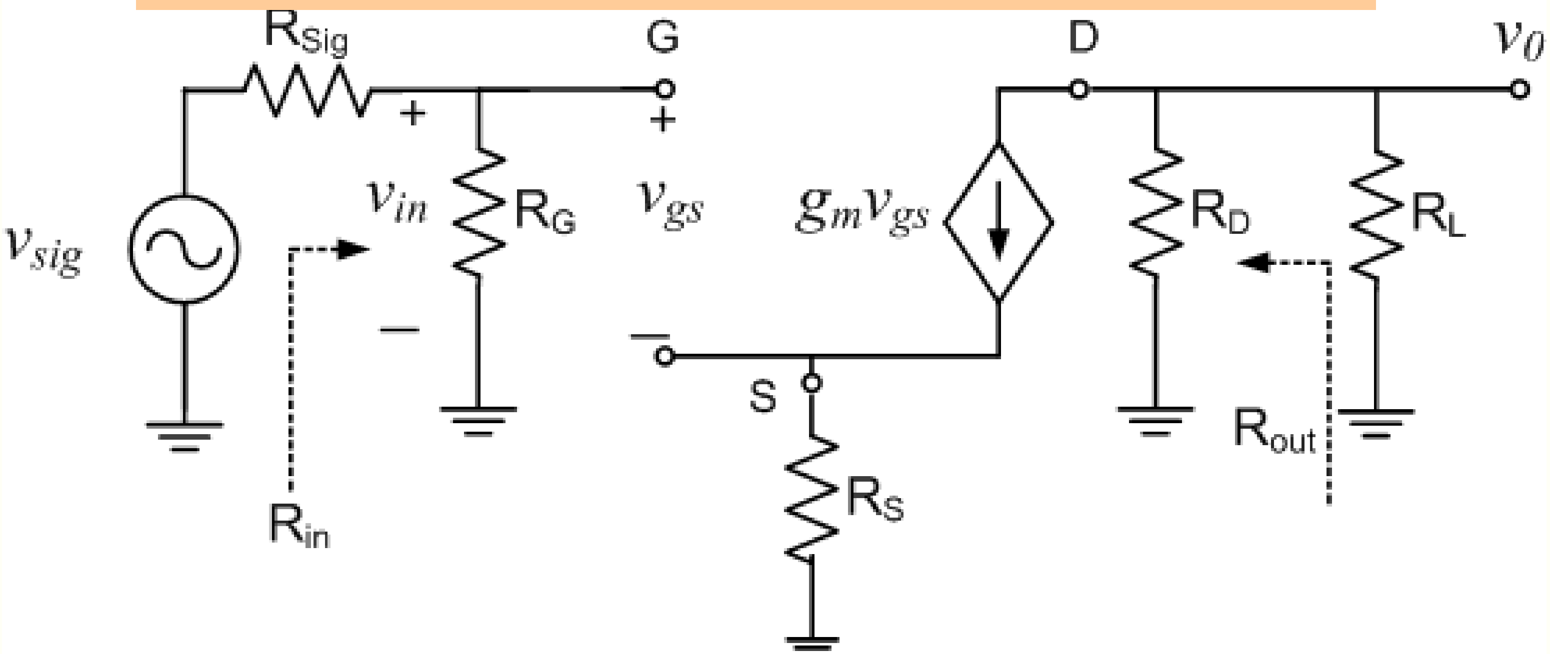
$$A_v = \frac{v_o}{v_{in}} = -\frac{g_m (R_D \parallel R_L)}{1 + g_m R_s}$$

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

Overall voltage gain

$$G_v = \frac{v_o}{v_{sig}} = \frac{v_o}{v_{in}} \frac{v_{in}}{v_{sig}} = A_v \frac{v_{in}}{v_{sig}}$$

$$G_v = \frac{v_o}{v_{sig}} = -\frac{R_G}{R_G + R_{sig}} \frac{g_m (R_D \parallel R_L)}{1 + g_m R_s}$$



Characteristics of CS Amplifier with a Source Resistance

- Input resistance $R_{in} = R_G$
- Voltage gain

$$A_v = -\frac{g_m (R_D // R_L)}{1 + g_m R_S}$$

- Overall voltage gain

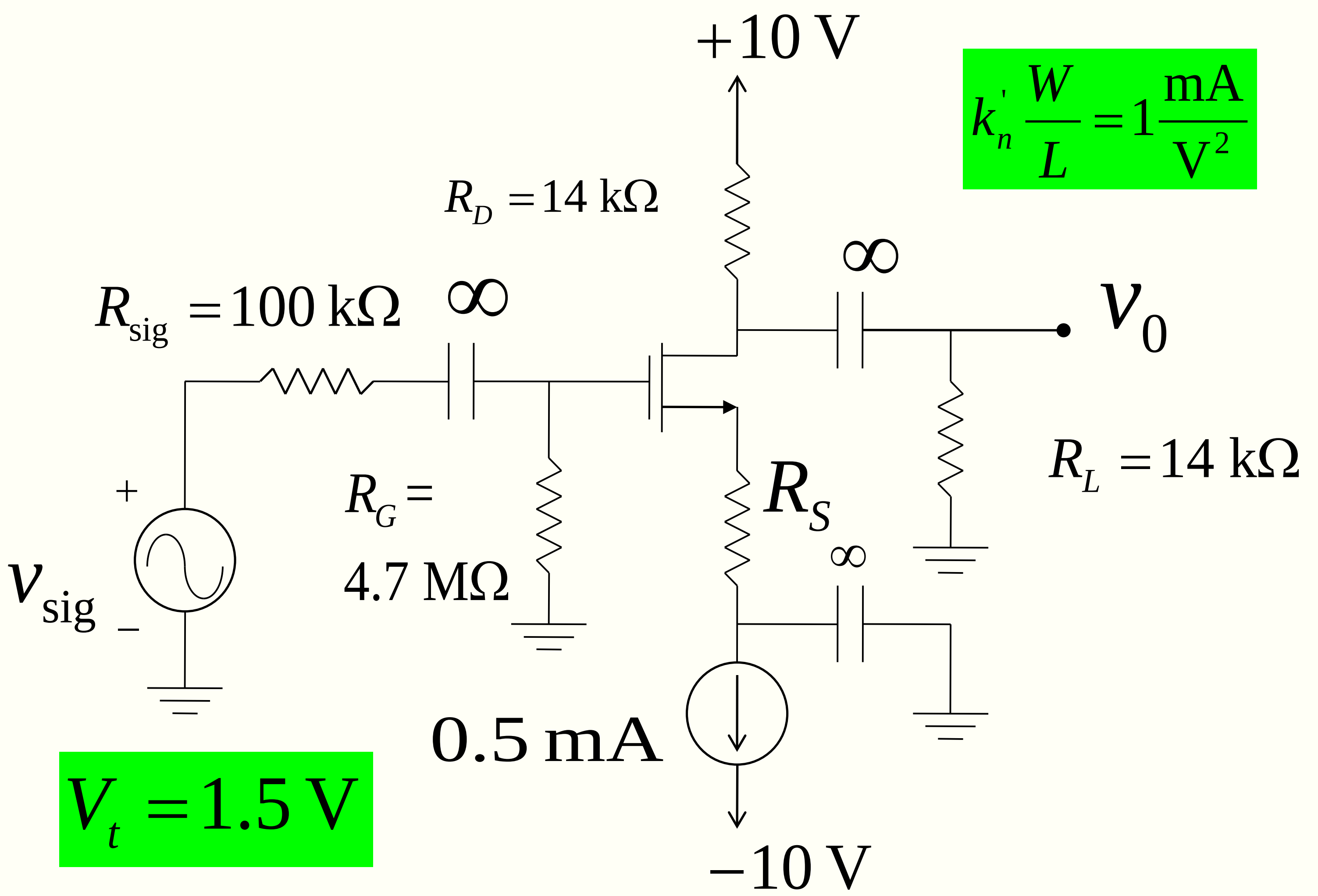
$$G_v = -\frac{R_G}{R_G + R_{sig}} \frac{g_m (R_D // R_L)}{1 + g_m R_S}$$

- Output resistance

$$R_{out} = R_D$$

Example 9: Common Source Amplifier

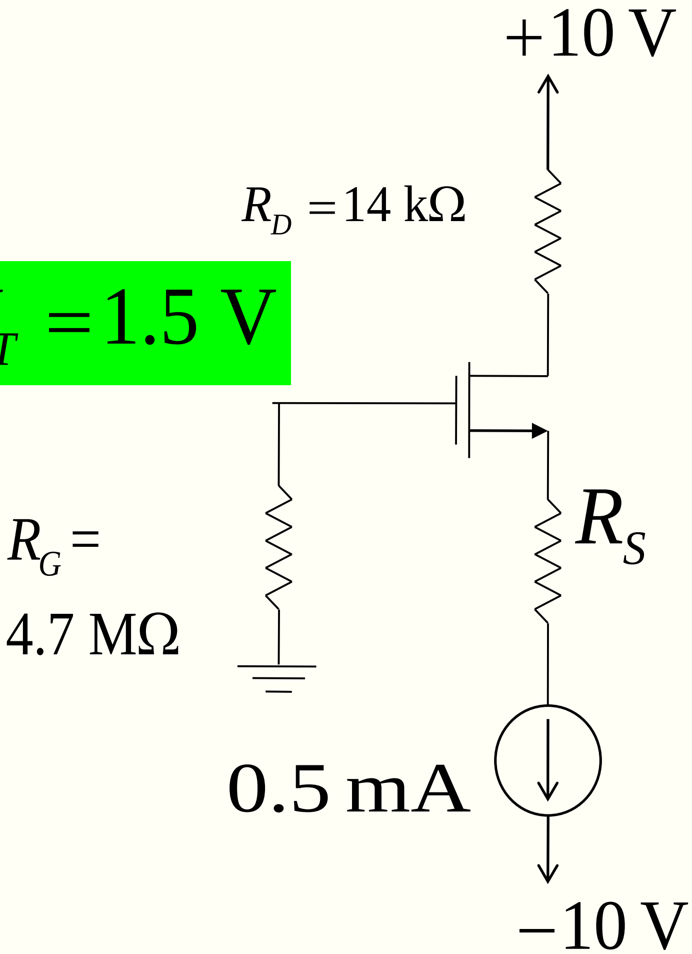
Compute the small- signal voltage gain for the circuit shown in figure below with R_s = 2 kΩ , $k_n' W/L = 1$ mA/V^2 , and V_t =1.5 V.



Example 9 (Contd.)

$V_G = 0$ and $I_D = I_S = 0.5$ mA

DC Analysis:



$$V_T = 1.5\ \text{V}$$

$$V_D = 10 - R_D I_D$$
$$= 10 - 14\text{k} \cdot 0.5\text{mA} = 3\ \text{V}$$

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

$$0.5\ \text{mA} = \frac{1}{2} 1 \times 10^{-3} (V_{GS} - 1.5)^2$$

$$\Rightarrow V_{GS} - 1.5 = \pm 1$$
$$\Rightarrow V_{GS} = 2.5\ \text{V} \quad \text{or} \quad 0.5\ \text{V}$$

MOSFET is in saturation mode

$$v_{GS} > V_T$$

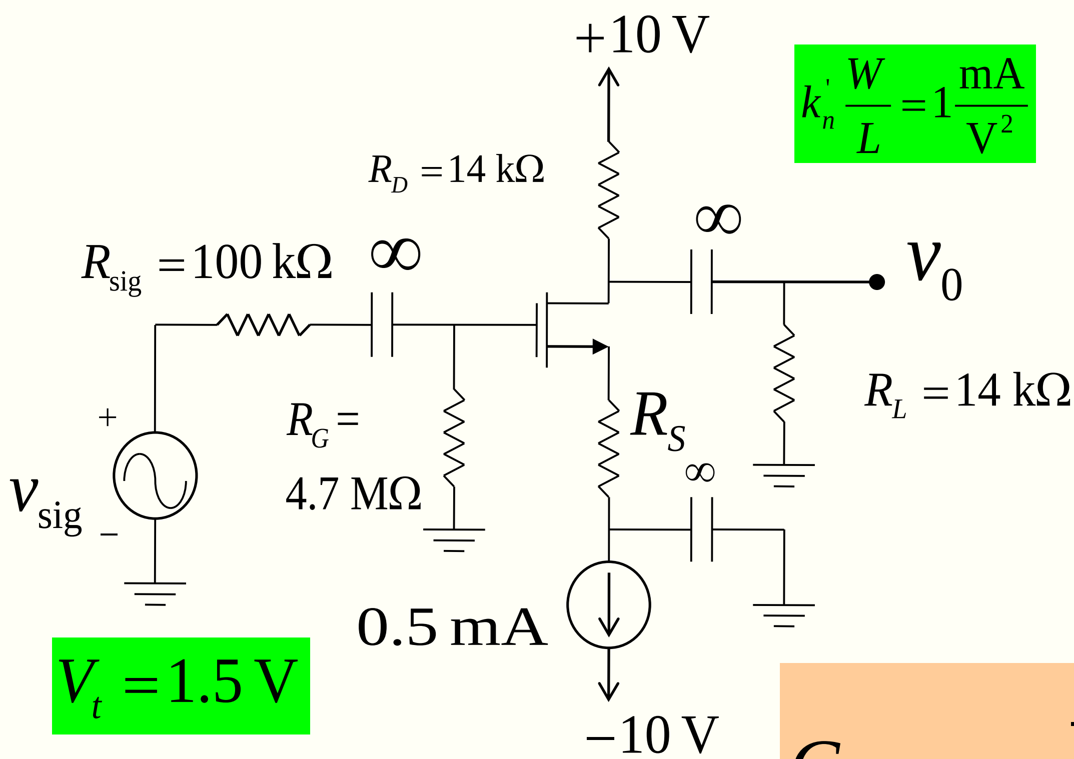
$$V_{GS} = 2.5\ \text{V}$$

For small signal analysis:

$$g_m = k_n' \frac{W}{L}(V_{GS} - V_t) = 10^{-3}(2.5 - 1.5) = 1\,\text{mS}$$

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

$$G_v = \frac{v_o}{v_{sig}} = -\frac{R_G}{R_G + R_{sig}} \frac{g_m (R_D \parallel R_L)}{1 + g_m R_s}$$



$$k_n' \frac{W}{L} = 1 \frac{\text{mA}}{\text{V}^2}$$

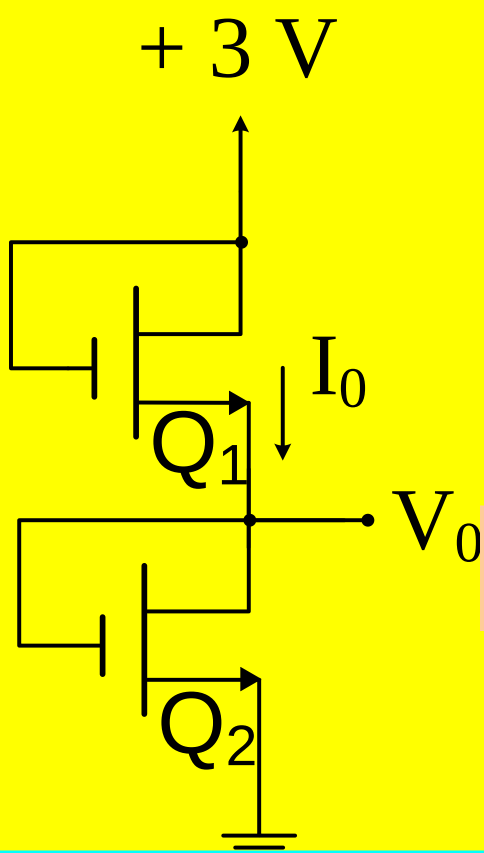
$$V_t = 1.5\ \text{V}$$

$$G_v = \frac{-4.7\text{M}}{4.7\text{M} + 100\ \text{k}} \frac{10^{-3}(14\text{k} \parallel 14\text{k})}{1 + 10^{-3} \times 2 \times 10^{-3}}$$

$$= \mathbf{-2.33}$$

Example: DC Analysis

For the circuit shown in Fig. below calculate the voltage V_0 and current I_0. Both the MOSFET Q_1 and Q_2 are identical with $V_t = 1$ V, $\mu_n C_{ox} = 2.5\ \mu A/V^2$, L = 10 μm, and W = 30 μm.



V_{GD}= 0 V for both the MOSFET.

$V_{GD} < V_t$ (MOSFET is in Saturation)

$$I_0 = I_{D1} = I_{D2}$$

$$\Rightarrow V_{GS1} = V_{GS2}$$

$$V_{GS1} + V_{GS2} = 3\ \text{V}$$

$$\Rightarrow V_{GS1} = V_{GS2} = 1.5\ \text{V}$$

$$V_0 = 1.5\ \text{V}$$

$$I_D = \frac{1}{2}\mu_0 C_{0x}\frac{W}{L}(V_{GS} - V_t)^2$$

$$= \frac{1}{2}2.5\times10^{-6}\cdot\frac{30}{10}(1.5-1)^2 = 0.9375\quad \mu A$$