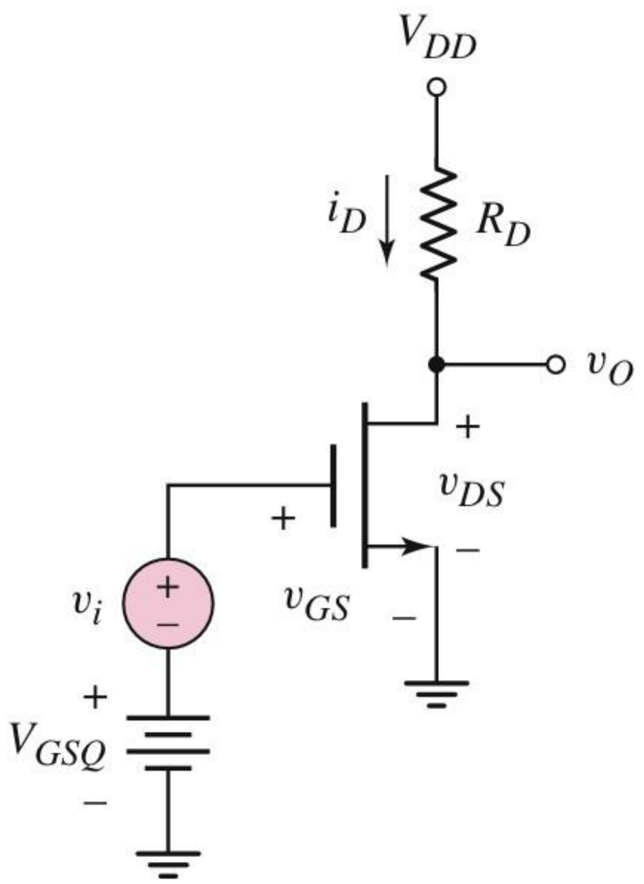
MOSFET Basic FET Amplifiers

The MOSFET Amplifier

The figure shows a basic MOSFET amplifier where the dc source V_{GSQ} is used to provide the bias voltage between gate and source.

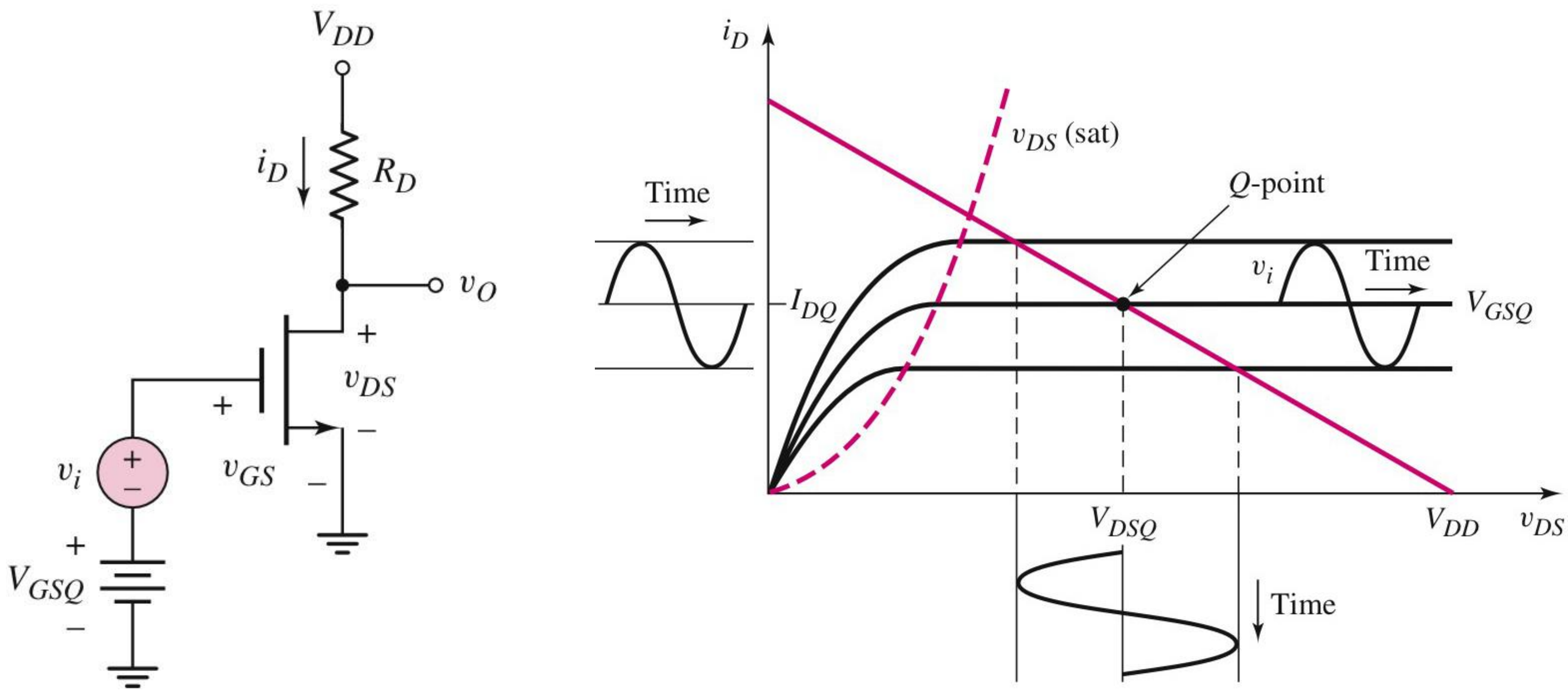
The ac voltage source v_i which represents the signal source is connected in series with the bias voltage V_{GSQ}.



MOSFET Basic FET Amplifiers

The MOSFET Amplifier

The Q-point is on dc load line and Q-point are functions of v_{GS}, V_{DD} and R_D and the transistor parameters.

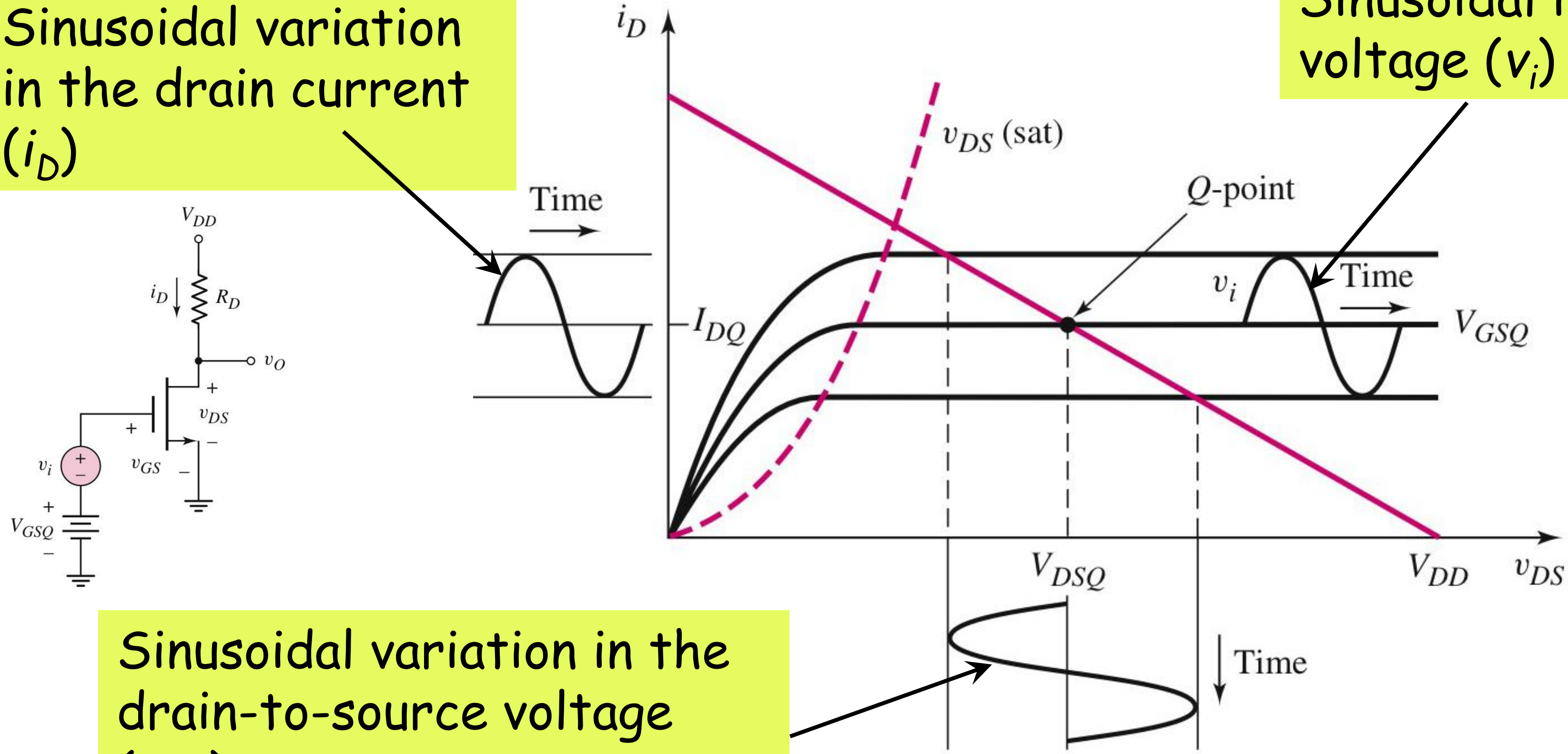


The MOSFET Amplifier

The sinusoidal input voltage (v_i) causes variations in the gate-to-source voltage (v_{GS}), drain current (i_D) and drain-to-source voltage (v_{DS}).

Sinusoidal variation in the drain current (i_D)

Sinusoidal input voltage (v_i)



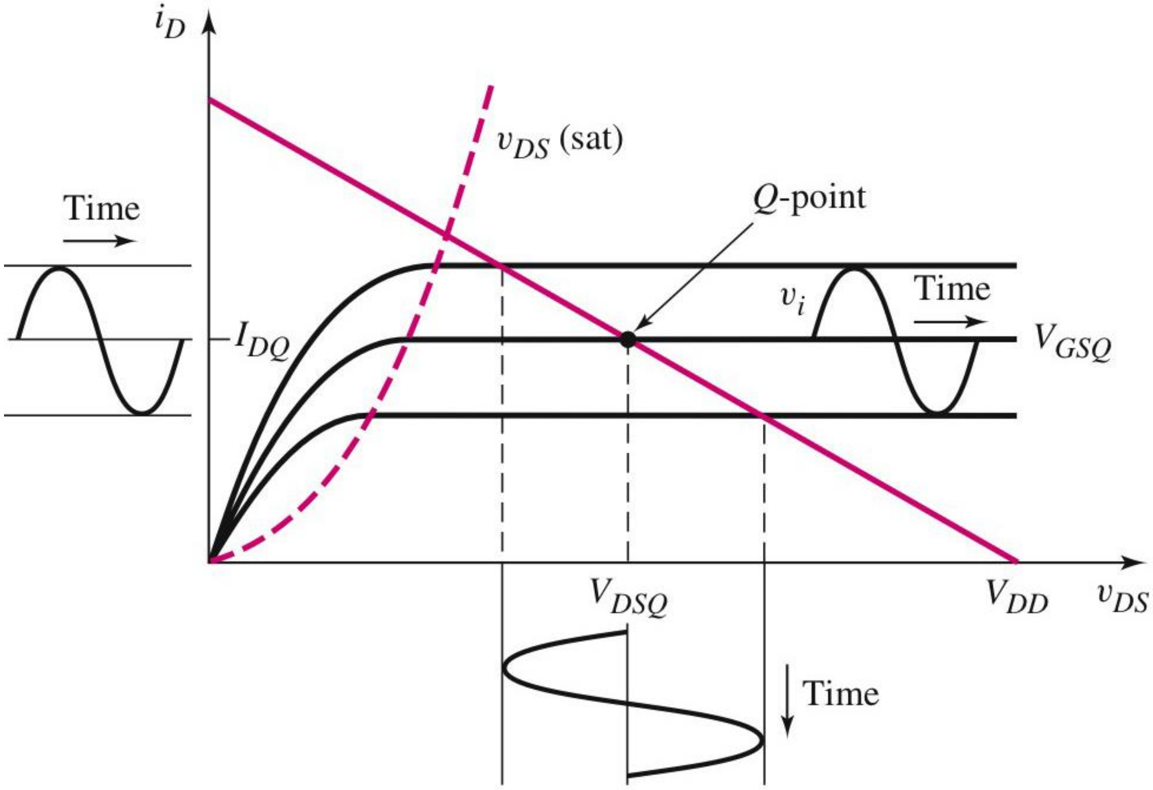
Sinusoidal variation in the drain-to-source voltage (v_{DS})

The MOSFET Amplifier

The total v_{GS} is the sum of V_{GSQ} and v_i i.e;

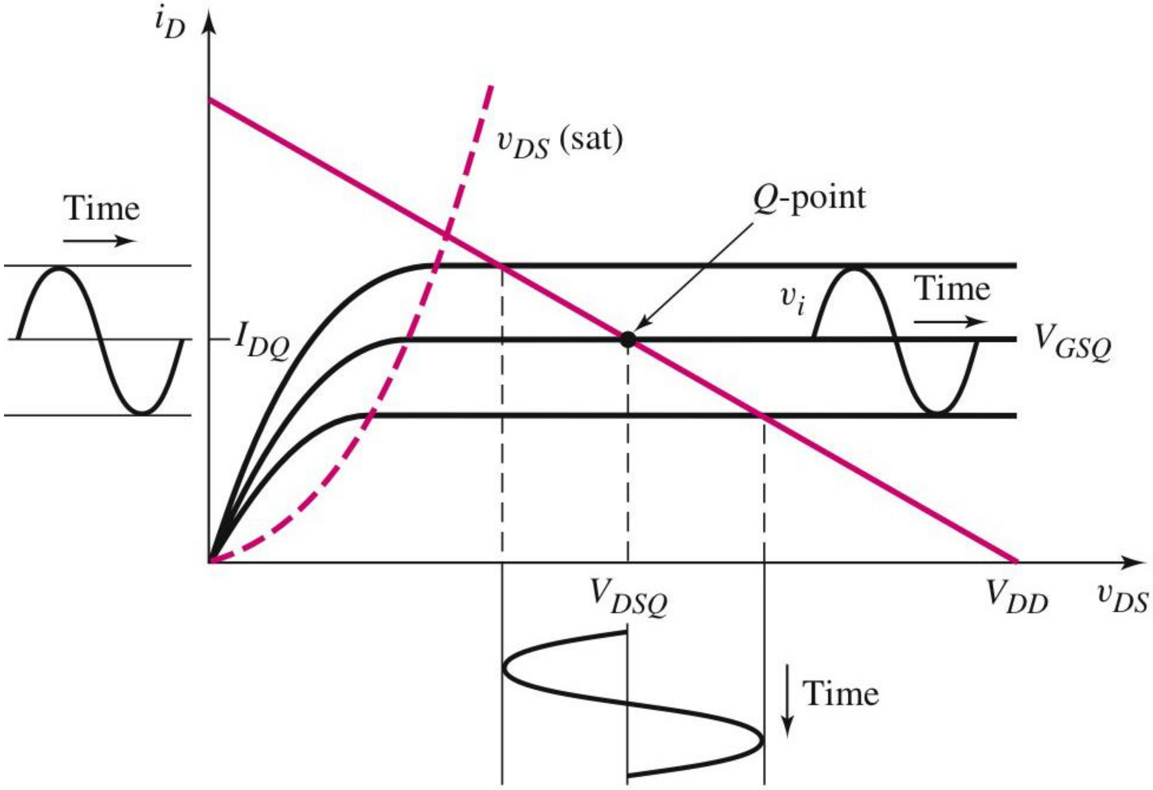
$$v_{GS} = V_{GSQ} + v_i$$

As v_i increases, the instantaneous value of v_{GS} increases, and the **bias point moves up on the load line.**



The MOSFET Amplifier

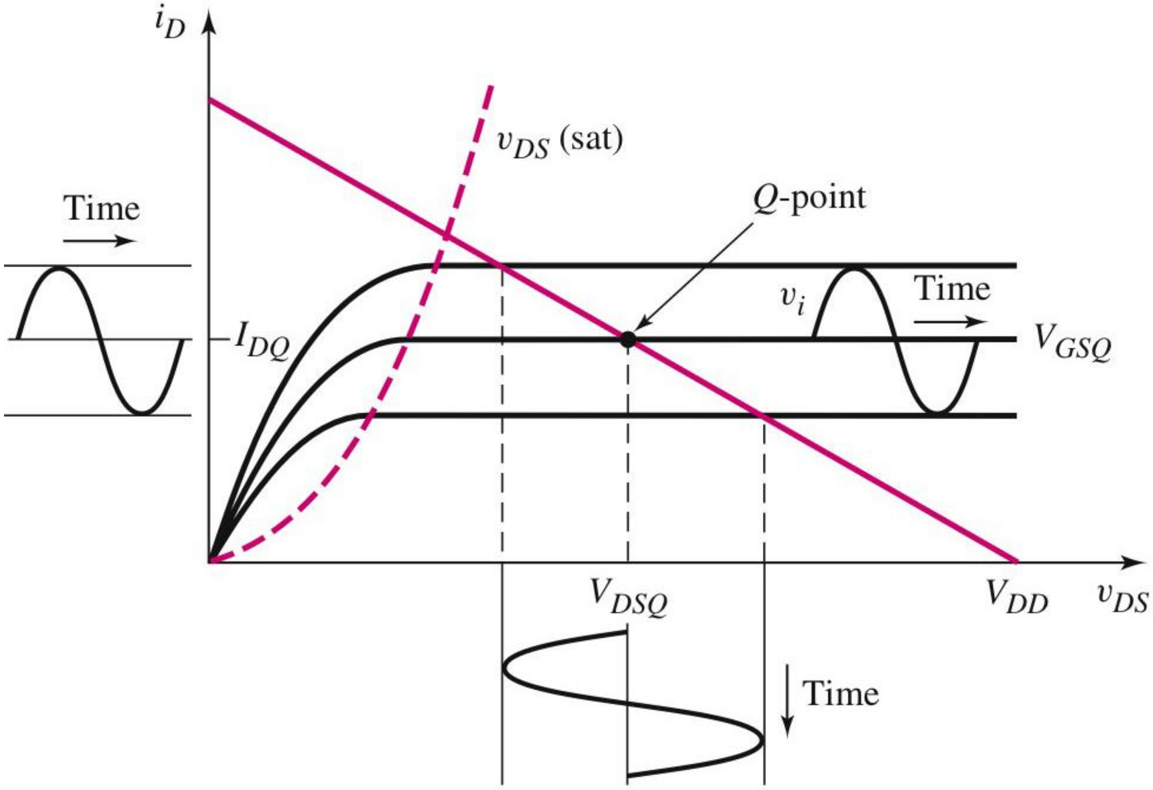
Larger value of v_{GS} means larger drain currrent i_D and smaller value of v_{DS}.



The MOSFET Amplifier

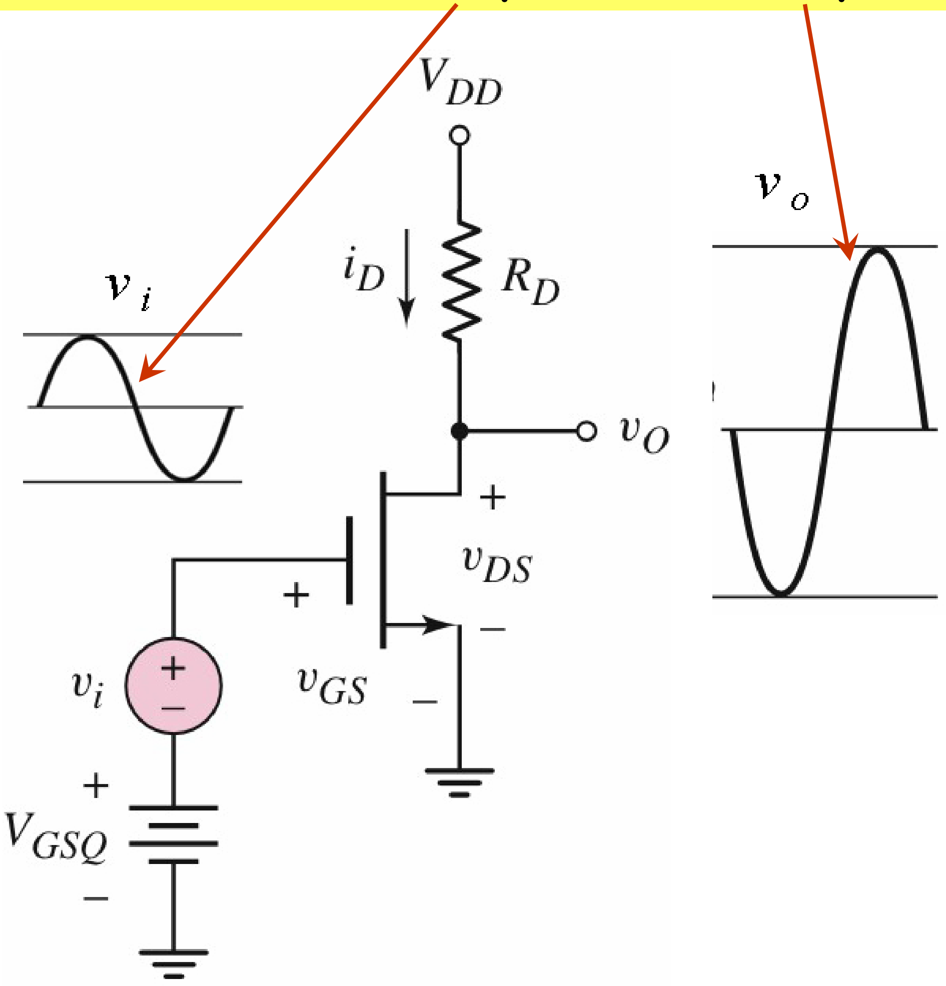
A smaller value of v_{GS} means smaller drain current i_D and larger value of v_{DS}.

Thus this configuration causes **phase inversion.**



The MOSFET Amplifier

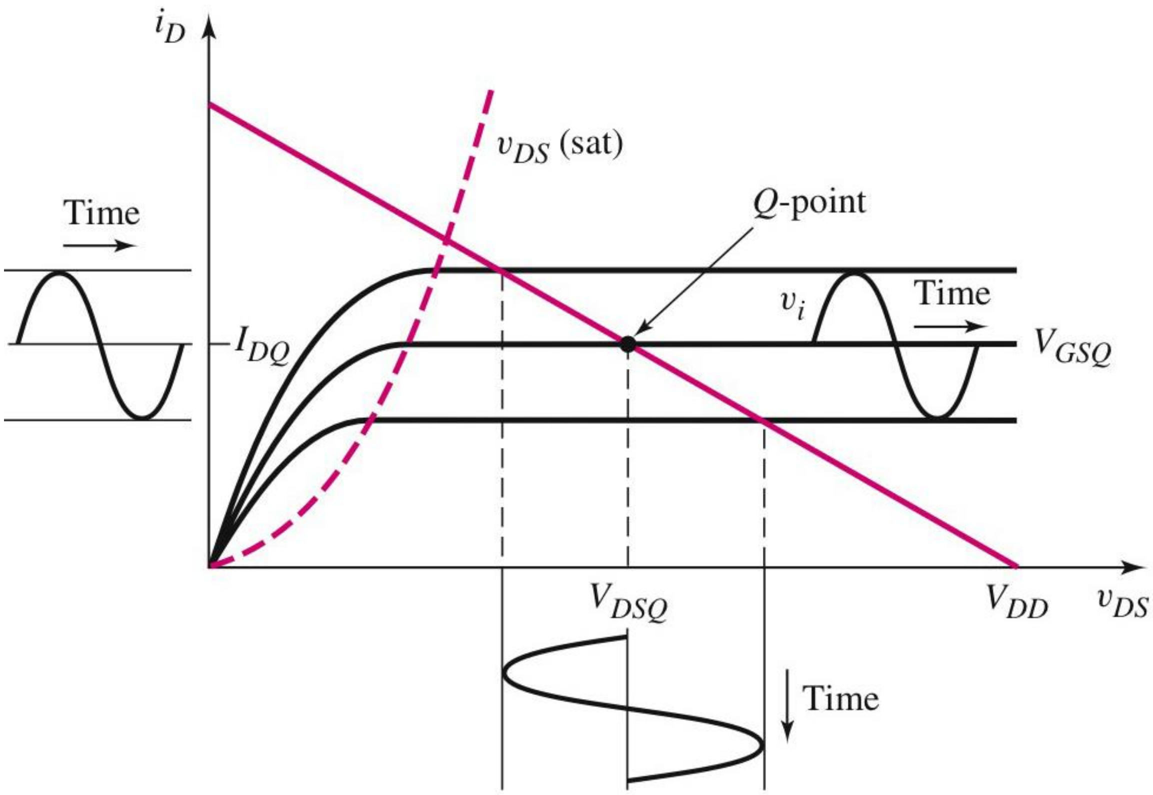
Phase inversion between input and output voltages



Basic FET Amplifiers

The MOSFET Amplifier

For the MOSFET to operate as a **linear amplifier**, it must be biased in the saturation region and the instantaneous drain current and drain-to-source voltage must also be confined to this region.

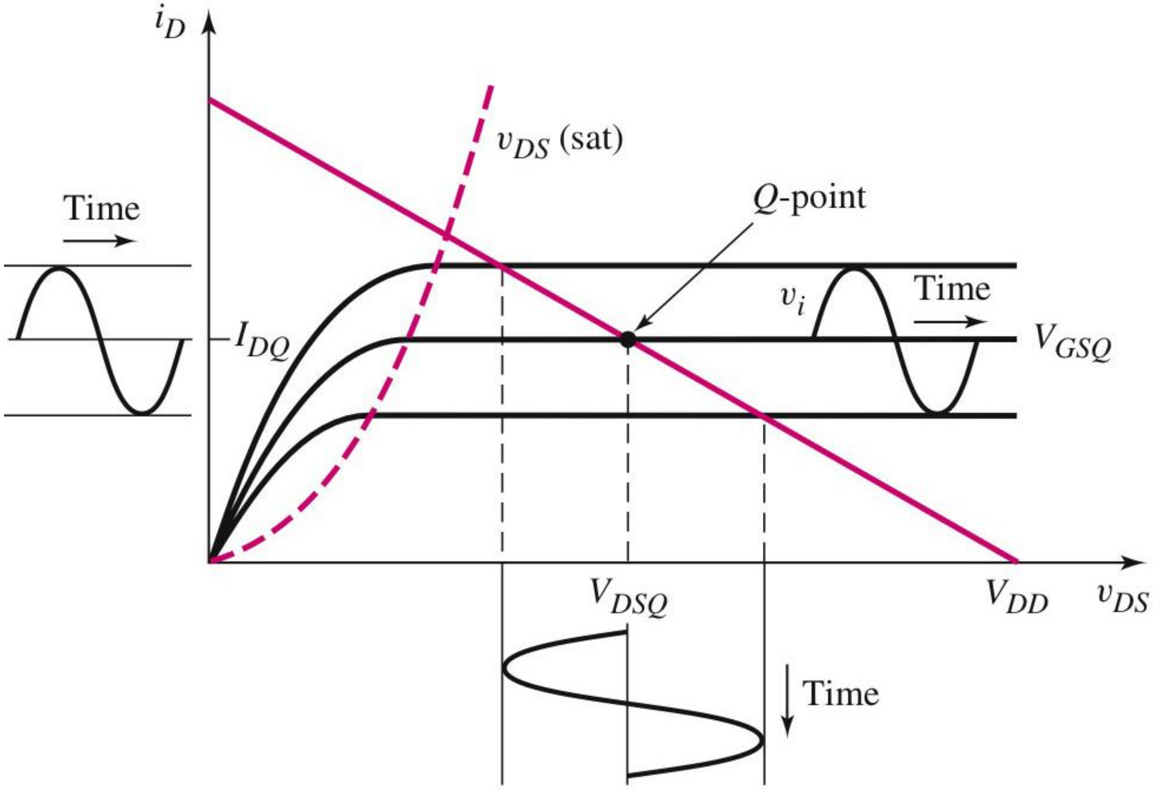


MOSFET Basic FET Amplifiers

The MOSFET Amplifier

As long as the amplifier operates in the linear region, symmetrical input signal will produce symmetrical output.

If the limit is exceeded, the output signal will be clipped and distortion will occur.



The MOSFET Amplifier

The total instantaneous value of the gate-to-source voltage is given by;

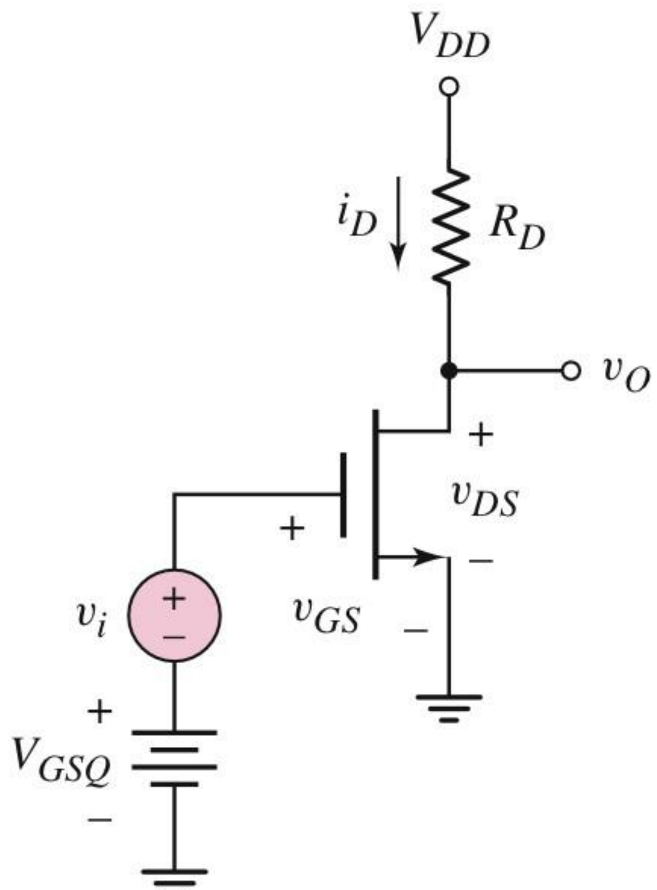
$$v_{GS} = V_{GSQ} + v_i$$

Considering only ac component;

$$v_{gs} = v_i$$

Hence;

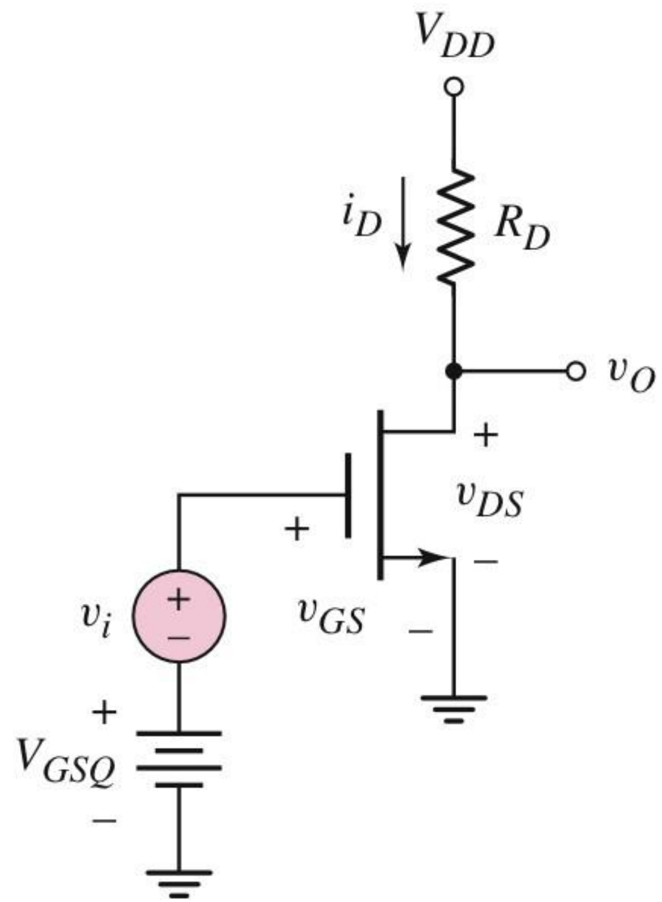
$$v_{GS} = \underbrace{V_{GSQ}}_{\text{dc component}} + \underbrace{v_{gs}}_{\text{ac component}}$$



The MOSFET Amplifier

The total instantaneous drain current is;

$$i_D = K_n\left(v_{GS} - V_{TN}\right)^2$$



Substituting for v_{GS};

$$\begin{aligned} i_D &= K_n\left(V_{GSQ} + v_{gs} - V_{TN}\right)^2 \\ &= K_n\left[\left(V_{GSQ} - V_{TN}\right) + v_{gs}\right]^2 \end{aligned}$$

or

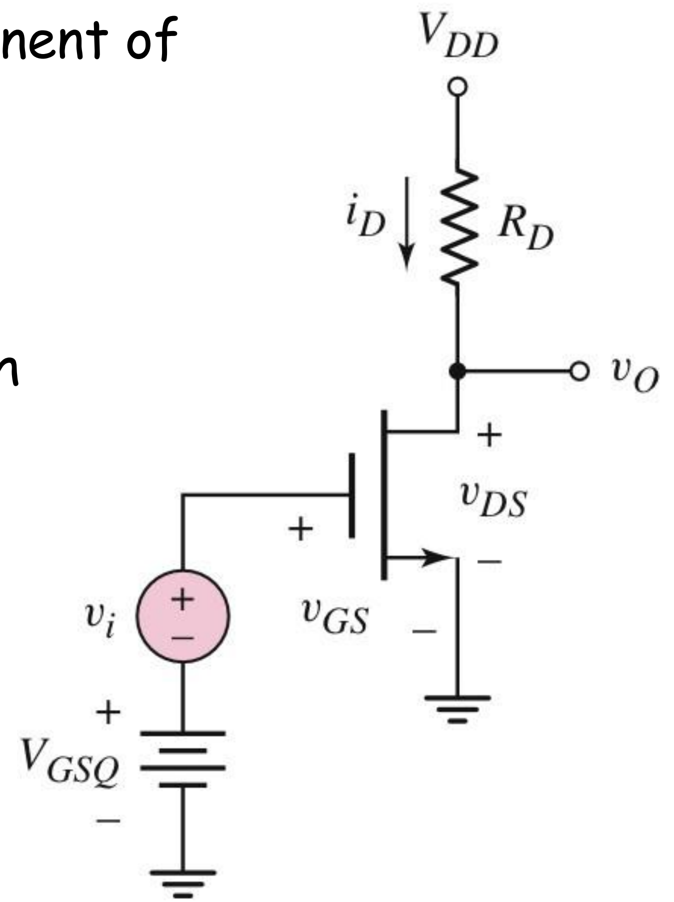
$$i_D = K_n\left(V_{GSQ} - V_{TN}\right)^2 + 2K_n\left(V_{GSQ} - V_{TN}\right)v_{gs} + K_n v_{gs}^2$$

The MOSFET Amplifier

The term $K_n\left(V_{GSQ}-V_{TN}\right)^2$ is the dc component of the drain current

The term $2K_n\left(V_{GSQ}-V_{TN}\right)v_{gs}$ is the time-varying component of the drain current which is linearly related to the input signal v_{gs}.

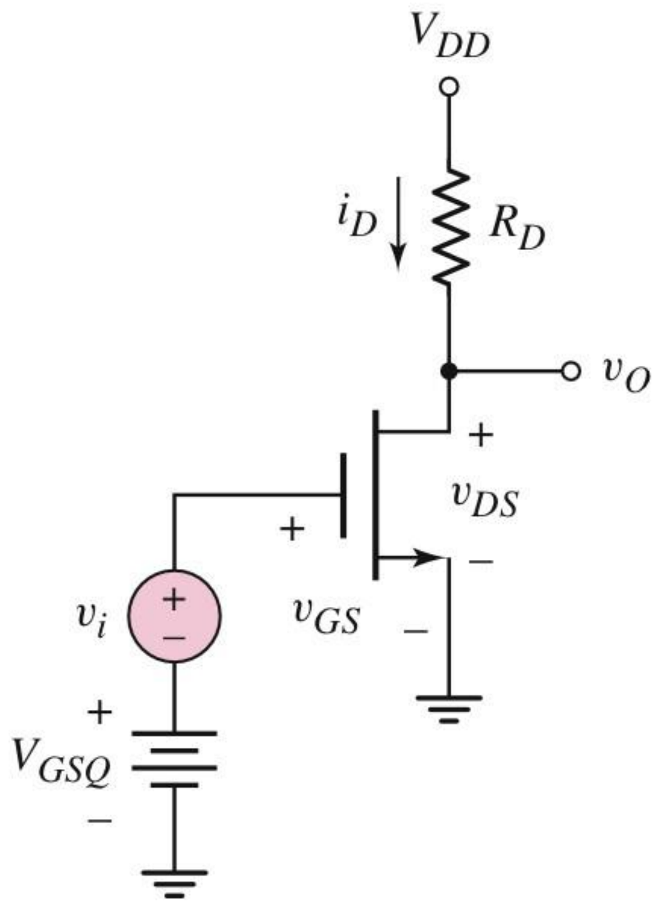
The term $K_n v_{gs}^2$ is the component of the drain current which is proportional to the square of the input signal v_{gs}.



$$i_D = K_n\left(V_{GSQ}-V_{TN}\right)^2 + 2K_n\left(V_{GSQ}-V_{TN}\right)v_{gs} + K_n v_{gs}^2$$

The MOSFET Amplifier

The term $K_n v_{gs}^2$ produces undesirable harmonics or non-linear distortion in the output voltage.



To minimize these harmonics, we must have;

$$v_{gs} << 2(V_{GSQ} - V_{TN})$$

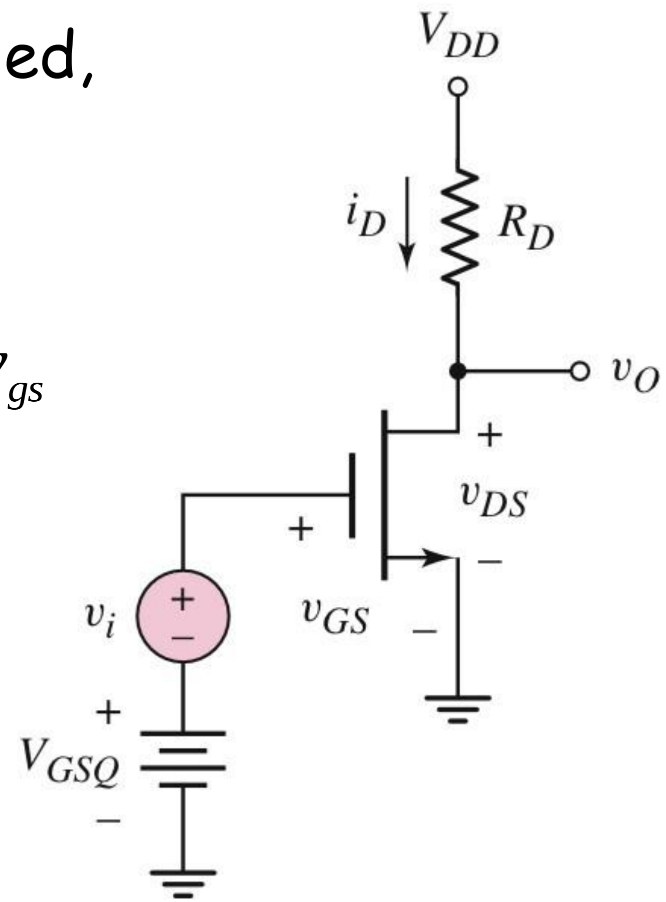
This is the small-signal condition that must be satisfied for **linear amplifier**.

$$i_D = K_n (V_{GSQ} - V_{TN})^2 + 2K_n (V_{GSQ} - V_{TN}) v_{gs} + K_n v_{gs}^2$$

The MOSFET Amplifier

If the small-signal condition is satisfied, the term containing v_{gs}^2 may be neglected and the equation for i_D becomes;

$$i_D = K_n(V_{GSQ} - V_{TN})^2 + 2K_n(V_{GSQ} - V_{TN})v_{gs}$$



The equation may be written as;

$$i_D = I_D + i_d$$

where;

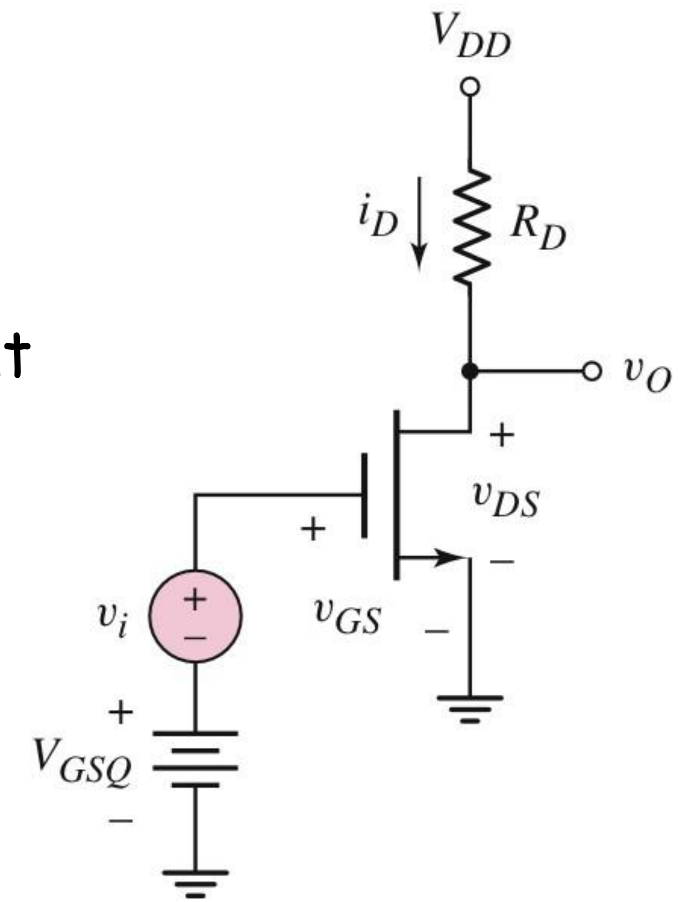
$$I_D = K_n(V_{GSQ} - V_{TN})^2$$ – the dc component

The MOSFET Amplifier

and;

$$i_d = 2K_n\left(V_{GSQ} - V_{TN}\right)v_{gs}$$

– the ac or signal component



From the above equation, we can write;

$$g_m = \frac{i_d}{v_{gs}} = 2K_n\left(V_{GSQ} - V_{TN}\right)$$

– the transconductance relating the output current to the input voltage

The MOSFET Amplifier

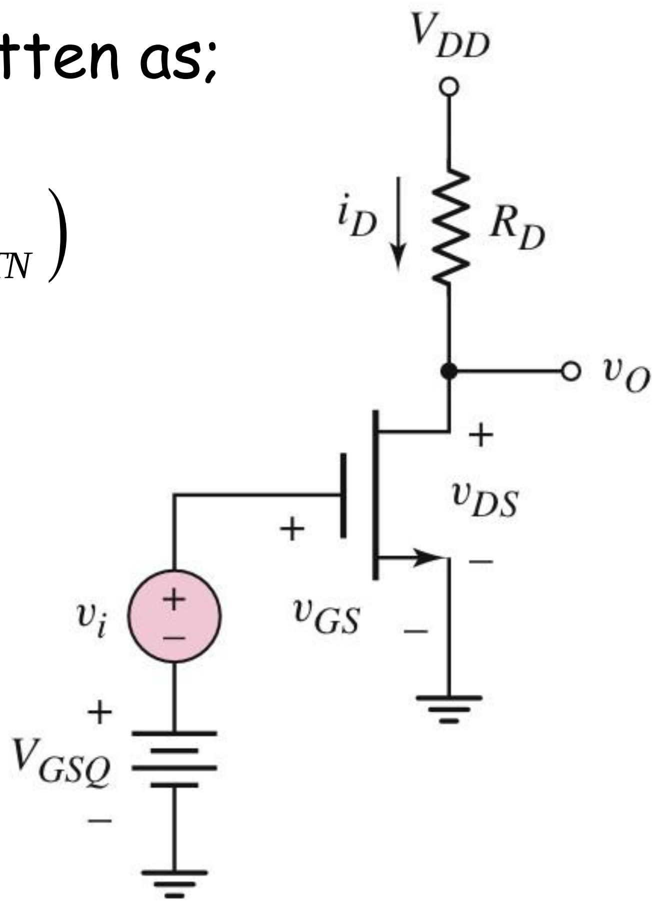
The transconductance can also be written as;

$$g_m = \left.\frac{\partial i_D}{\partial v_{GS}}\right|_{v_{GS}=V_{GSQ}=\text{const.}} = 2K_n\left(V_{GSQ} - V_{TN}\right)$$

$$I_D = K_n\left(V_{GSQ} - V_{TN}\right)^2$$

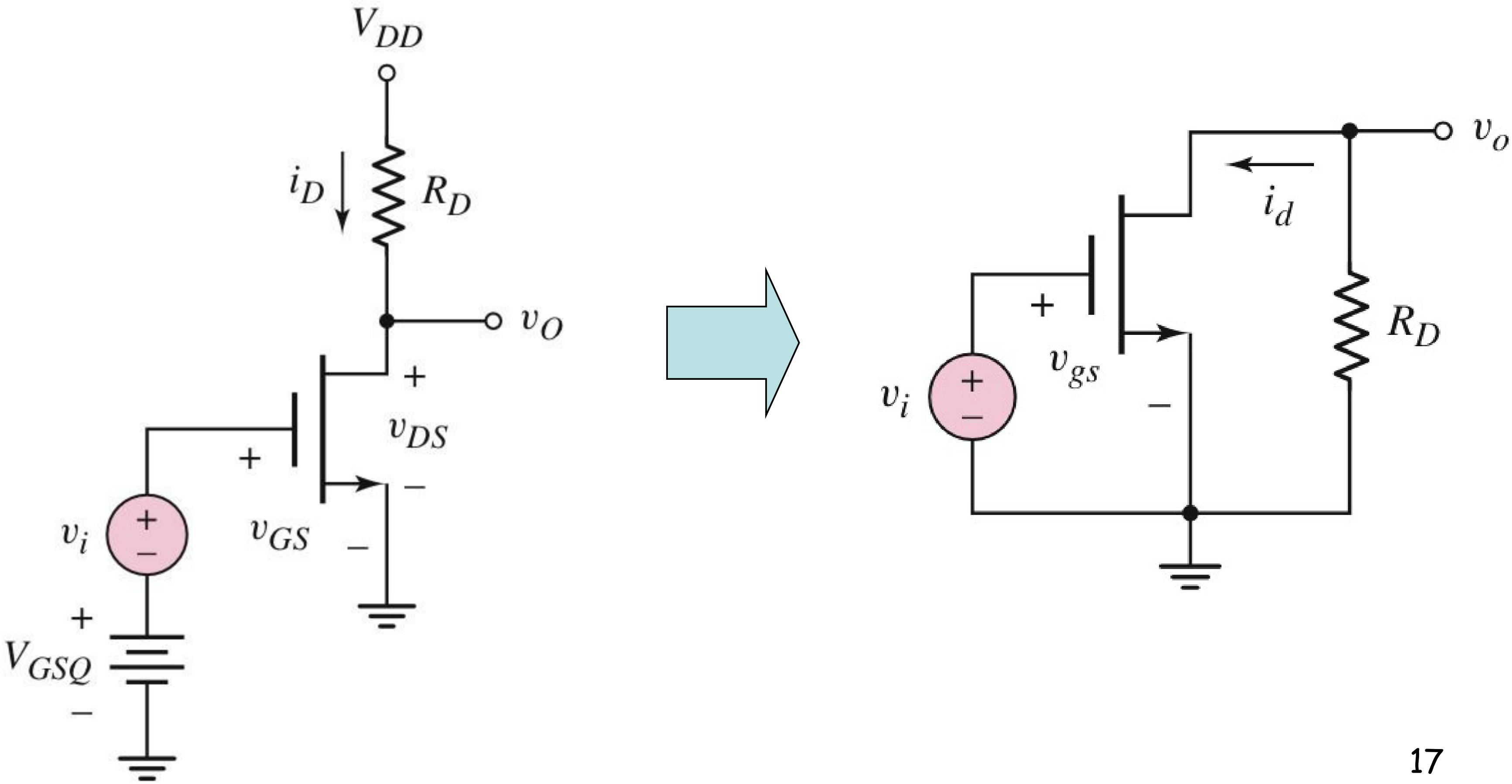
which gives us;

$$g_m = 2\sqrt{K_n I_{DQ}}$$

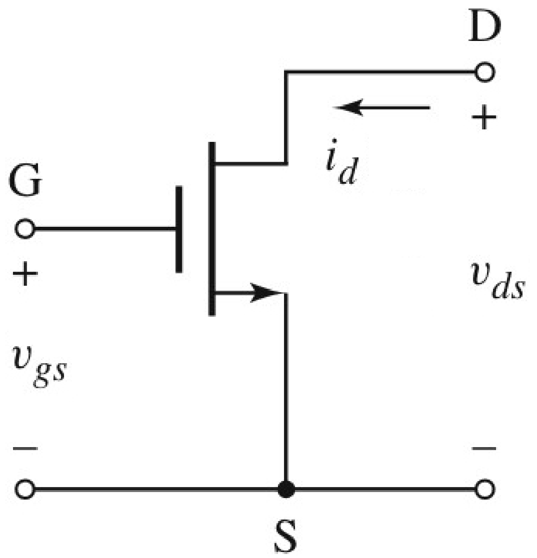


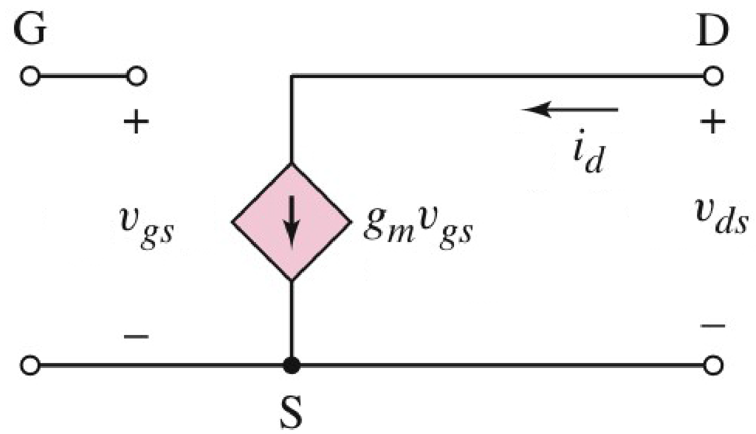
The MOSFET Amplifier | AC Equivalent Circuit

In the **ac equivalent circuit**, all **dc sources are set to zero** and V_{DD} is considered to be at signal ground.

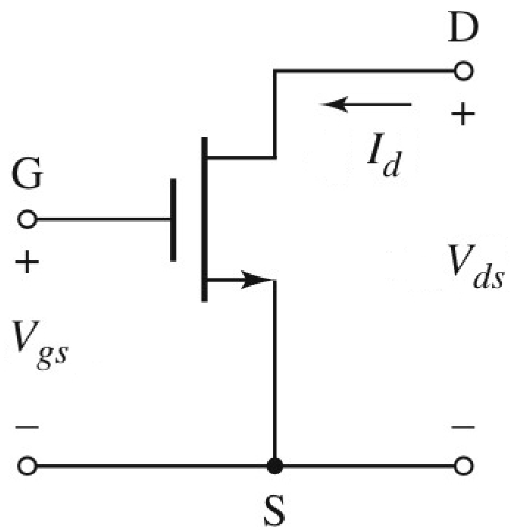


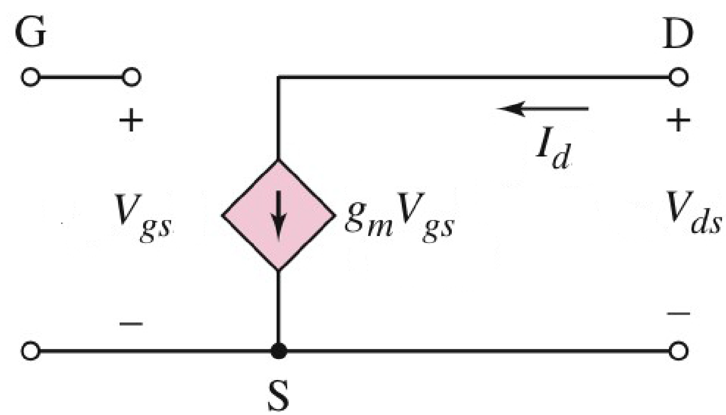
If we neglect the effect of the **output resistance r_o**, the MOSFET and its small-signal equivalent circuit are as follows (in terms of instantaneous ac values):





The small-signal equivalent circuit in terms of phasor components (note the notation used):





$$v(t) = 6 * cos(120\pi + 30^\circ)$$

$$V = 6\angle 30^\circ$$

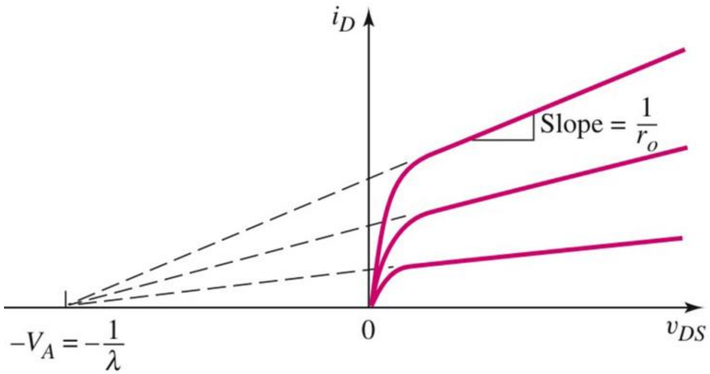
which is the phasor of v(t)

$$i(t) = 2 * cos(120\pi + 30^\circ)$$

$$I = 2\angle 30^\circ$$

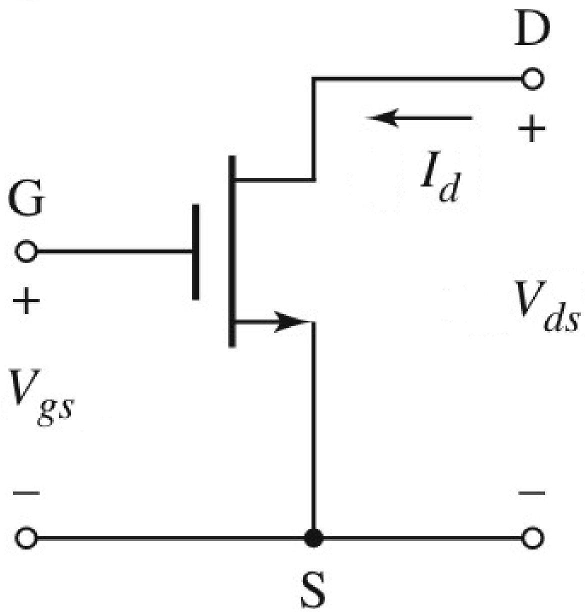
the phasor of i(t).

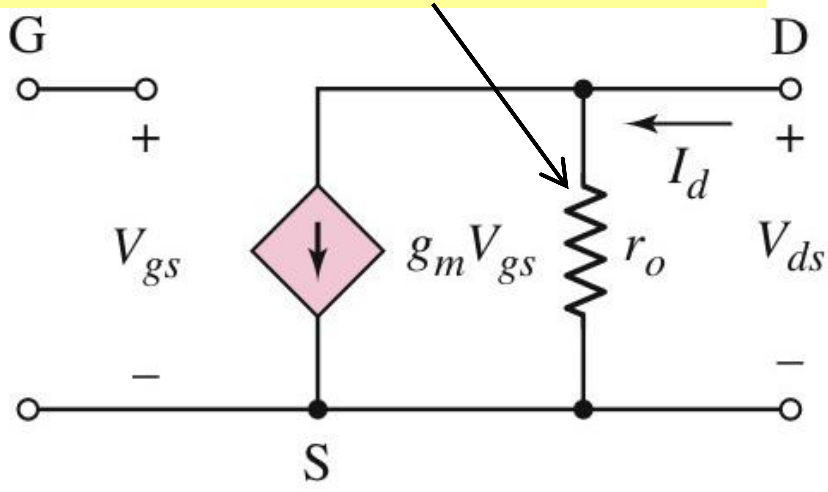
The small-signal equivalent circuit with r_o taken into account.

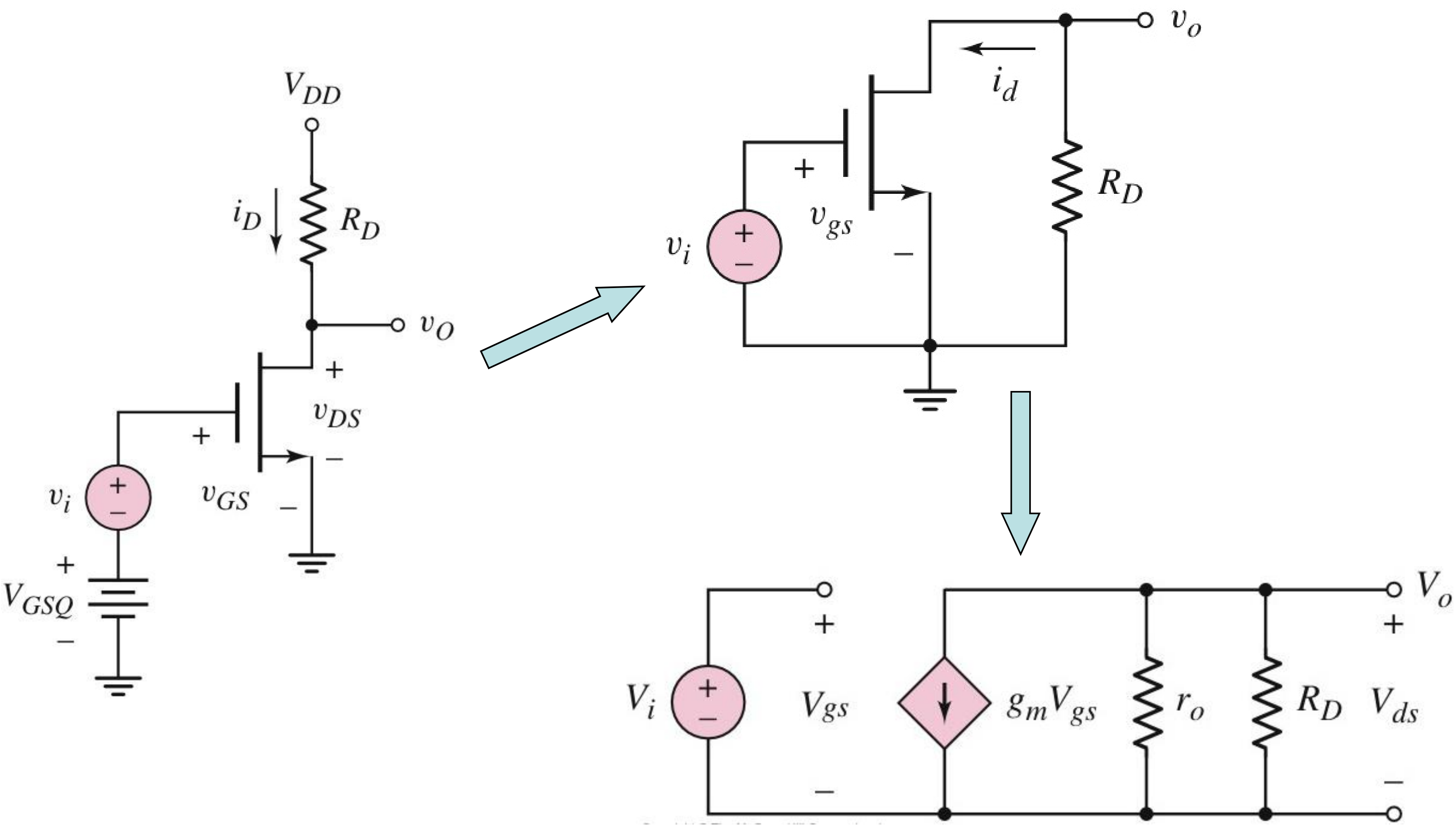


$$i_D = K_n (v_{GS} - V_{TN})^2 (1 + \lambda v_{DS})$$

$$r_o = \left. \frac{\partial i_D}{\partial v_{DS}} \right|^{-1}_{v_{GS} = V_{GSQ} = \text{const.}} \cong [\lambda I_{DQ}]^{-1}$$







V_{DD}
i_D
R_D
v_O
v_{DS}
v_{GS}
v_i
V_{GSQ}
v_o
i_d
R_D
v_{gs}
v_i
V_o
V_i
V_{gs}
g_mV_{gs}
r_o
R_D
V_{ds}

The MOSFET Amplifier Example 1

The MOSFET in the figure has the following parameters;

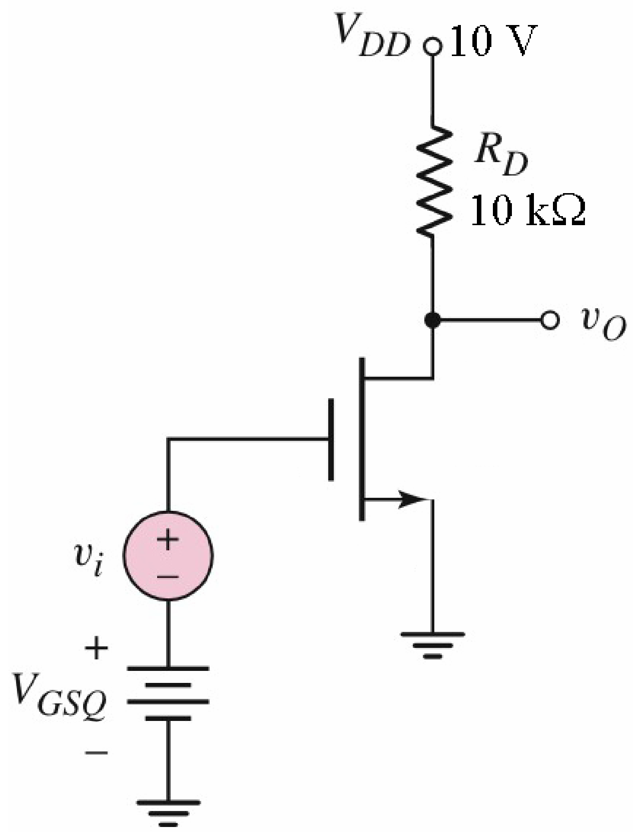
$$V_{TN} = 2\text{ V},\ \ K_n = 0.5\text{ mA/V}^2,\ \text{and}\ \ \lambda = 0$$

The transistor is biased for I_{DQ} = 0.4 mA.

(a) Draw the ac equivalent circuit.

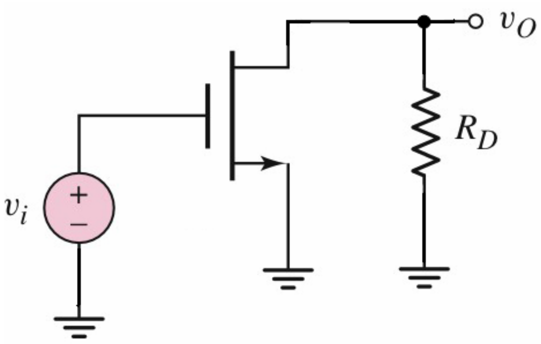
(b) Draw the small-signal equivalent circuit.

(c) Determine the small-signal voltage gain A_v.

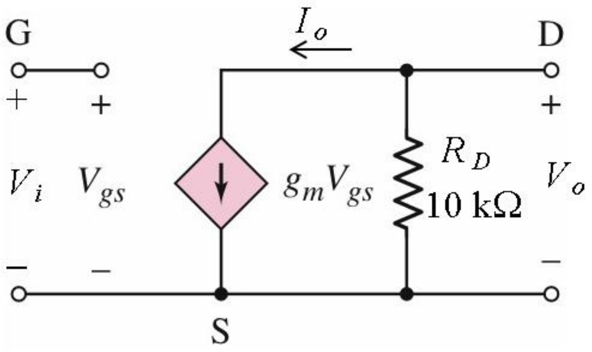


Example 1 – *Solution*

(a) For the ac equivalent circuit, all dc voltage sources are set to zero;

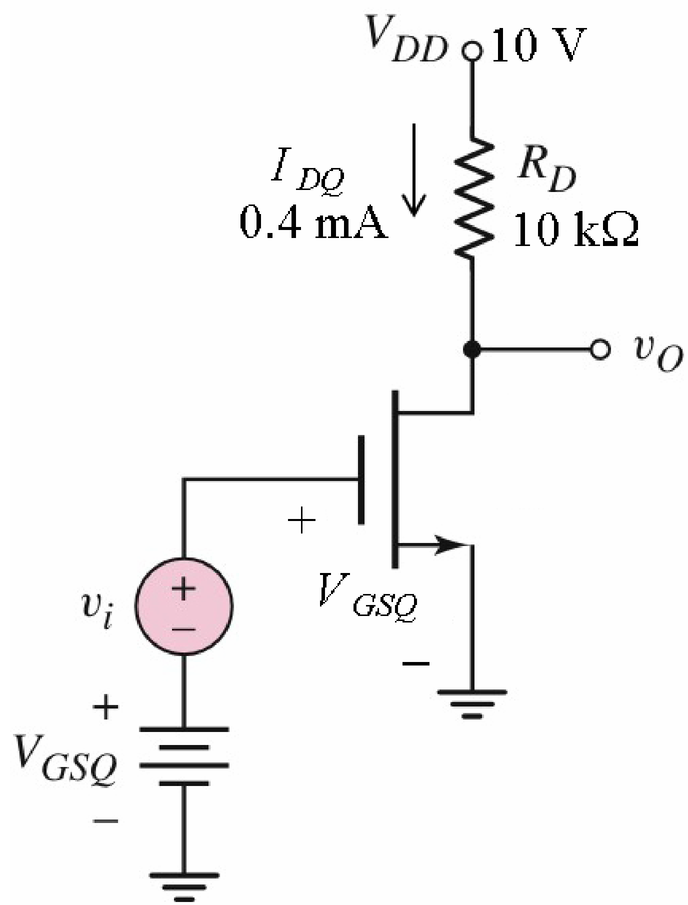


(b) Since λ = 0, the output resistance r_o is omitted in the small-signal equivalent circuit;



Example 1 – *Solution* (*cont'd*)

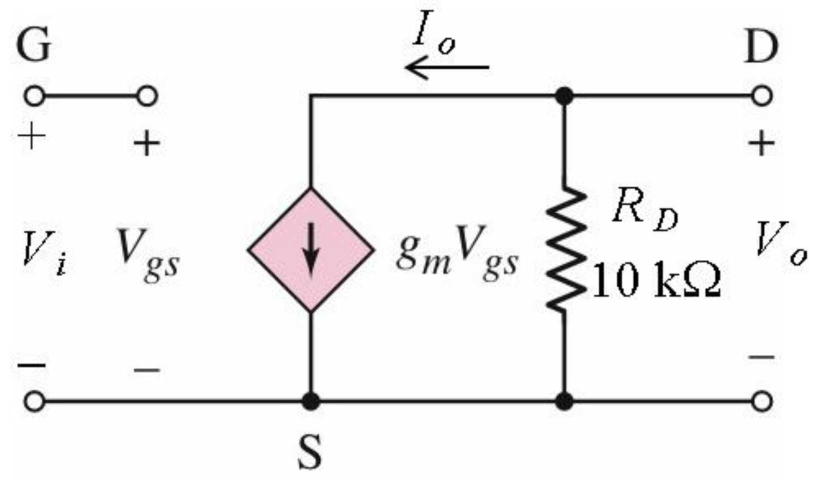
(c)
$$g_m = 2\sqrt{K_n I_{DQ}}$$
$$= 2\times 10^{-3}\sqrt{0.5\times 0.4}$$
$$= 0.894 \text{ mA/V}$$



The MOSFET Amplifier Example 1 – *Solution (cont'd)*

At the output terminal;

$$V_o = -g_m V_{gs} R_D$$



At the input terminal;

$$V_i = V_{gs}$$

Substituting for V_{gs};

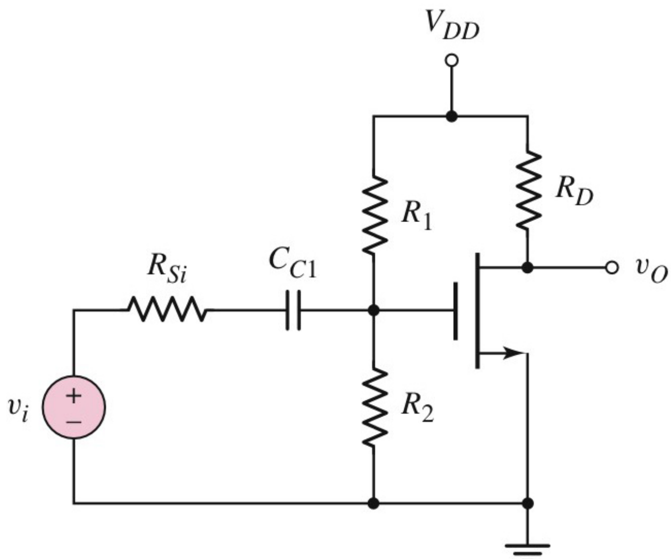
$$V_o = -g_m R_D V_i$$

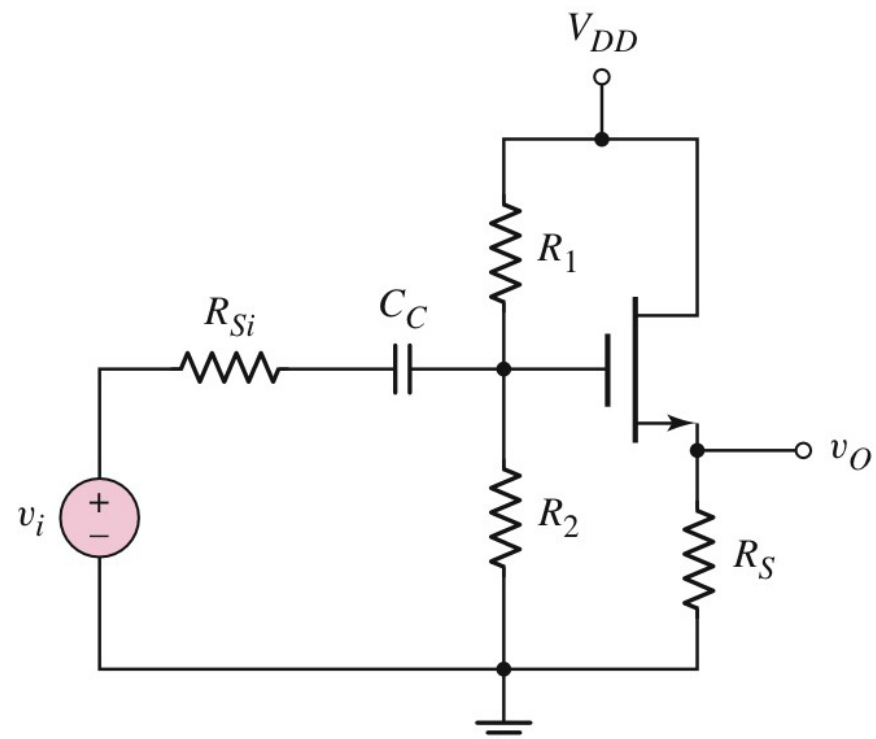
The small-signal voltage gain is;

$$A_v \equiv \frac{V_o}{V_i} = -g_m R_D$$

$$A_v = -g_m R_D = -0.894 \times 10 = -8.94 \text{ V/V}$$

Amplifier Circuits

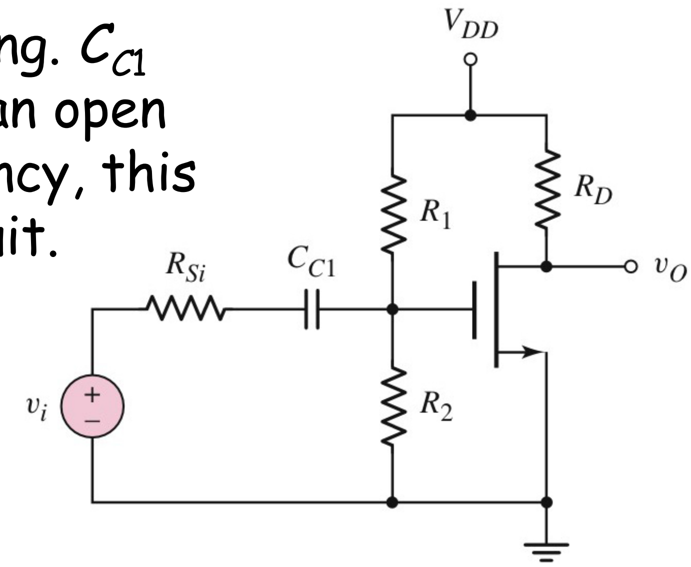


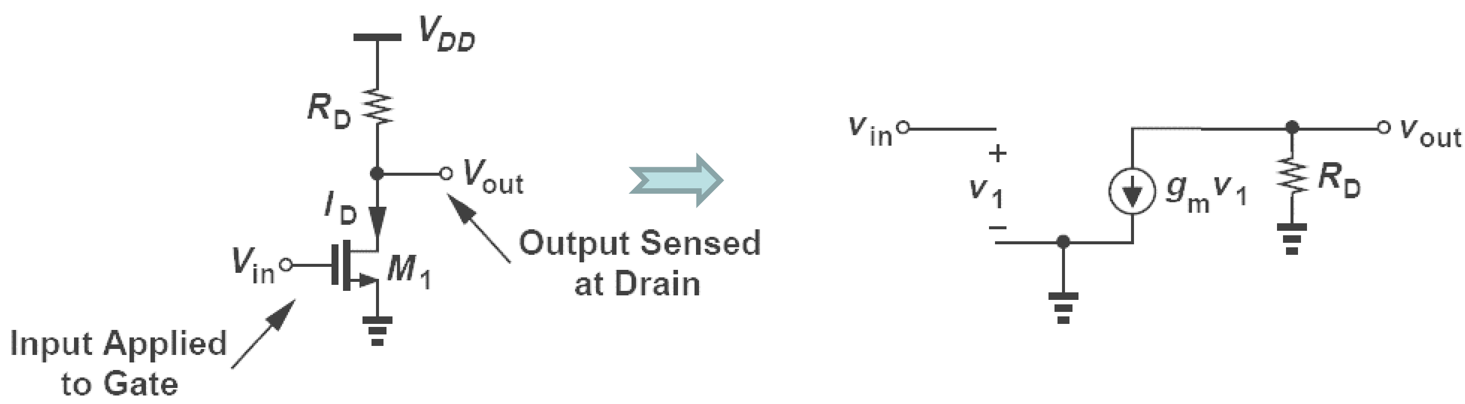


Common-source

R_1 and R_2 establish the transistor biasing. C_{C1} couples the signal to the input acts as an open circuit for dc voltage. At signal frequency, this capacitor is considered as a short circuit.

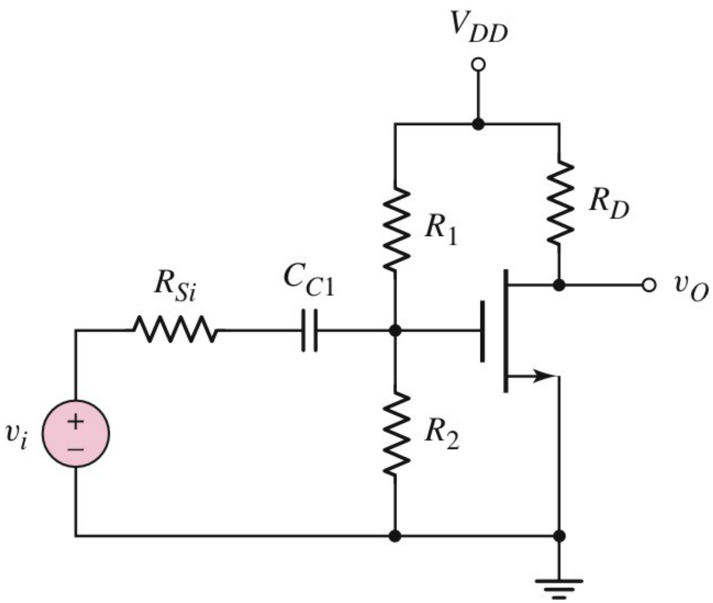
The source is grounded and is common to both input and output – hence the name common-source.

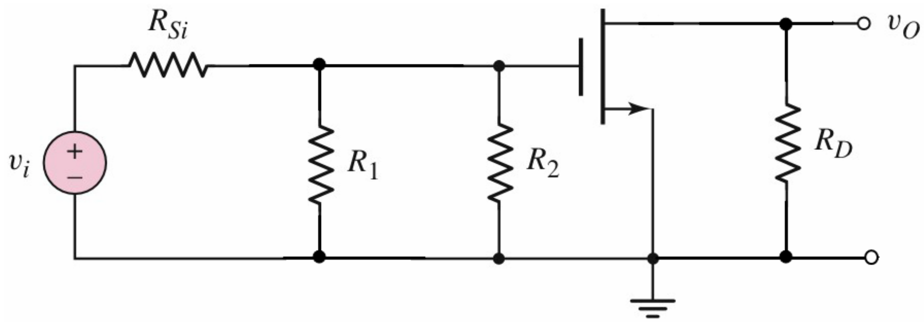




Common-source

Since the coupling capacitor is considered as a short circuit at signal frequency and all dc sources are set to zero under ac condition, the ac equivalent circuit for the amplifier may drawn as follows;



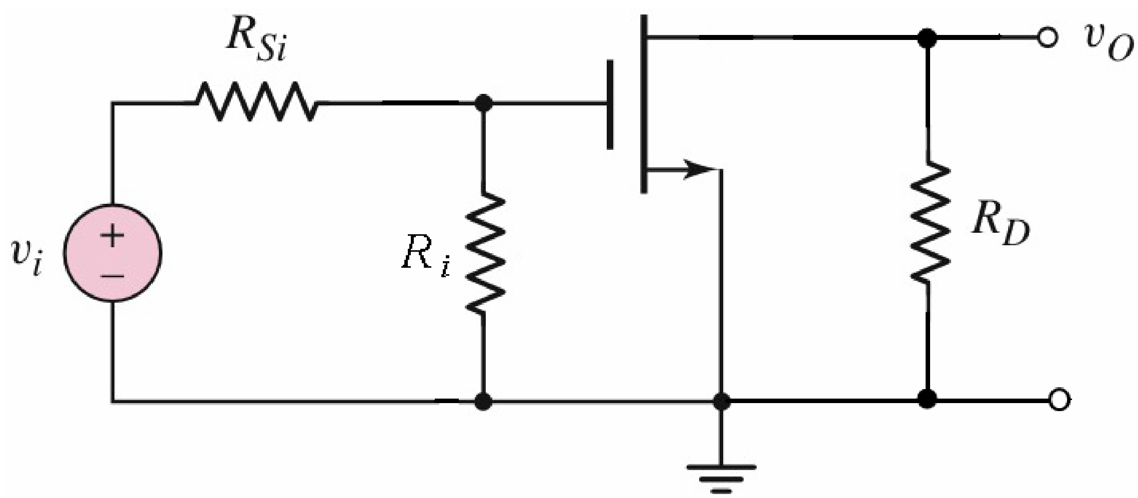


Common-source

The parallel combination of R_1 and R_2 may be replaced by R_i where;

$$R_i = R_1 \| R_2 = \frac{R_1 R_2}{R_1 + R_2}$$

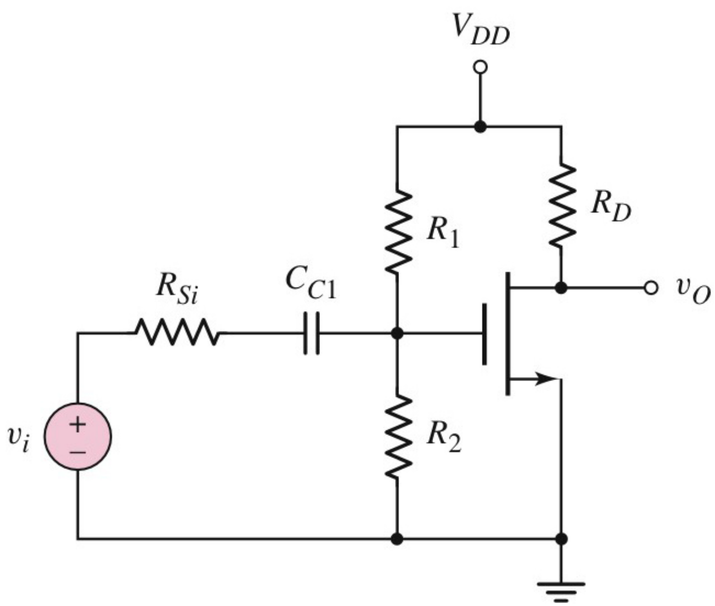
R_i is the **input resistance** of the amplifier.

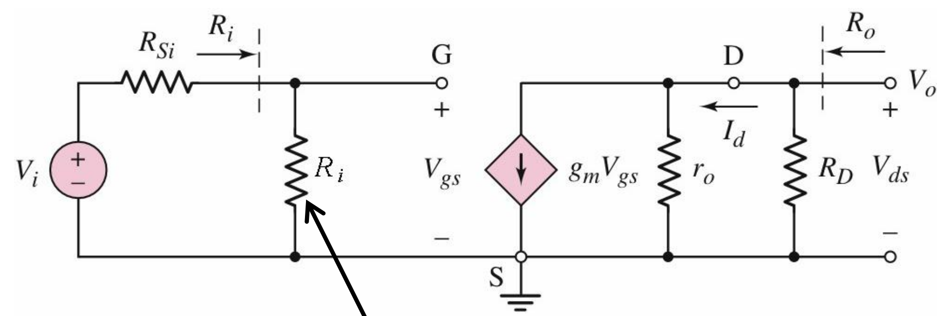


MOSFET Basic Amplifier Configurations

Common-source

The small-signal equivalent circuit may drawn as shown below;





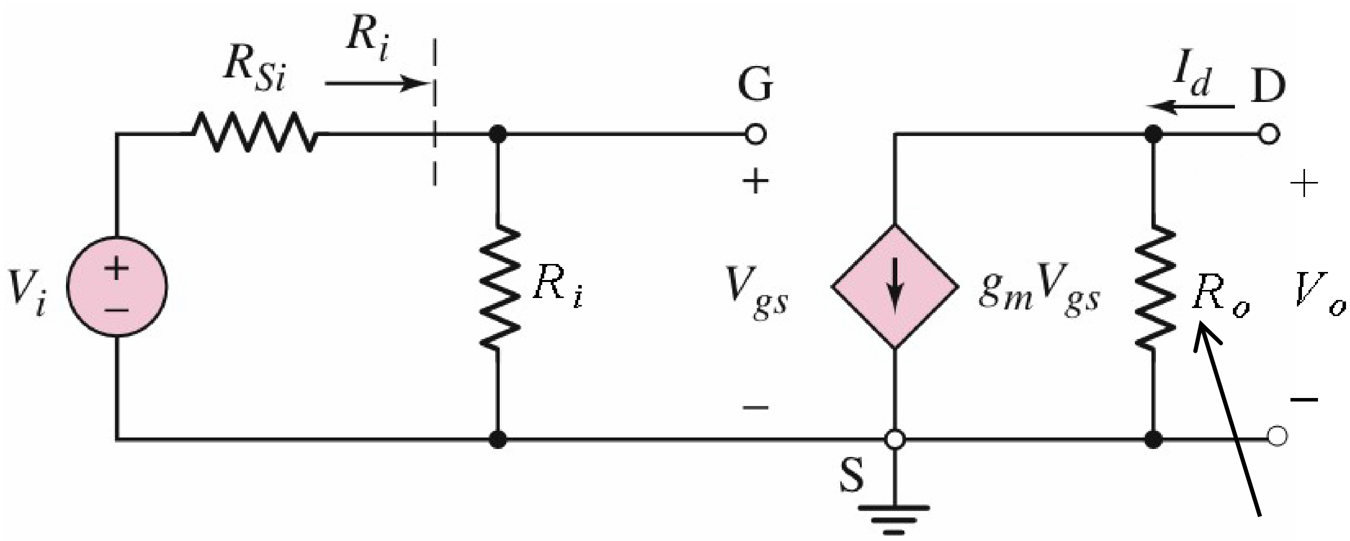
$$R_i = R_1 \| R_2$$

In the above circuit, the **output resistance of the transistor, r_o** is finite and taken into account.

MOSFET Basic Amplifier Configurations

Common-source

Since R_D and the output resistance of the transistor, r_o are in parallel, the small-signal equivalent circuit may be redrawn as shown below.

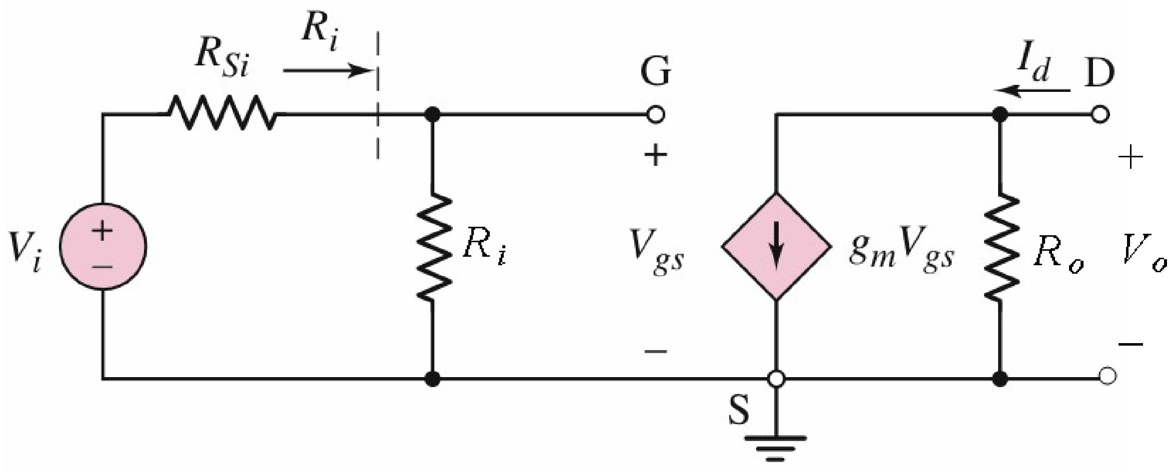


$$R_o = r_o \| R_D$$

MOSFET Basic Amplifier Configurations

Common-source

Using this equivalent circuit, at the output terminal;



$$V_o = -g_m V_{gs} R_o$$

At the input terminal;

$$V_{gs} = V_i \left(\frac{R_i}{R_{Si} + R_i} \right) \Rightarrow V_o = -g_m V_i \left(\frac{R_i}{R_{Si} + R_i} \right) R_o$$

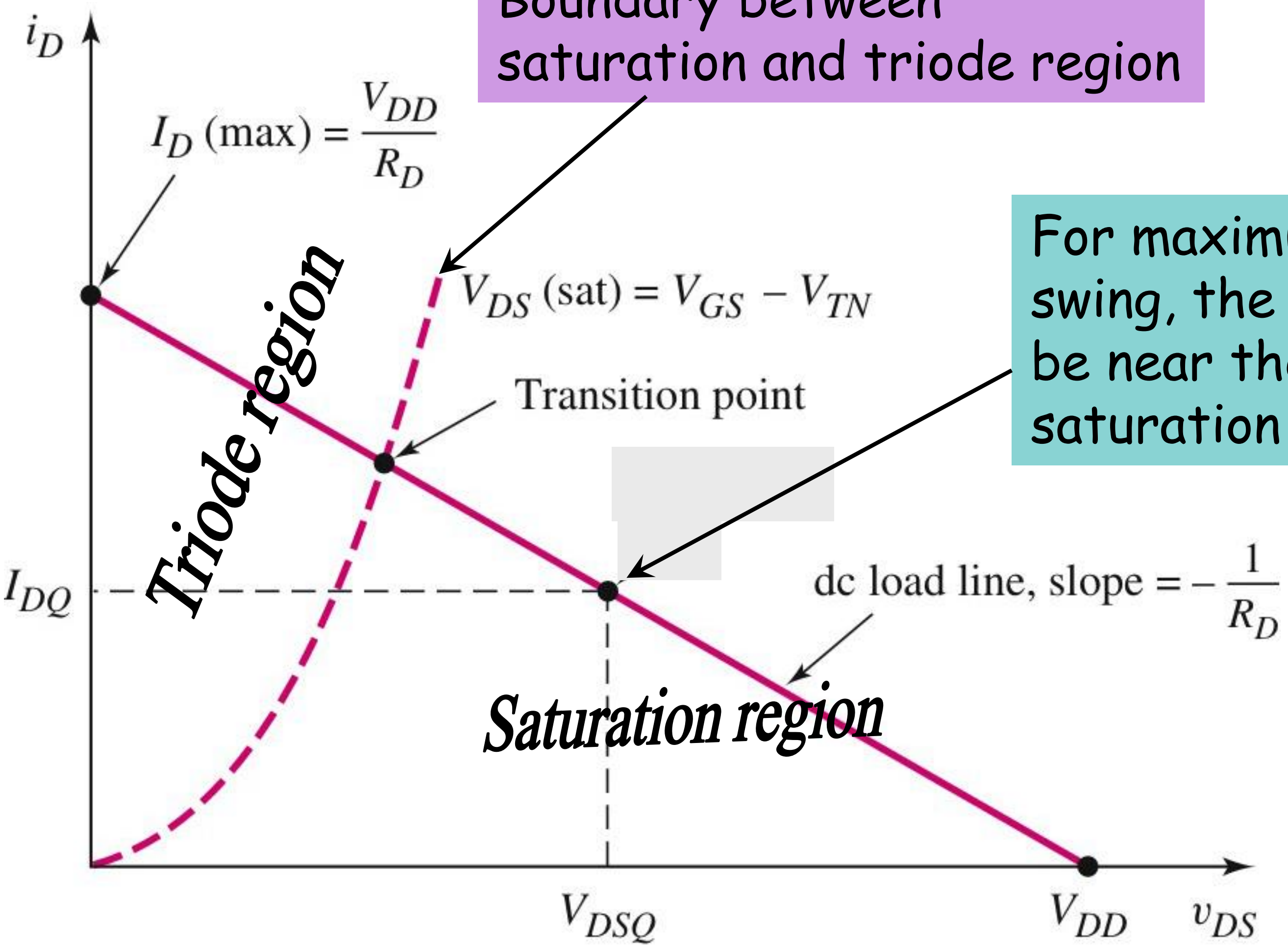
Hence the voltage gain is;

$$A_v \equiv \frac{V_o}{V_i} = -g_m \left(\frac{R_i R_o}{R_{Si} + R_i} \right)$$

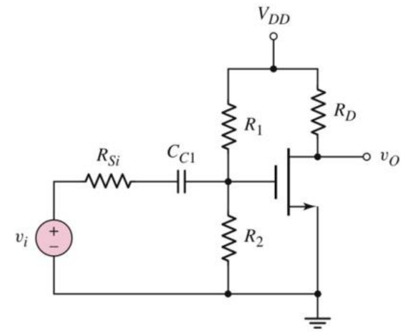
MOSFET Basic Amplifier Configurations

Common-source

Boundary between saturation and triode region

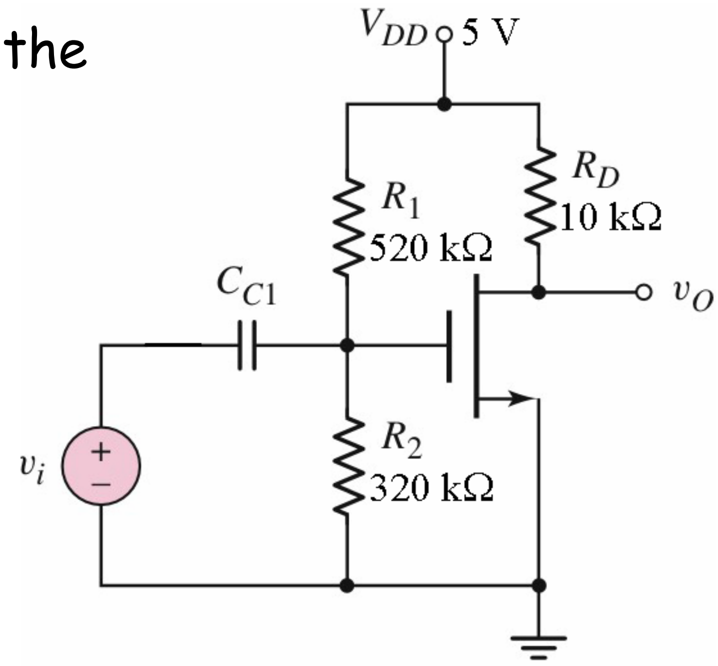


For maximum symmetrical swing, the **Q-point** must be near the middle of the saturation region



The transistor in the figure has the following parameters;

$$V_{TN} = 0.8\text{ V},\quad K_n = 0.2\text{ mA/V}^2,$$
$$\text{and}\ \ \lambda = 0$$



Find the following;

(a) g_m and r_o;

(b) A_v;

(c) R_i and R_o.

(a)

$$V_{GS} = V_G = V_{DD}\left(\frac{R_2}{R_1 + R_2}\right)$$

$$= 5\left(\frac{320}{520 + 320}\right) = \mathbf{1.905\,V}$$

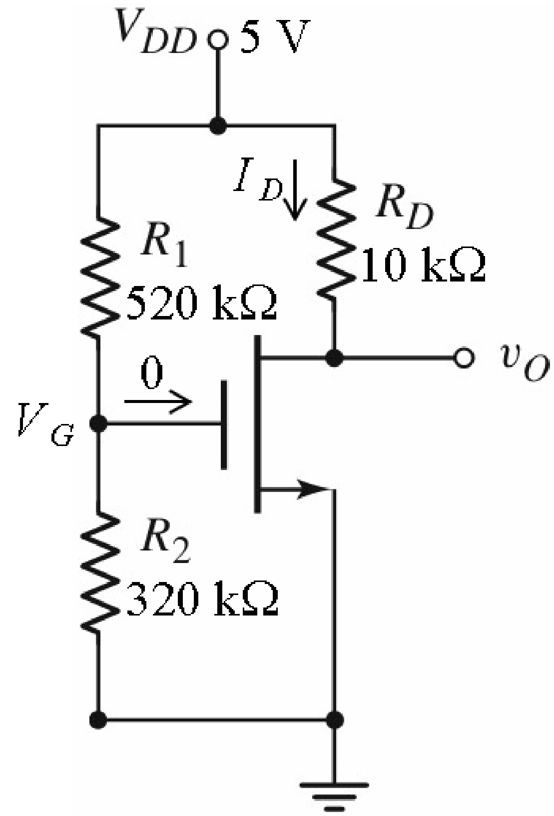
$$g_m = 2K_n\left(V_{GS} - V_{TN}\right)$$

$$= 2 \times 0.2 \times 10^{-3}\left(1.905 - 0.8\right)$$

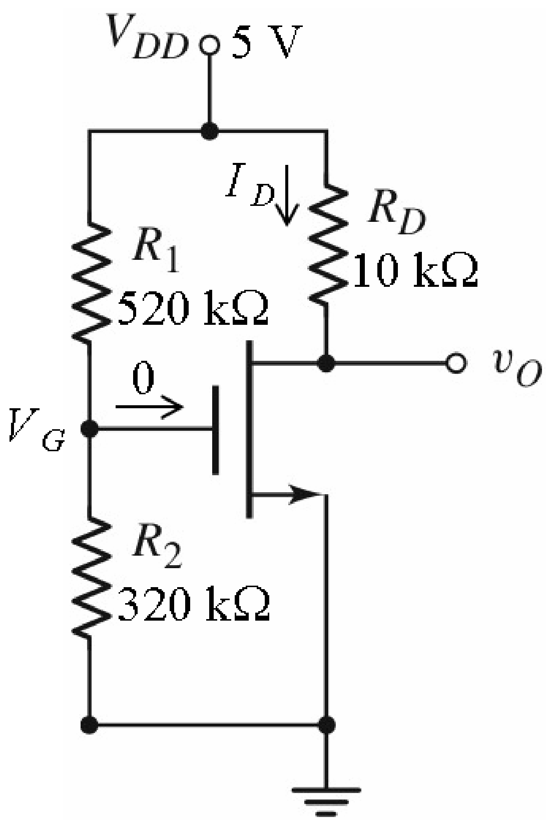
$$= \mathbf{0.442\,mA/V}$$

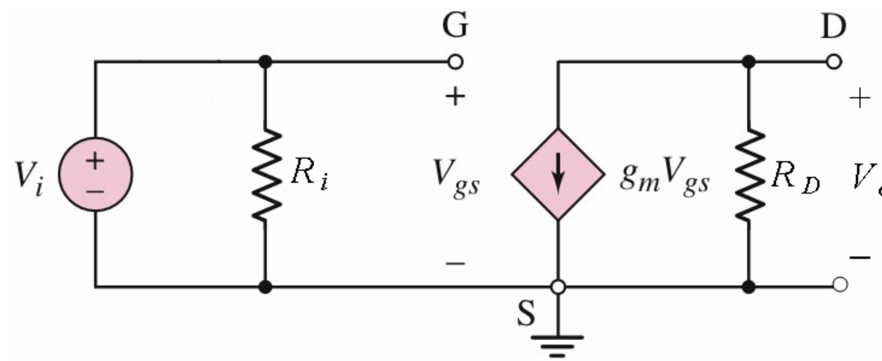
$$r_o = \frac{1}{\lambda I_D} = \infty$$

The circuit under dc condition



(b)





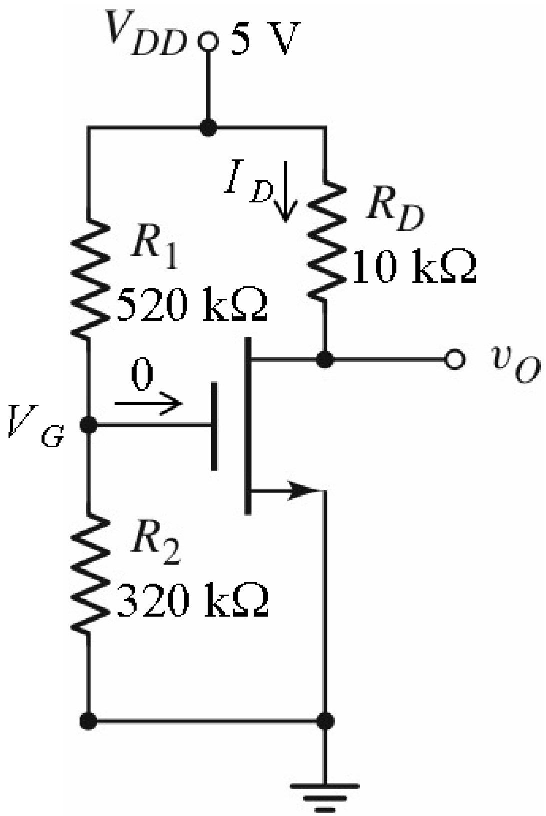
$$V_i = V_{gs}$$

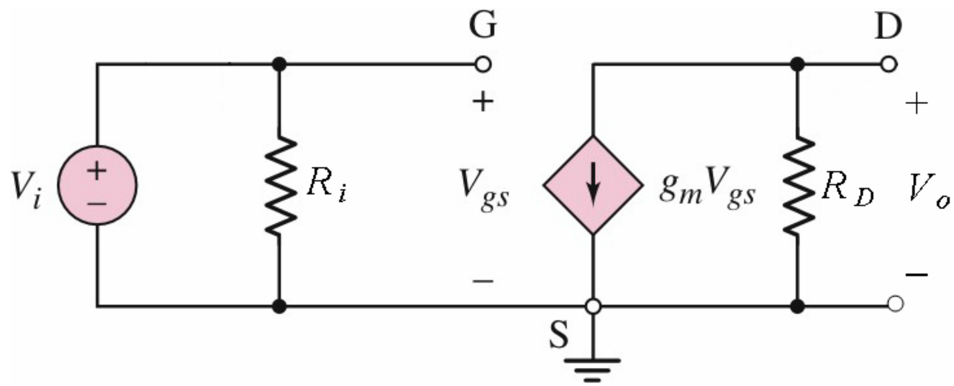
$$V_o = -g_m V_{gs}\, R_D$$

$$A_v = \frac{V_o}{V_i} = -g_m R_D$$

$$= -0.442 \times 10 = -4.42\ \mathrm{V/V}$$

(c)

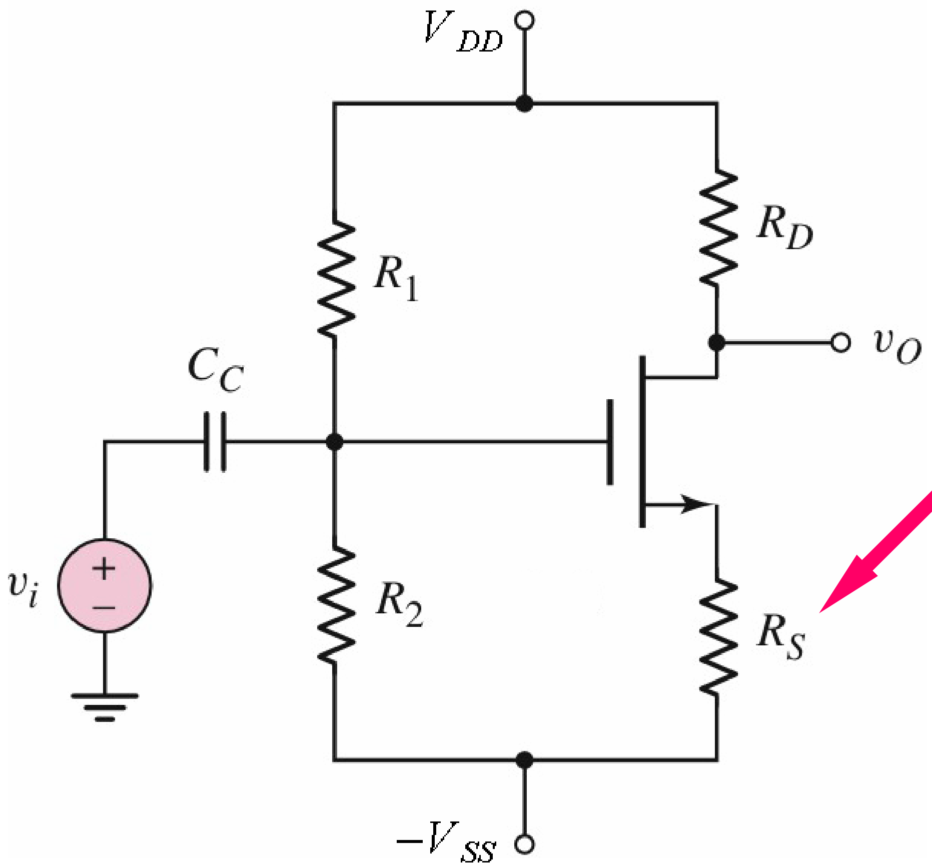




$$R_o = R_D = \mathbf{10\,k\Omega}$$

$$R_i = R_1 \| R_2$$
$$= 520 \| 320$$
$$= \mathbf{198\,k\Omega}$$

Common-source with R_S



The source resistor R_S tends to stabilize the Q-point against variations in transistor parameters.

However, the inclusion of this resistor reduces the amplifier gain.

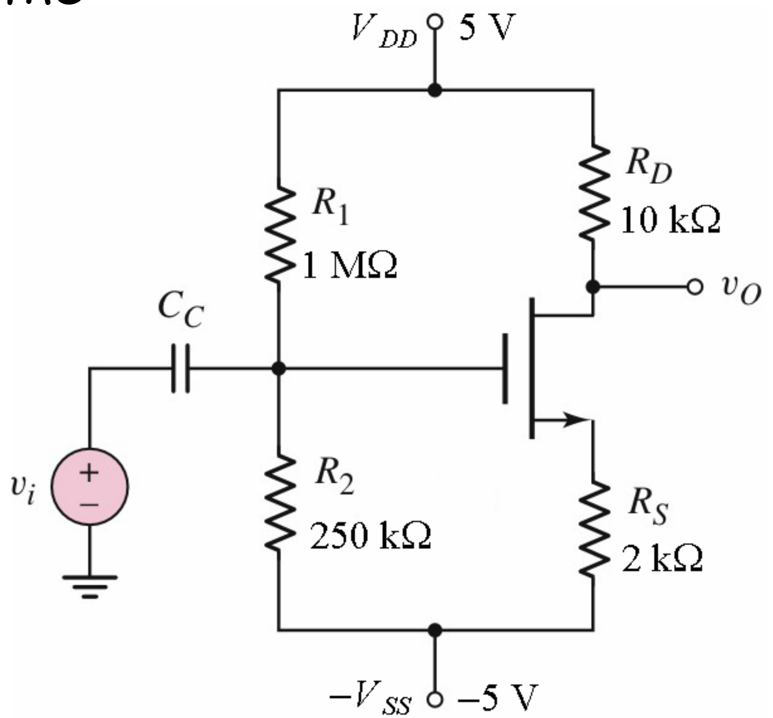
The transistor in the figure has the following parameters;

$$V_{TN} = 0.6\text{ V},\ \ K_n = 0.5\,\text{mA/V}^2,$$

$$\text{and}\ \ \lambda = 0$$

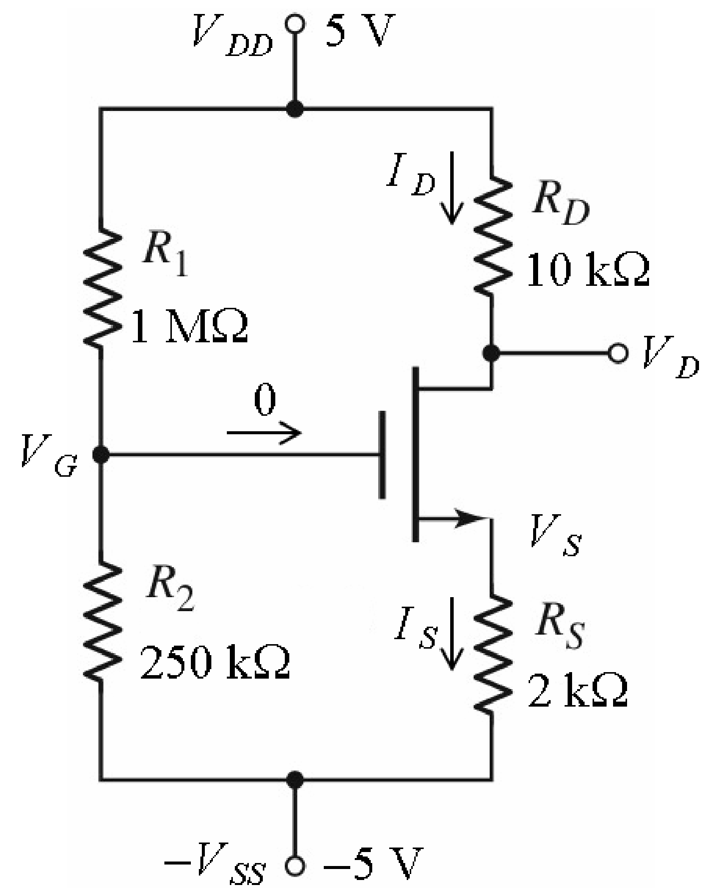
(a) Determine the Q-point of the amplifier.

(b) Find the small-signal voltage gain



Common-source with R_S — Example 2 - *Solution*

The circuit under dc condition



The gate voltage:

$$V_G = \underbrace{10\left(\frac{0.25}{1+0.25}\right)}_{\text{Voltage drop on } R_2} - 5 = -3\text{ V}$$

$$V_S = -5 + I_D R_S = -5 + 2\times 10^3 I_D$$

$$V_{GS} = V_G - V_S = 2 - 2\times 10^3 I_D$$

$$\therefore \qquad I_D = (1 - 0.5V_{GS})10^{-3}$$

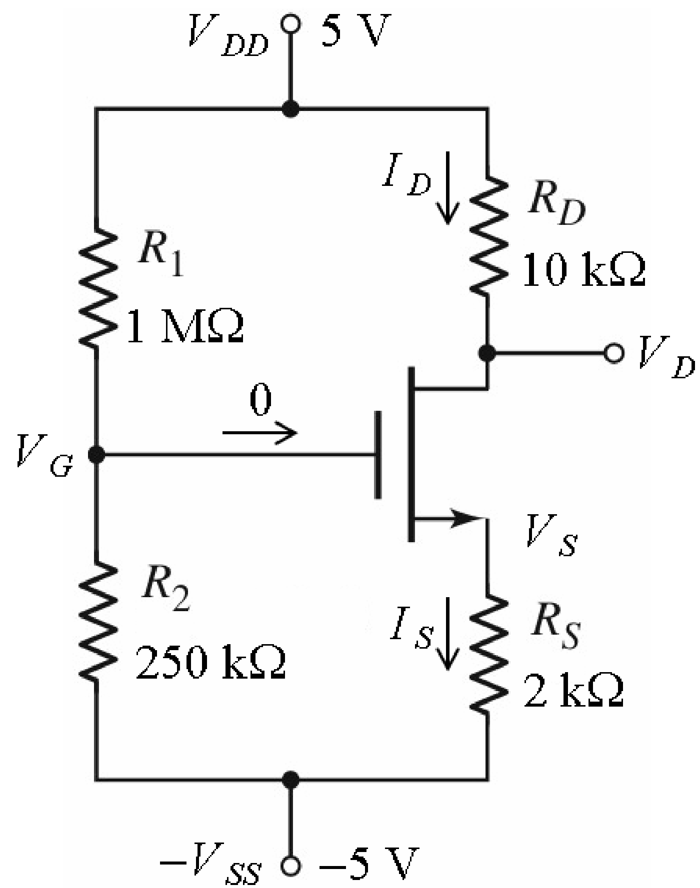
MOSFET Basic Amplifier Configurations

Common-source with R_S — Example 2 - *Solution* (*cont'd*)

(1) $I_D = (1 - 0.5V_{GS})10^{-3}$

(2) $I_D = K_n(V_{GS} - V_{TN})^2$
$= (0.5V_{GS}^2 - 0.6V_{GS} + 0.18)10^{-3}$

The circuit under dc condition



Substituting for I_D and rearranging, we have;

$$(1 - 0.5V_{GS})10^{-3} = (0.5V_{GS}^2 - 0.6V_{GS} + 0.18)10^{-3}$$

or;

$$V_{GS}^2 - 0.2V_{GS} - 1.64 = 0$$

Quadratic Formula Calculator

$x^2 + 4x + 3 = 0$

Calculate it!

Use quadratic formula with a=1, b=4, c=3

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$x = \frac{-(4) \pm \sqrt{(4)^2 - 4(1)(3)}}{2(1)}$$

$$x = \frac{-4 \pm \sqrt{4}}{2}$$

$$\boxed{x = -1 \quad \text{or} \quad x = -3}$$

MOSFET Basic Amplifier Configurations

Common-source with R_S — Example 2 – *Solution* (*cont'd*)

Solving the quadratic equation, gives us;

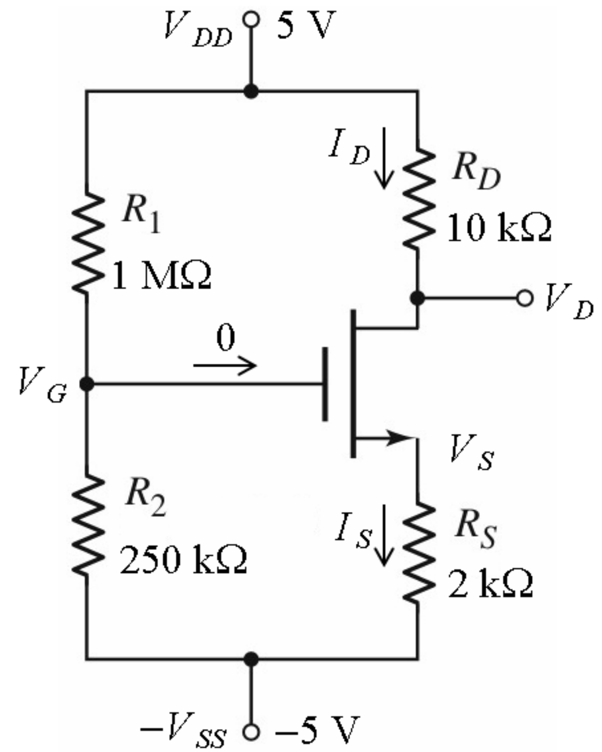
$$V_{GS}^2 - 0.2V_{GS} - 1.64 = 0$$

$$V_{GS} = \frac{0.2 \pm \sqrt{0.2^2 + 4 \times 1.64}}{2}$$

$$= 1.385\ \text{V}$$

V_{GS} = -1.18 (second root)

The circuit under dc condition



Substituting for V_{GS} in;

$$I_D = K_n(V_{GS} - V_{TN})^2$$

we obtain; $I_D = 0.308\ \text{mA}$

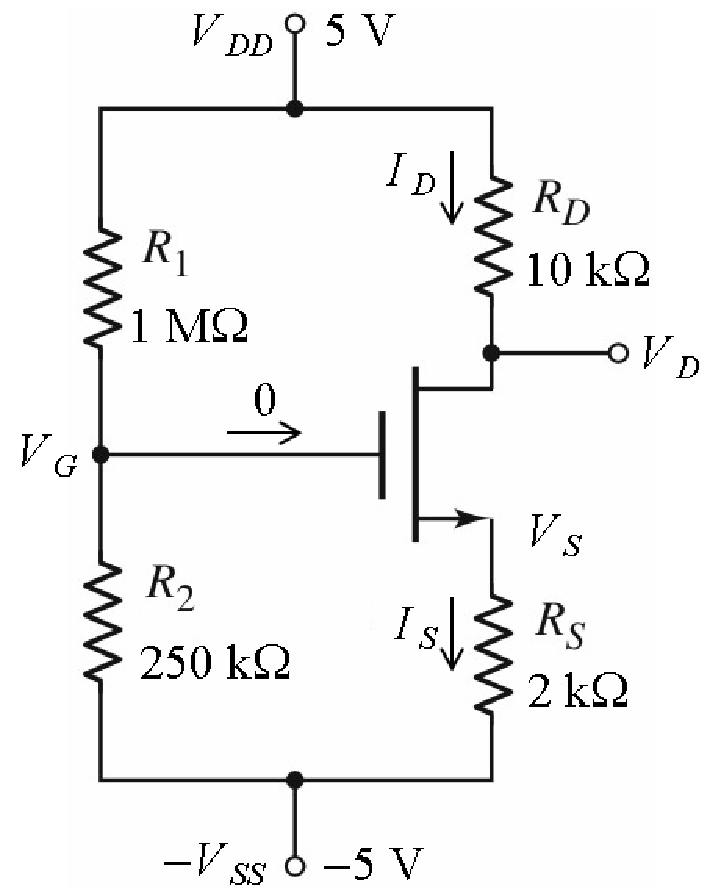
Common-source with R_S — Example 2 – *Solution* (*cont'd*)

$$V_D = 5 - I_D R_D = 5 - 0.308 \times 10$$
$$= 1.92\ \mathrm{V}$$

$$V_S = -5 + I_D R_S = -5 + 0.308 \times 2$$
$$= -4.384\ \mathrm{V}$$

$$V_{DS} = V_D - V_S = 1.92 + 4.384$$
$$= 6.304\ \mathrm{V}$$

The circuit under dc condition



$$V_{TN} = 0.6\ \mathrm{V} \quad V_{GS} = 1.385\ \mathrm{V}$$

$$V_{DS} > V_{GS} - V_{TN}$$

Saturation region

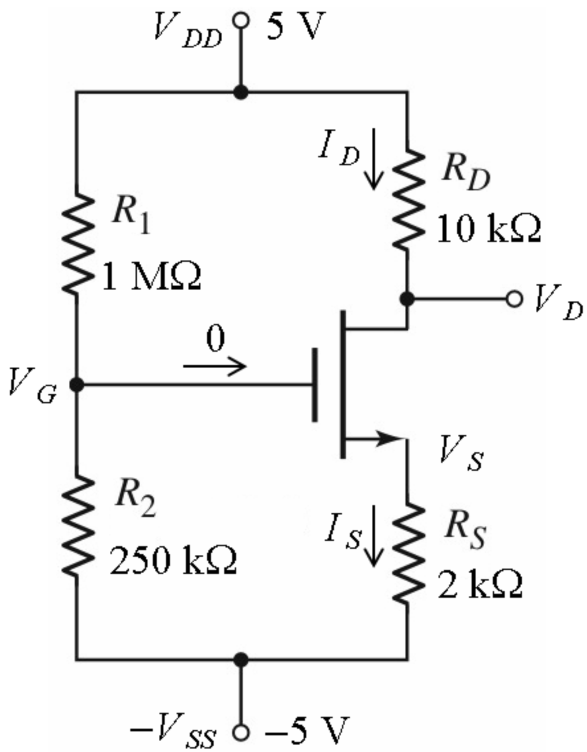
The Q-point:

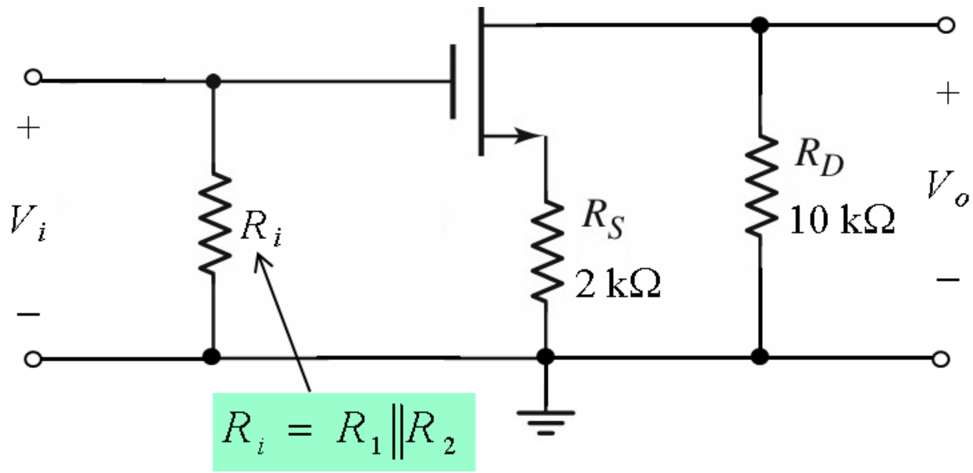
$$\boldsymbol{I_{DQ} = 0.308\,\mathrm{mA}\,;\quad V_{DSQ} = 6.304\,\mathrm{V}}$$

The transconductance is;

$$\begin{aligned} g_m &= 2K_n\left(V_{GSQ} - V_{TN}\right) \\ &= 2\times 0.5\times 10^{-3}\left(1.385 - 0.6\right) \\ &= 0.785\,\mathrm{mA/V} \end{aligned}$$

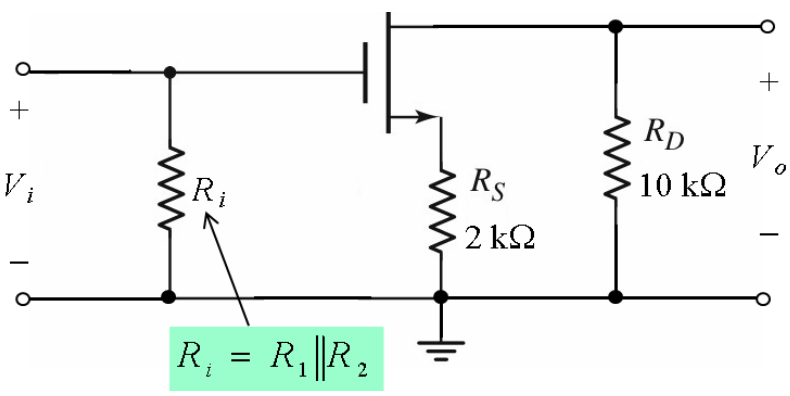
The ac equivalent circuit may be drawn as follows;

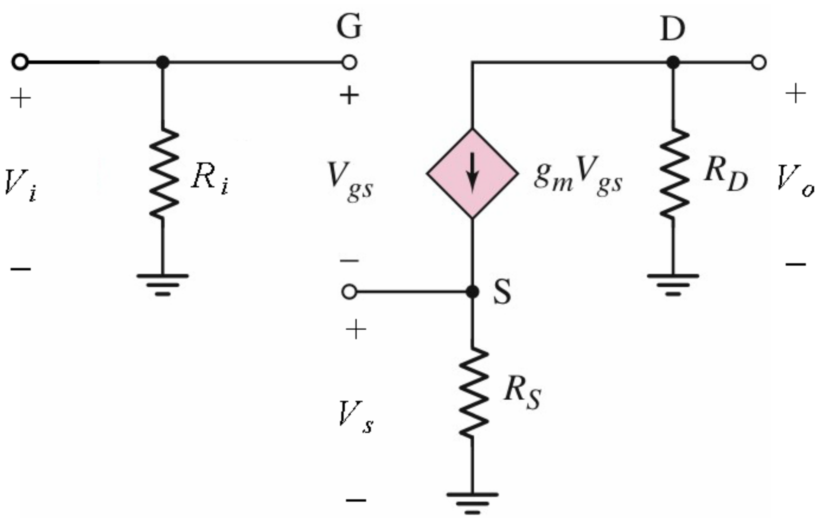




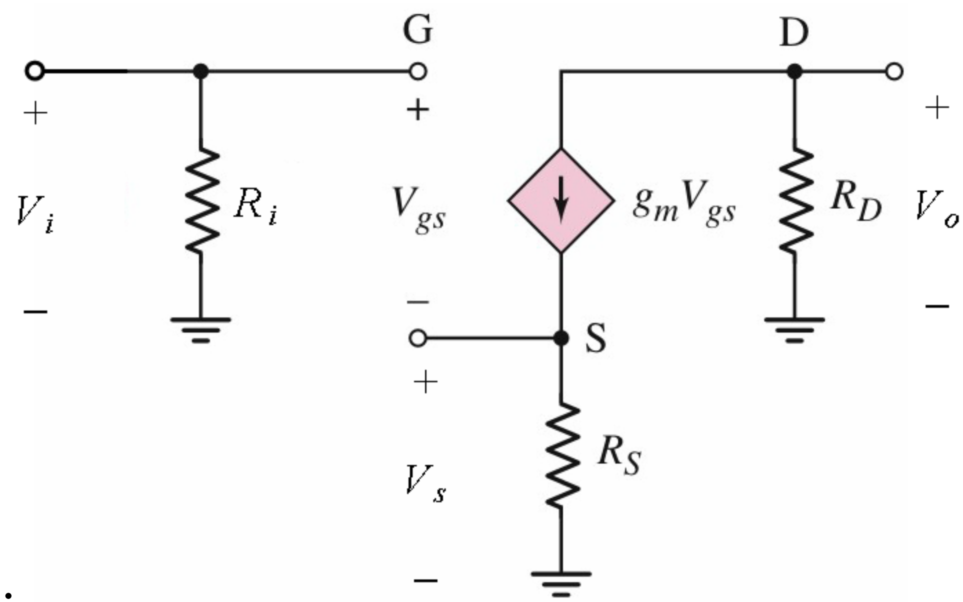
Common-source with R_S Example 2 – *Solution (cont'd)*

The small-signal equivalent circuit may be drawn as follows;





Common-source with R_S | Example 2 - *Solution (cont'd)*



$$V_i = V_{gs} + V_s$$
$$= V_{gs} + g_m V_{gs} R_s$$

$$V_o = -g_m V_{gs} R_D$$

The small-signal voltage gain is;

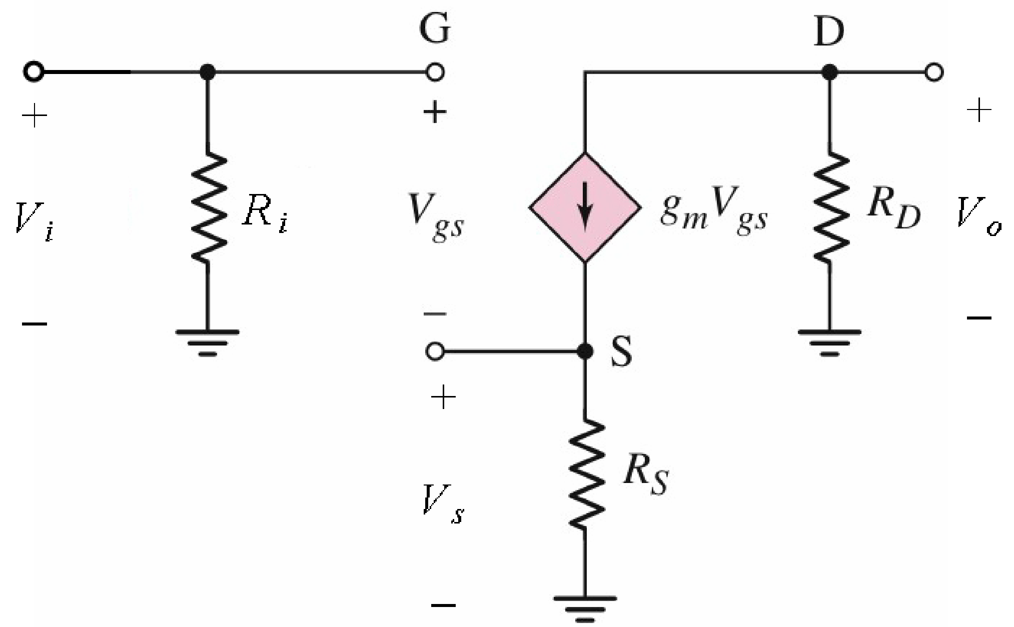
$$A_v = \frac{V_o}{V_i} = \frac{-g_m V_{gs} R_D}{V_{gs} + g_m V_{gs} R_S} = -\frac{g_m R_D}{1 + g_m R_S}$$

Common-source with R_S — Example 2 – *Solution* (*cont'd*)

Substituting values;

$$A_v = -\frac{0.785 \times 10}{1 + 0.785 \times 2}$$

$$= \mathbf{-3.05\ V/V}$$



MOSFET Basic Amplifier Configurations

Common-source with C_S Example 3

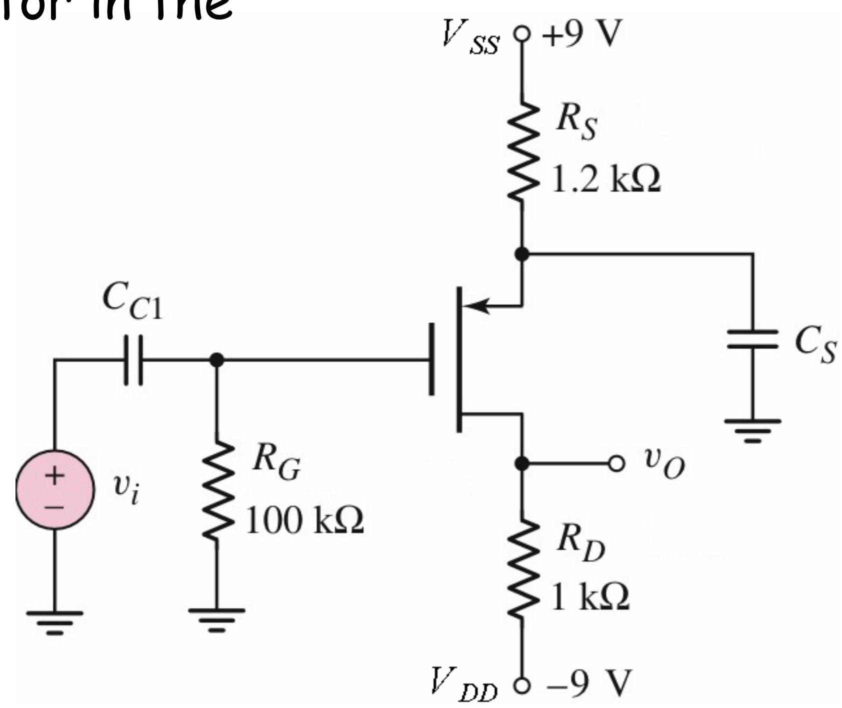
The parameters for the transistor in the figure are;

$$K_p = 2\,\mathrm{mA/V^2},\ V_{TP} = -2\,\mathrm{V, and}$$

$$\lambda = 0.01\,\mathrm{V^{-1}}$$

(a) Determine the Q-point

(c) Calculate the small-signal voltage gain A_v.

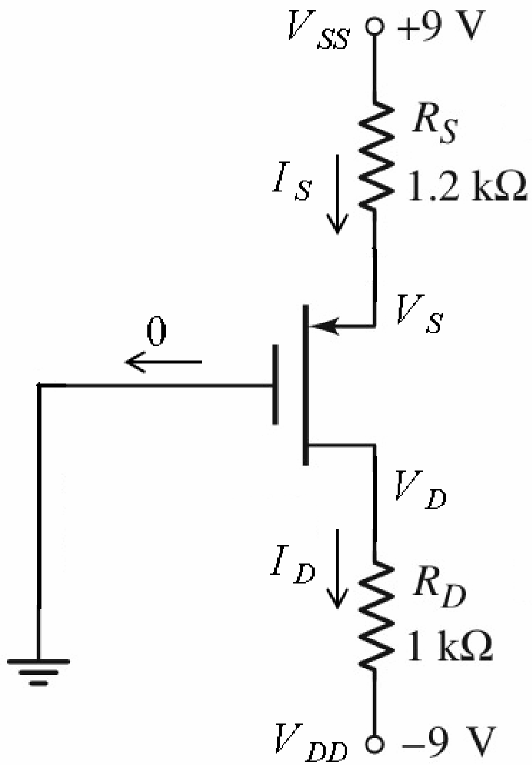


Since I_G is assumed to be zero,
G is at the ground potential
and $I_S = I_D$.

$$I_D = K_p(V_{SG} + V_{TP})^2$$
$$= 2 \times 10^{-3}(V_{SG} - 2)^2$$
$$= 2 \times 10^{-3}(V_{SG}^2 - 4V_{SG} + 4)$$

$$V_{SG} = 9 - I_D R_S$$
$$= 9 - 1.2 \times 10^3 I_D$$
$$I_D = (7.5 - 0.833 V_{SG})10^{-3}$$

The circuit under dc condition



MOSFET Basic Amplifier Configurations

Common-source with C_S — Example 3 – *Solution* (*cont'd*)

Substituting for I_D;

$$(7.5 - 0.833V_{SG})10^{-3} = 2\times10^{-3}\left(V_{SG}^2 - 4V_{SG} + 4\right)$$

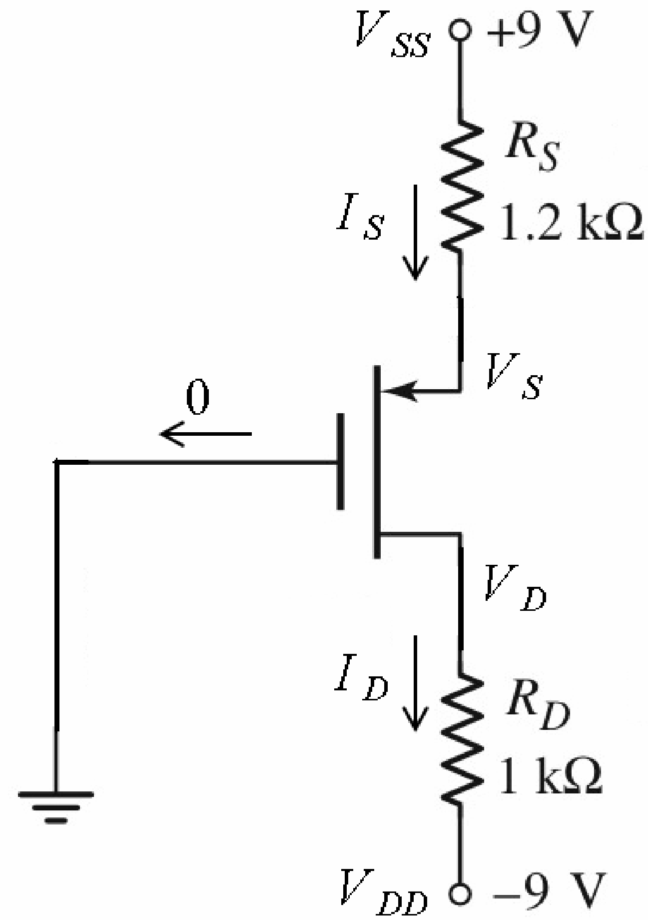
or;

$$V_{SG}^2 - 3.583V_{SG} + 0.25 = 0$$

Solving the equation for V_{SG}, we obtain;

$$V_{SG} = 3.512\ \text{V}$$

The circuit under dc condition



Common-source with C_S — Example 3 – *Solution (cont'd)*

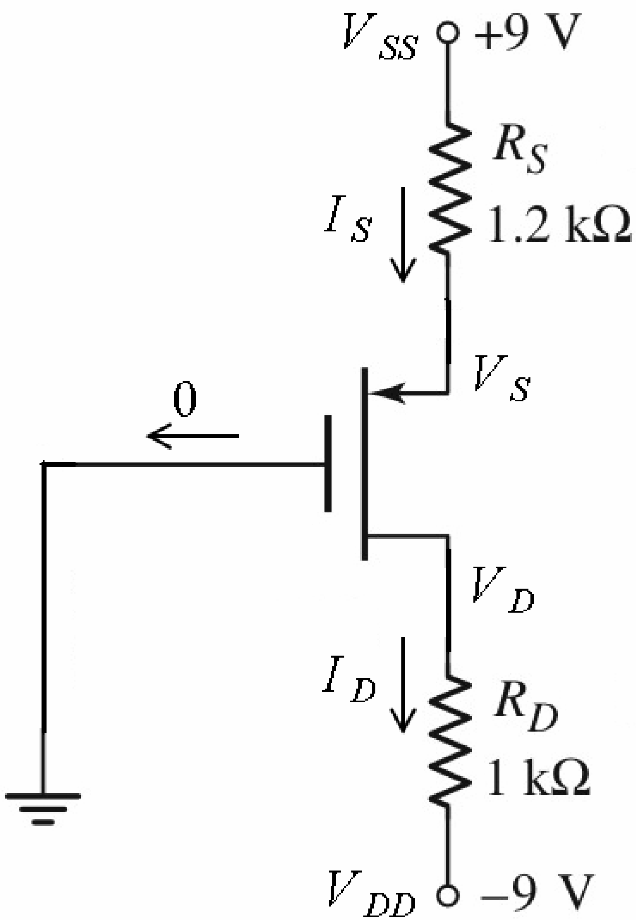
$$V_{SG} = 3.512 \text{ V}$$

$$I_D = I_S = \frac{9-3.512}{1.2\times10^3} = 4.57\,\text{mA}$$

$$V_D = 4.57\times10^{-3}\times1\times10^3 - 9$$
$$= -4.427 \text{ V}$$

$$V_{SD} = V_S - V_D$$
$$= 3.512 + 4.427$$
$$= 7.94\,\text{V}$$

<u>The circuit under dc condition</u>



MOSFET — Basic Amplifier Configurations

Common-source with C_S — Example 3 – *Solution (cont'd)*

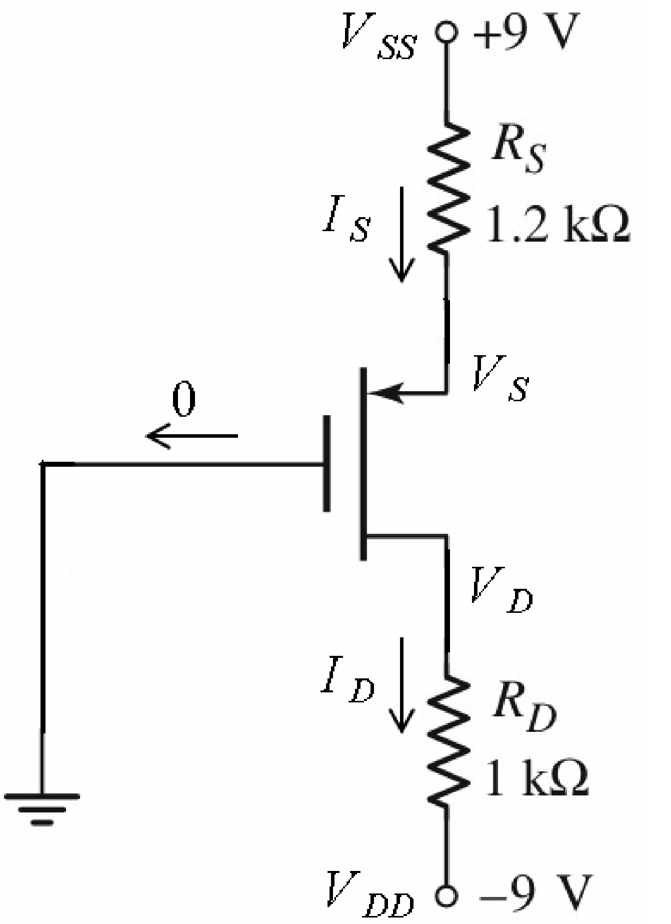
(a)

The Q-point is;

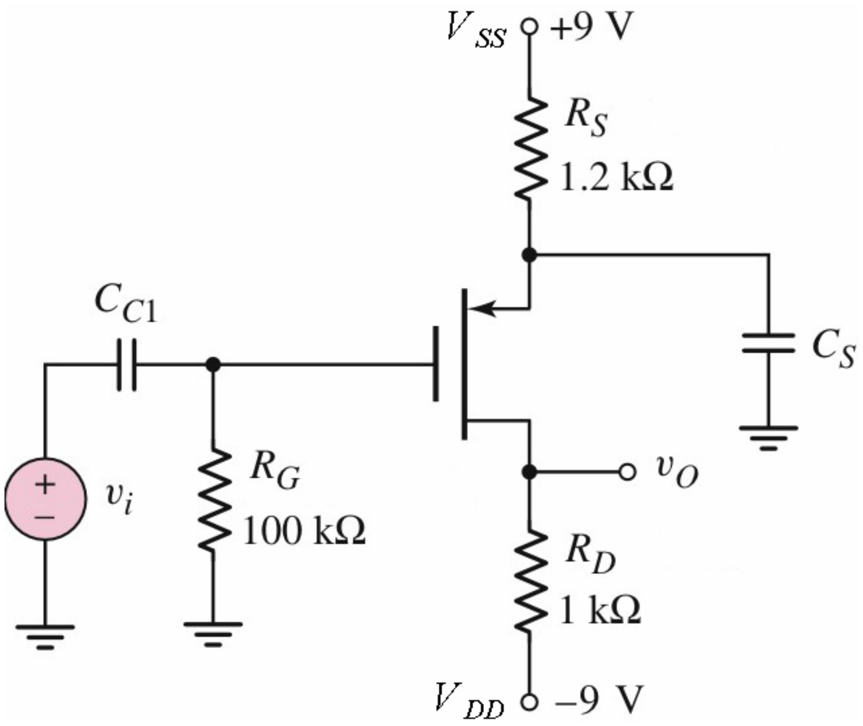
$$I_{DQ} = 4.57 \text{ mA}, \ V_{SDQ} = 7.94 \text{ V}$$

$$g_m = 2K_p\left(V_{SG} + V_{TP}\right)$$
$$= 2\left(3.512 - 2\right)$$
$$= 6.048 \,\text{mA/V}$$

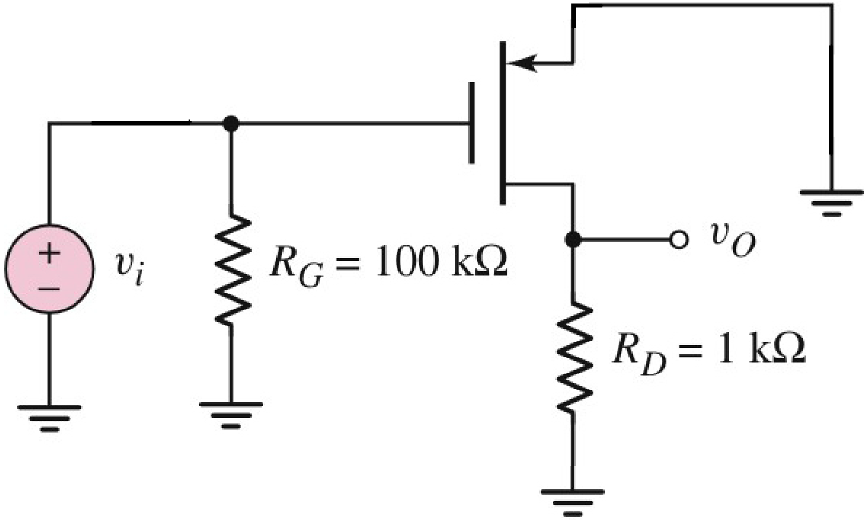
The circuit under dc condition



Common-source with C_S — Example 3 – *Solution (cont'd)*

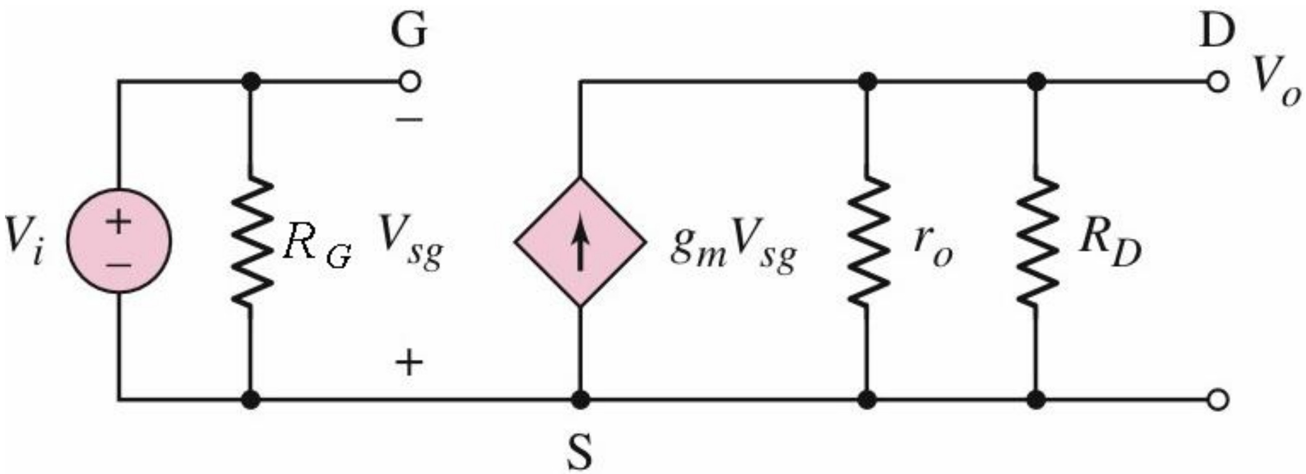


The ac equivalent circuit



Common-source with C_S — Example 3 – *Solution (cont'd)*

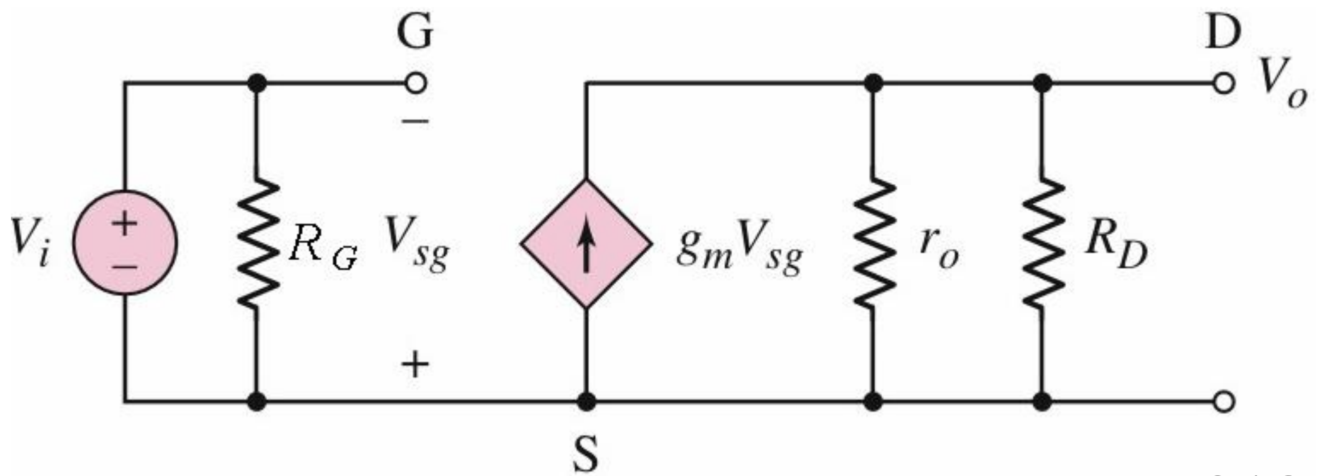
The small-signal equivalent circuit may drawn as follows;



Note that r_o is included in the equivalent circuit because the value of λ is given.

$$r_o = \frac{1}{\lambda I_{DQ}} = \frac{1}{0.01 \times 4.57 \times 10^{-3}} = 218.8\,\mathrm{k\Omega}$$

Common-source with C_S — Example 3 – *Solution* (*cont'd*)



(b)

$$r_o = 218.8\ \mathrm{k\Omega}$$

$$R_D = 1\mathrm{k\Omega}$$

$$r_o // R_D \cong R_D$$

The small-signal voltage gain is;

$$A_v \equiv \frac{V_o}{V_i} \cong -g_m R_D = -6.05 \times 10^{-3} \times 1 \times 10^{3}$$

$$A_v = -6.05\ \mathrm{V/V}$$

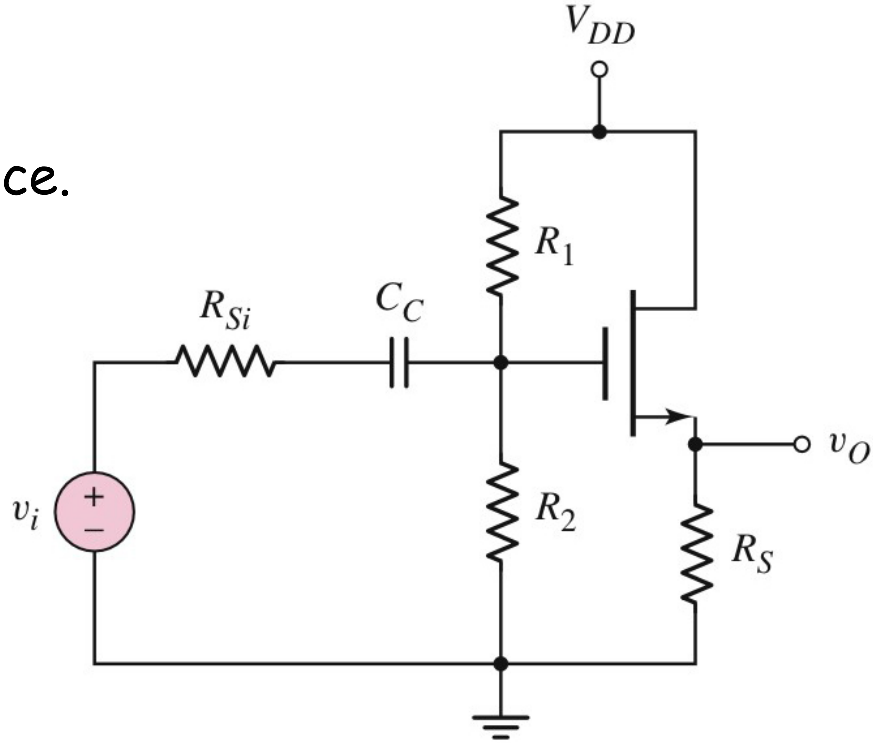
MOSFET Basic Amplifier Configurations

Common-drain

Also known as **source-follower**

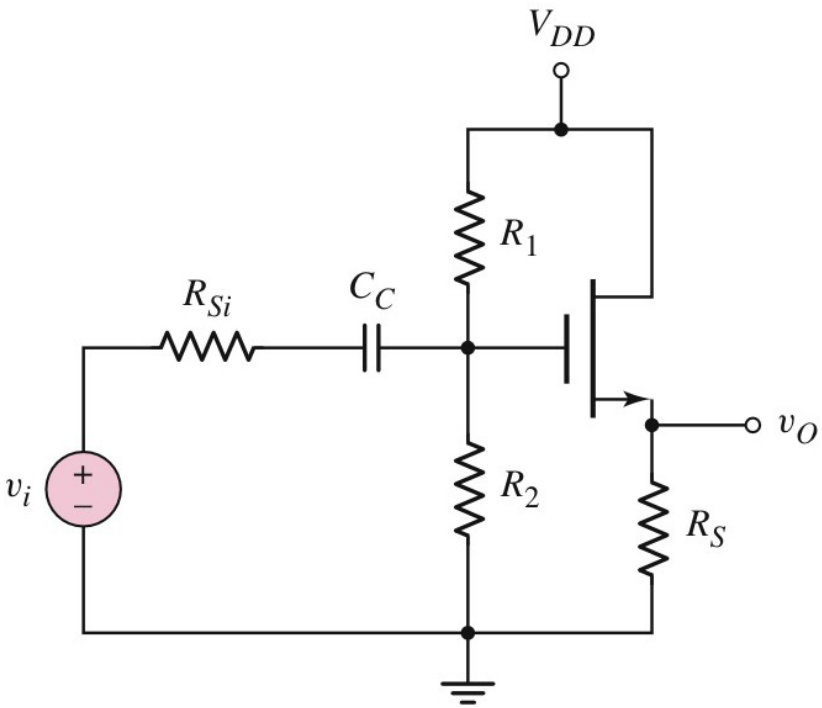
The output is taken from the source.

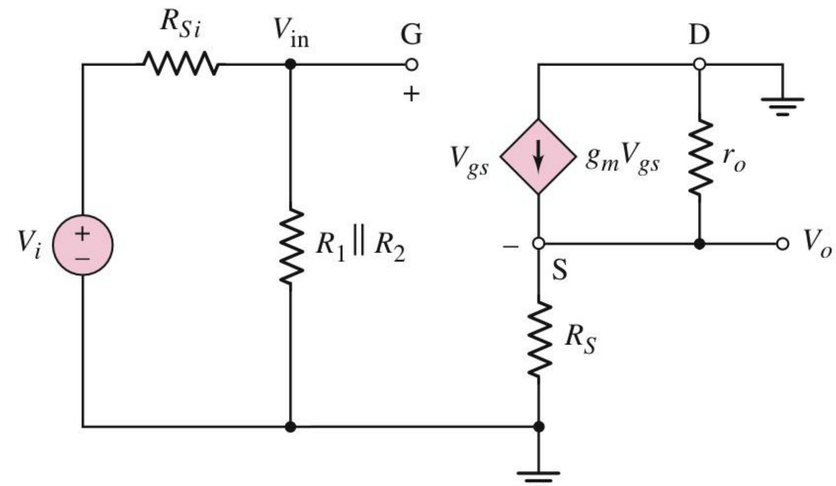
The drain is connected to V_{DD} which is the signal ground and becomes the common terminal for the input and output, hence the name common-drain.



Common-drain

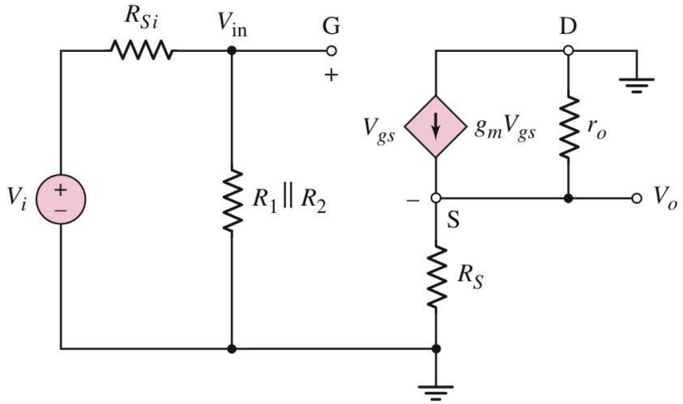
The small-signal analysis may be performed using the following small-signal equivalent circuit.

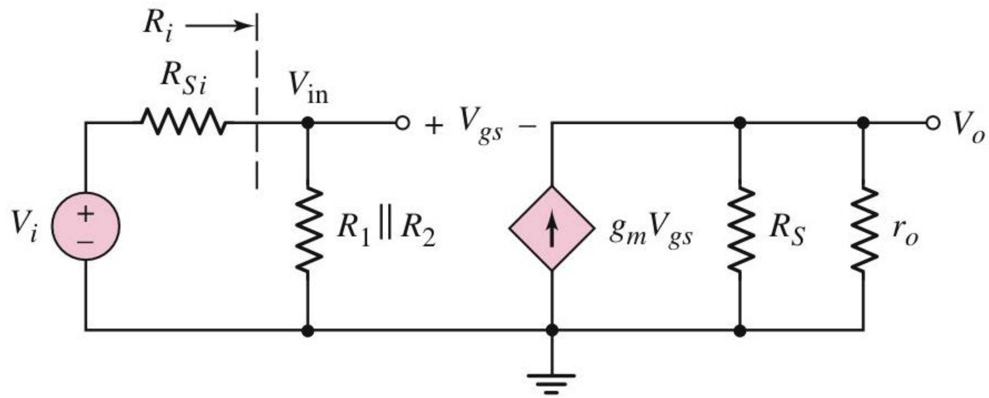




Common-drain – Voltage gain A_v

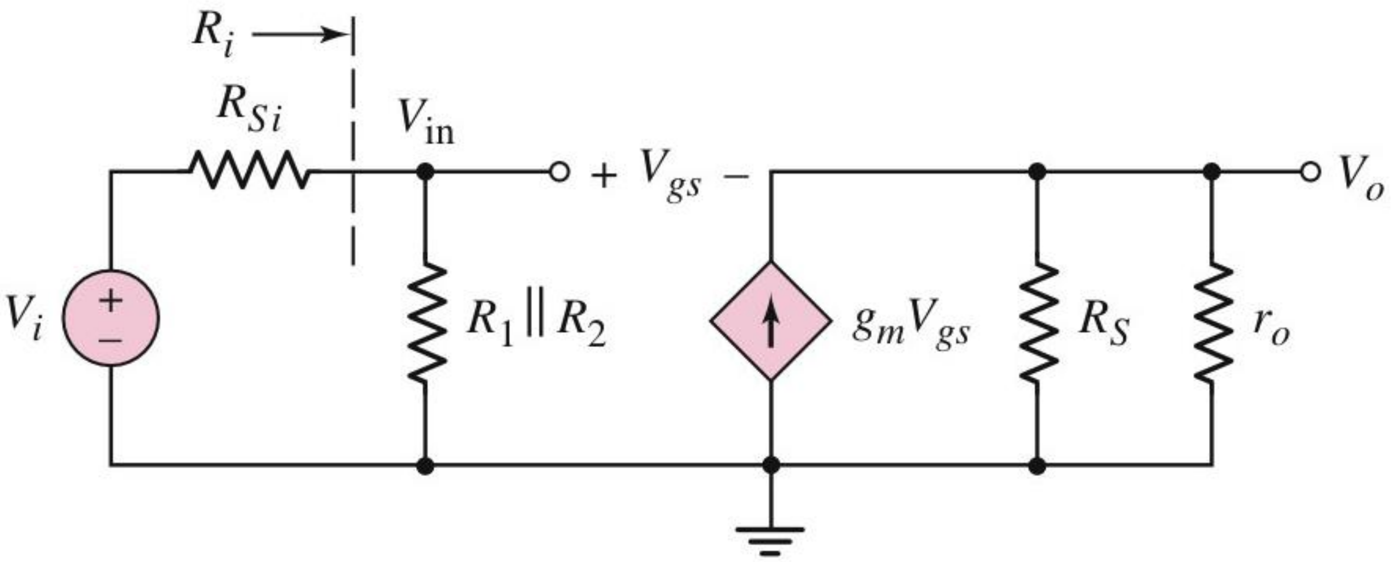
The small-signal equivalent circuit may be redrawn as follows;





$$V_o = g_m V_{gs}\left(R_S \| r_o\right) \quad \Rightarrow \quad \frac{V_o}{V_{gs}} = g_m\left(R_S \| r_o\right)$$

Common-drain – Voltage gain A_v

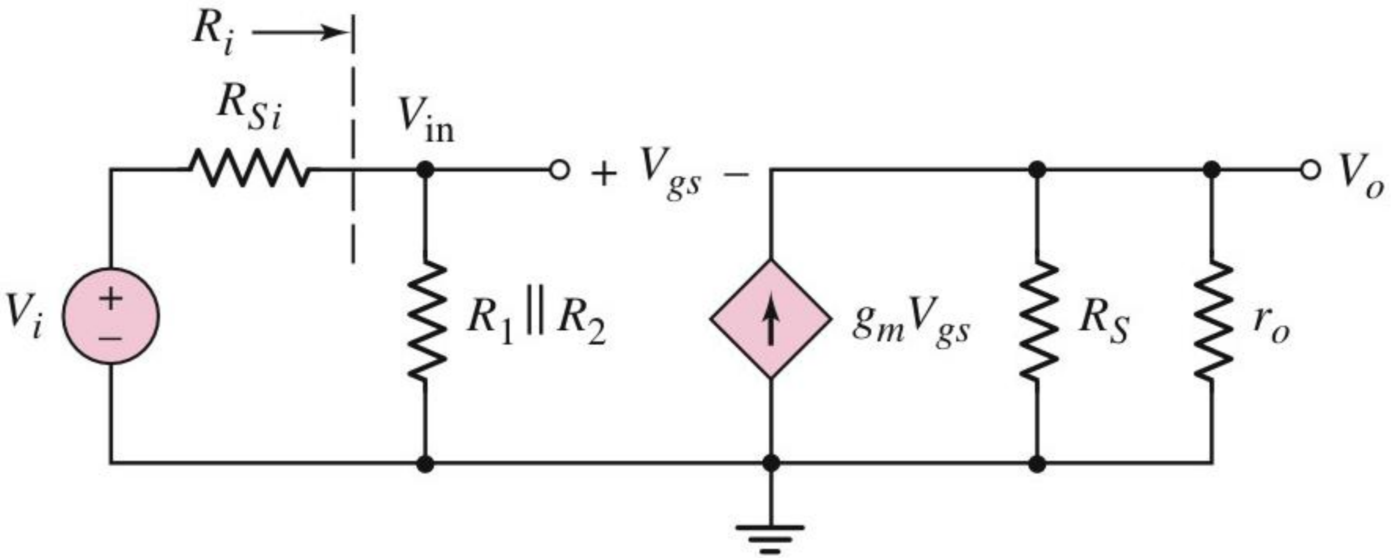


$$V_{in} = V_{gs} + V_o = V_{gs} + g_m V_{gs}\left(R_S \| r_o\right) \quad \Rightarrow \quad V_{gs} = \frac{V_{in}}{1 + g_m\left(R_S \| r_o\right)}$$

$$V_o = g_m V_{gs}\left(R_S \| r_o\right)$$

MOSFET Basic Amplifier Configurations

Common-drain – Voltage gain A_v



At the input side;

$$V_{in} = V_i \left(\frac{R_i}{R_{Si} + R_i} \right) \quad \text{where} \quad R_i = R_1 \| R_2$$

MOSFET Basic Amplifier Configurations

Common-drain – Voltage gain A_v

$$V_{gs} = \frac{V_{in}}{1 + g_m\left(R_S \| r_o\right)} \quad \text{and} \quad V_{in} = V_i\left(\frac{R_i}{R_{Si} + R_i}\right)$$

Combining the two equations, gives us;

$$V_{gs} = \frac{R_i}{\left[1 + g_m\left(R_S \| r_o\right)\right]\left(R_{Si} + R_i\right)} V_i$$

Hence;

$$\frac{V_{gs}}{V_i} = \frac{R_i}{\left[1 + g_m\left(R_S \| r_o\right)\right]\left(R_{Si} + R_i\right)}$$

Common-drain – Voltage gain A_v

$$\frac{V_o}{V_{gs}} = g_m\left(R_S \| r_o\right) \qquad \frac{V_{gs}}{V_i} = \frac{R_i}{\left[1 + g_m\left(R_S \| r_o\right)\right]\left(R_{Si} + R_i\right)}$$

The small-signal voltage gain is;

$$A_v = \frac{V_o}{V_i} = \frac{V_o}{V_{gs}} \times \frac{V_{gs}}{V_i}$$

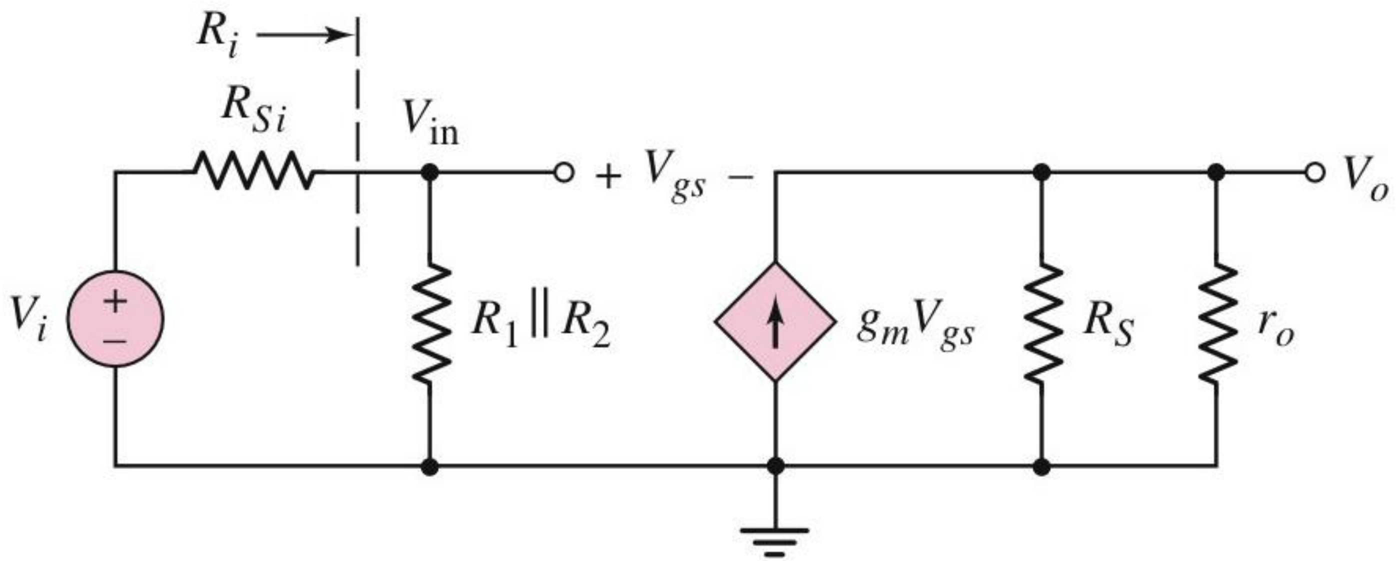
$$= \frac{g_m\left(R_S \| r_o\right)}{1 + g_m\left(R_S \| r_o\right)}\left(\frac{R_i}{R_{Si} + R_i}\right)$$

Common-drain – Voltage gain A_v

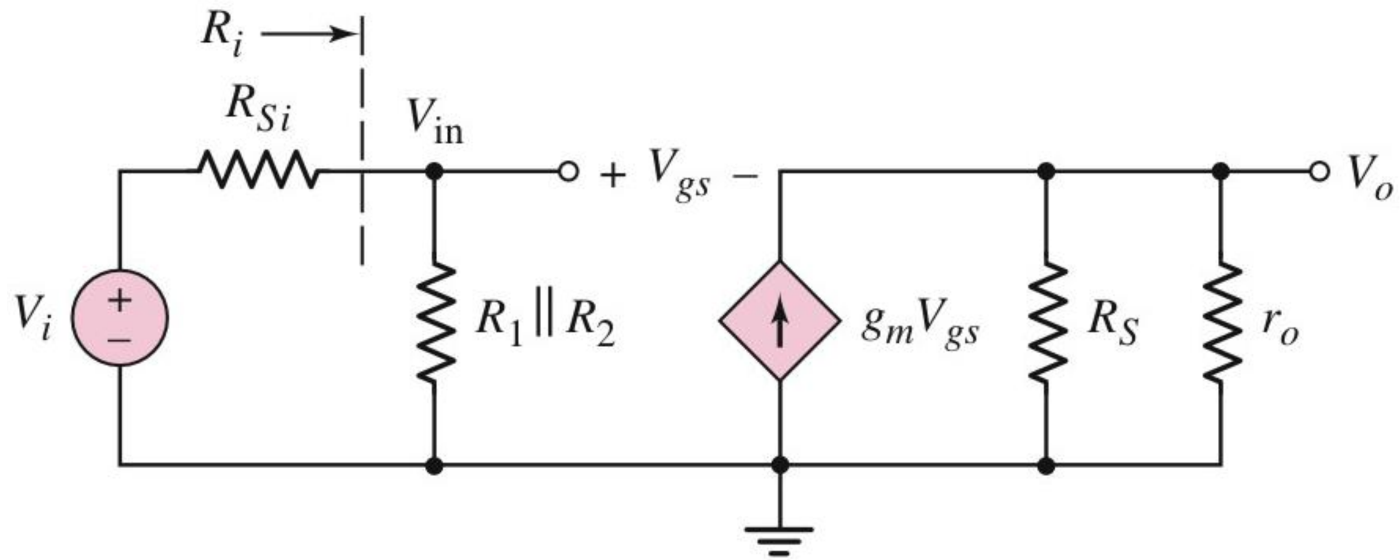
The small-signal voltage gain also can be written as;

$$A_v = \frac{(R_S \| r_o)}{1/g_m + (R_S \| r_o)} \left(\frac{R_i}{R_{Si} + R_i} \right)$$

Note that there is no phase shift



Common-drain – Input resistance R_i

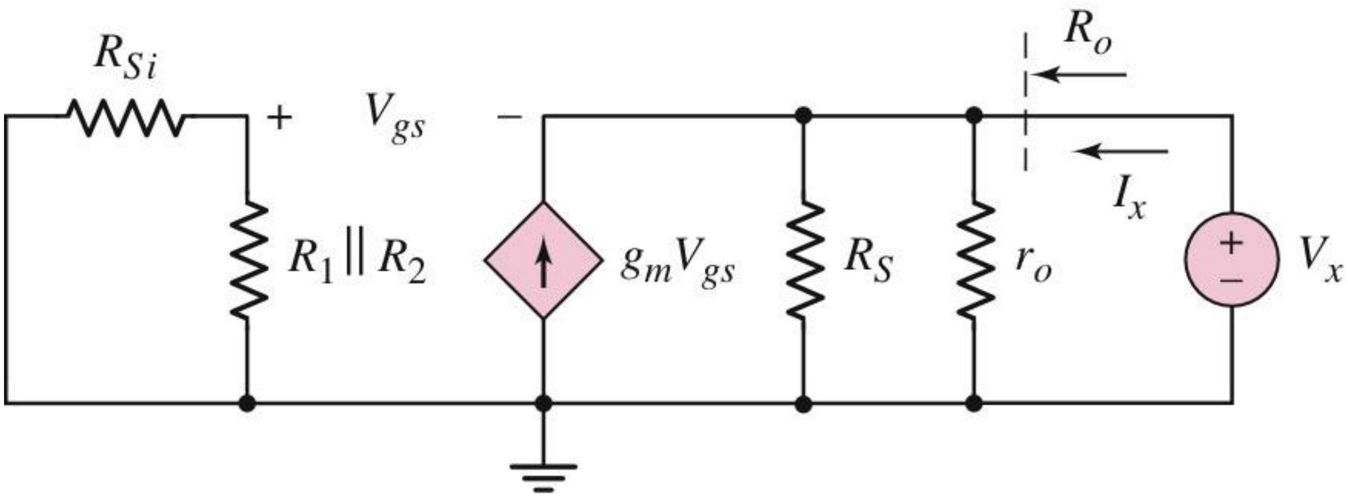


The input resistance of the common-drain amplifier is;

$$R_i = (R_1 \| R_2)$$

Common-drain – Output resistance R_o

To calculate the output resistance, set all the independent voltage source to zero and apply a test voltage V_x at the output terminal as shown below;

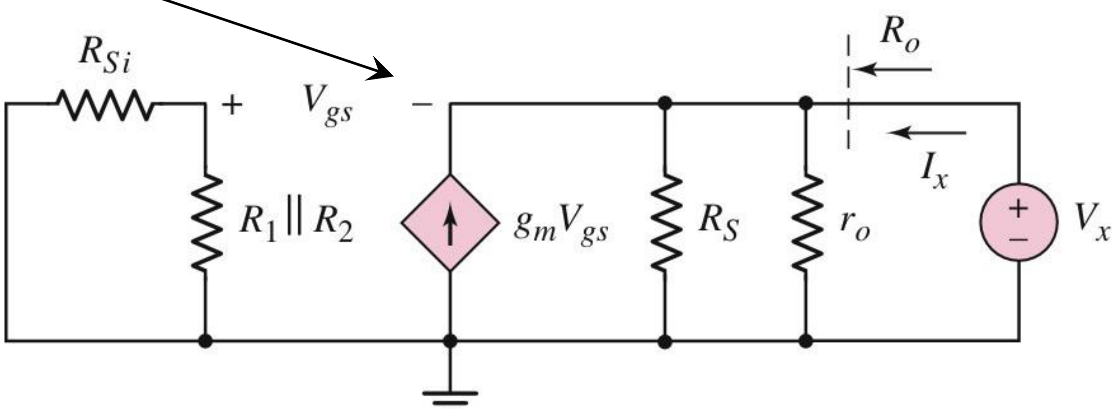


$$R_o = \frac{V_x}{I_x}$$

Common-drain – Output resistance R_o

Applying KCL at this node gives the equation

$$I_x + g_m V_{gs} = \frac{V_x}{R_S} + \frac{V_x}{r_o}$$

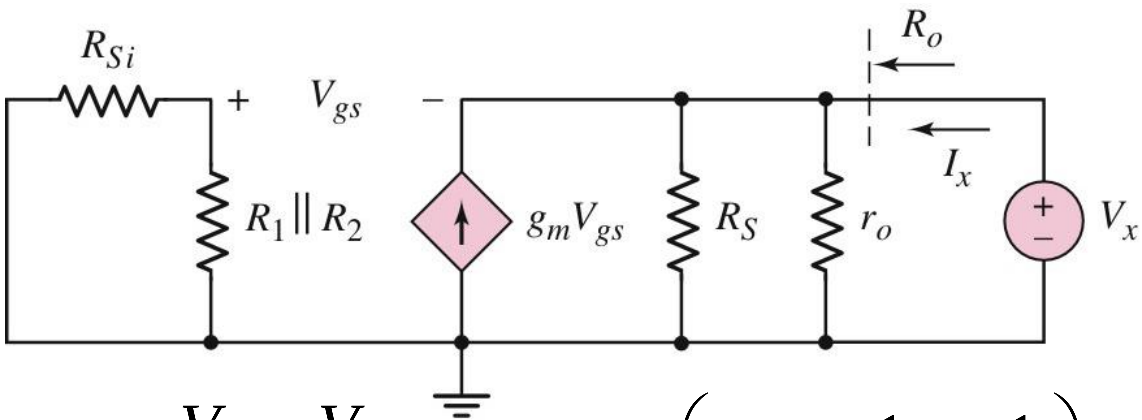


Since there is no current in the input side, we have;

$$V_{gs} = -V_x$$

Substituting for V_{gs}, we have; $$I_x - g_m V_x = \frac{V_x}{R_S} + \frac{V_x}{r_o}$$

Common-drain – Output resistance R_o



Or; $$I_x = g_m V_x + \frac{V_x}{R_S} + \frac{V_x}{r_o} \qquad I_x = \left(g_m + \frac{1}{R_S} + \frac{1}{r_o} \right) V_x$$

$$\frac{I_x}{V_x} = \frac{1}{R_o} = \left(g_m + \frac{1}{R_S} + \frac{1}{r_o} \right)$$

The output resistance is: $R_o = \left(1/g_m \| R_S \| r_o \right)$

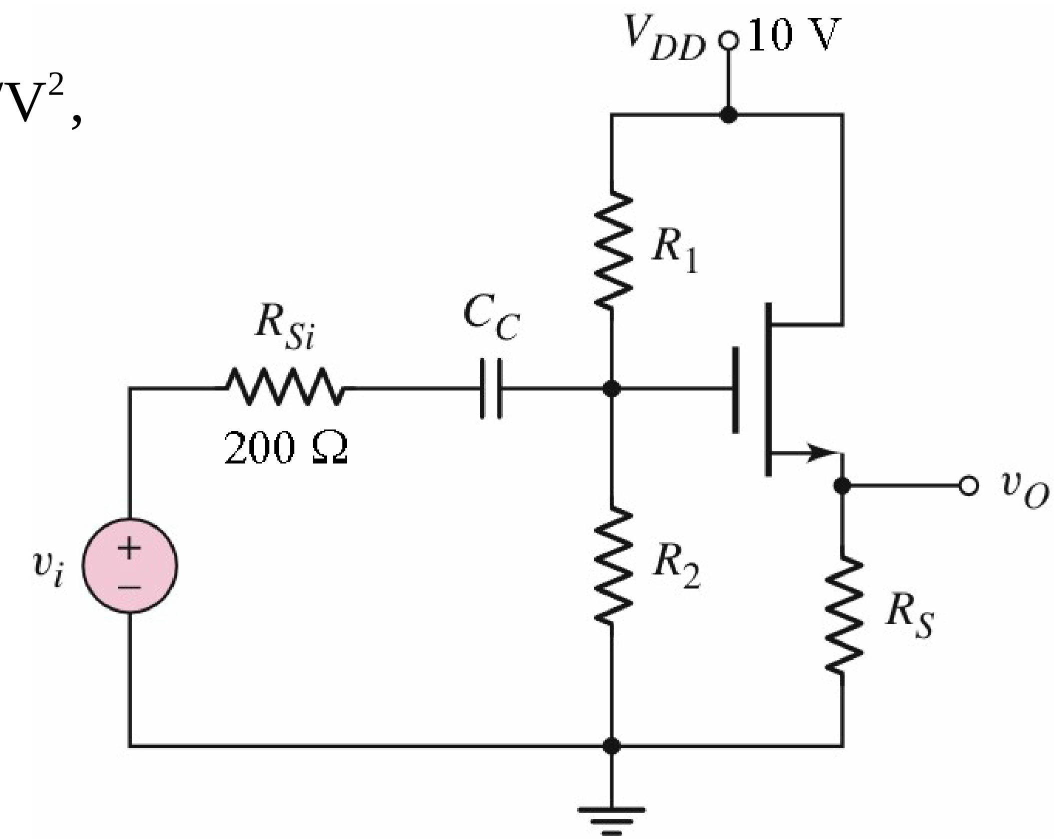
MOSFET Basic Amplifier Configurations

Common-drain Example 4

The transistor parameters in the figure are as follows;

$$V_{TN} = +0.8\,\text{V},\ \ K_n = 1\,\text{mA/V}^2,$$

$$\text{and}\ \lambda = 0.015\,\text{V}^{-1}$$



Design the circuit such that;

$$R_1 + R_2 = 400\ \text{k}\Omega,$$

$$I_{DQ} = 1.5\,\text{mA}$$

$$\text{and}\ \ V_{DSQ} = 5\,\text{V}$$

Determine the small-signal voltage gain

MOSFET Basic Amplifier Configurations

Common-drain | Example 4 – *Solution*

$R_1 + R_2 = 400\ \text{k}\Omega$, $I_{DQ} = 1.5\ \text{mA}$ and $V_{DSQ} = 5\ \text{V}$

$$V_S = V_{DD} - V_{DS} = 10 - 5 = 5\ \text{V}$$

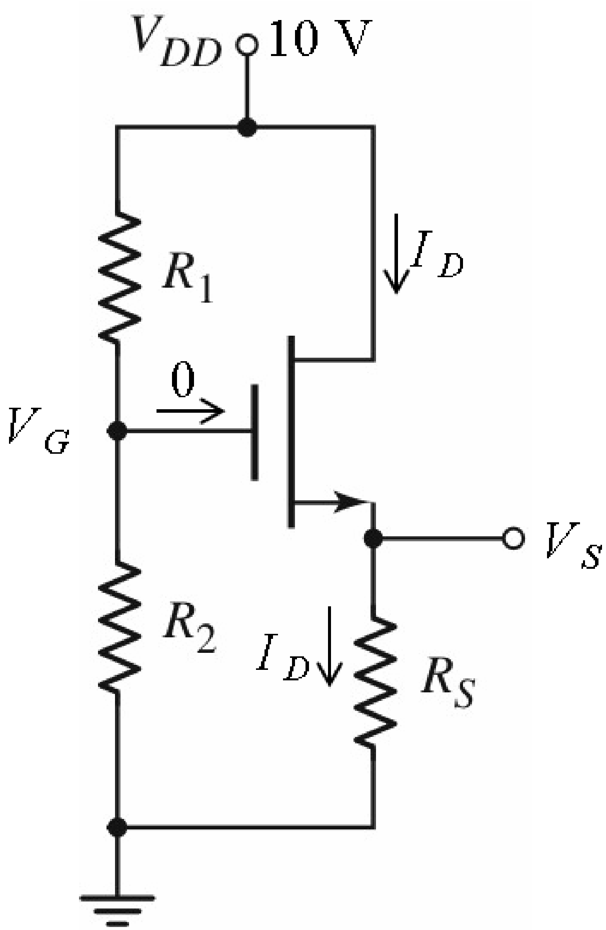
$$R_S = \frac{V_S}{I_D} = \frac{5}{1.5\times10^{-3}} = 3.33\ \text{k}\Omega$$

$$V_G = V_{GS} + V_S = V_{GS} + 5$$

$$V_{GS} + 5 = 10\left(\frac{R_2}{R_1 + R_2}\right) = \frac{R_2}{40\times10^3}$$

$$V_{GS} = \frac{R_2}{40\times10^3} - 5$$

The dc equivalent circuit;



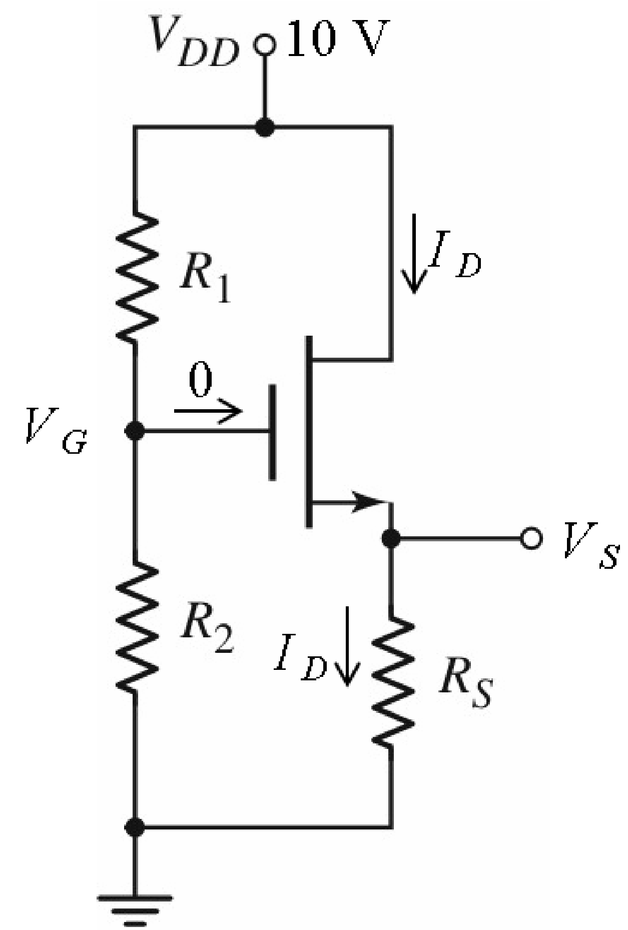
The dc equivalent circuit;

$$I_D = K_n (V_{GS} - V_{TN})^2$$

$$1.5 = 1\left[\left(\frac{R_2}{40\times10^3} - 5\right) - V_{TN}\right]^2$$

$$= \left[\left(\frac{R_2}{40\times10^3} - 5\right) - 0.8\right]^2$$

$$= \left[\frac{R_2}{40\times10^3} - 5.8\right]^2$$



Example 4 – *Solution (cont'd)*

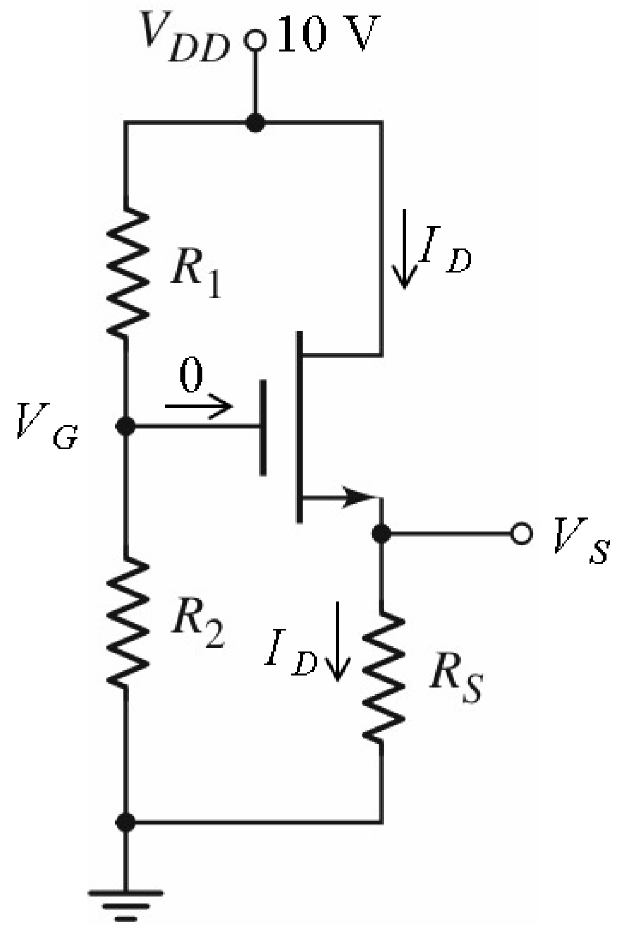
$$\frac{R_2}{40\times10^3}-5.8=\pm\sqrt{1.5}=\pm1.225$$

$$R_2=(\pm1.225+5.8)40\times10^3$$

$$R_2=281\ \mathrm{k}\Omega$$

$$R_2=183\ \mathrm{k}\Omega$$

The dc equivalent circuit;



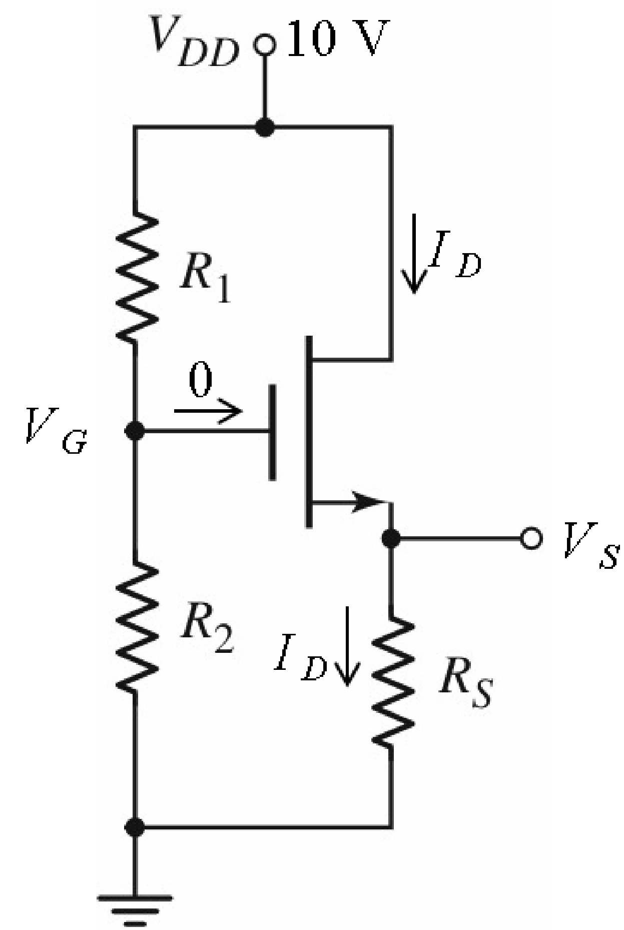
The dc equivalent circuit;

If $R_2 = 281\ \text{k}\Omega$

$$R_1 = 400 - 281 = 119\ \text{k}\Omega$$

$$V_G = 10\left(\frac{281}{119 + 281}\right) = 7.025\ \text{V}$$

$$V_{GS} = V_G - V_S = 7.025 - 5 = 2.025\ \text{V}$$



The dc equivalent circuit;

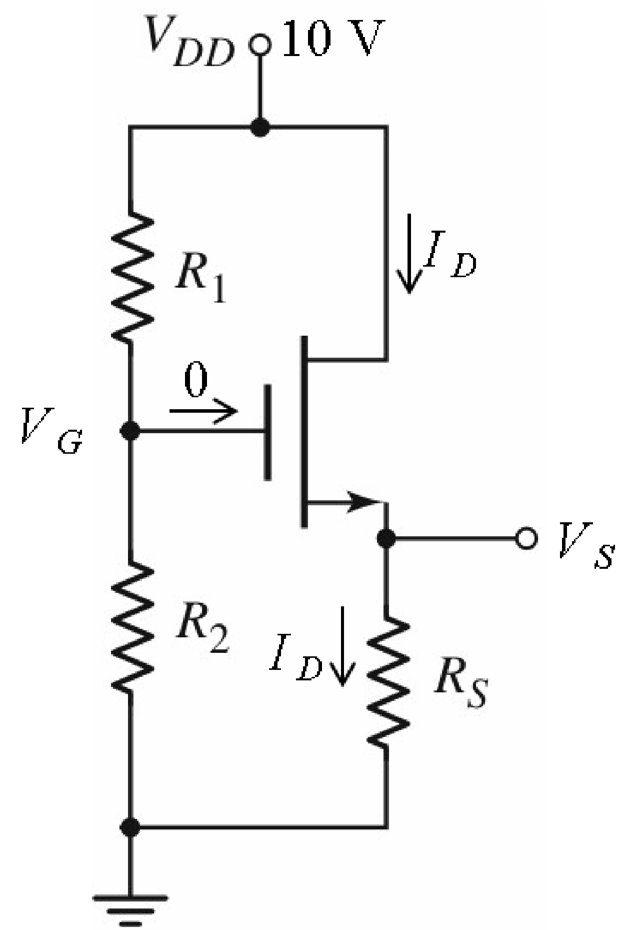
If $R_2 = 183\ \text{k}\Omega$

$$R_1 = 400 - 183 = 217\ \text{k}\Omega$$

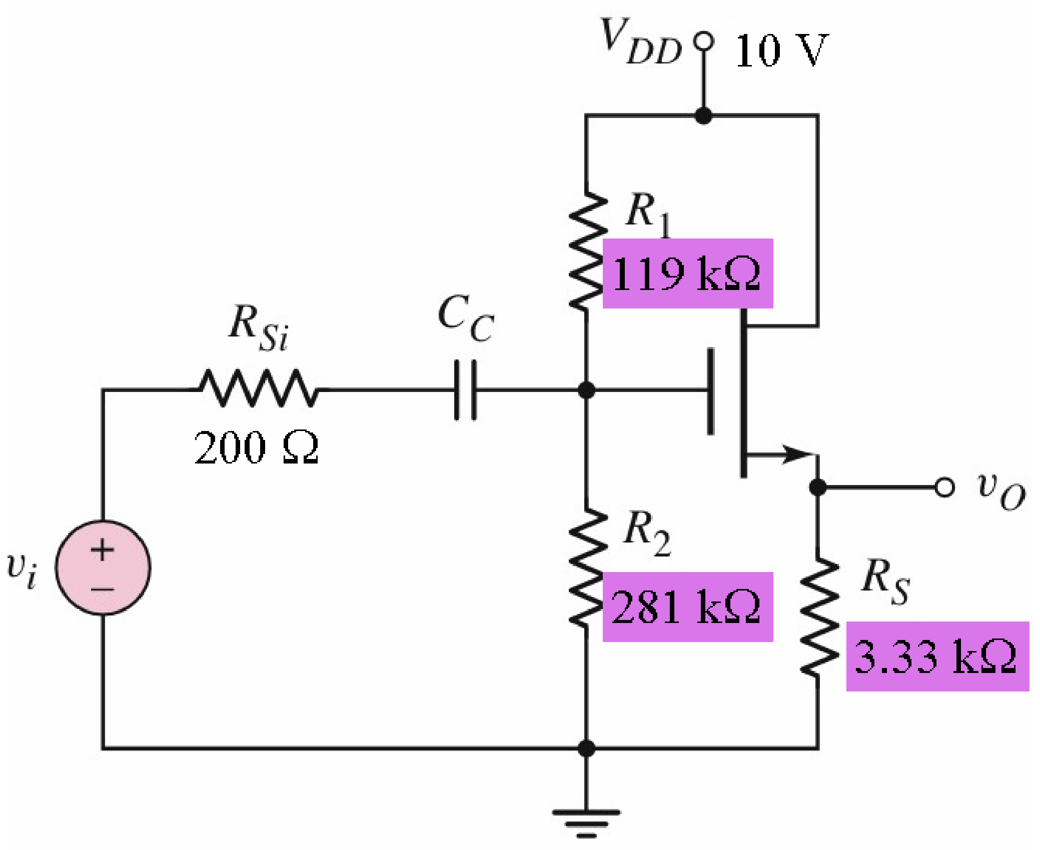
$$V_G = 10\left(\frac{183}{217+183}\right) = 4.575\ \text{V}$$

$$V_{GS} = V_G - V_S = 4.575 - 5 = -0.425\ \text{V}$$

Unrealistic – negative V_{GS}.



The circuit with all the designed values;



The transconductance is;

$$
\begin{aligned}
g_m &= 2K_n\left(V_{GS} - V_{TN}\right) \\
&= 2\times 10^{-3}\left(2.025 - 0.8\right) \\
&= 2.45\ \mathrm{mA/V}
\end{aligned}
$$

The output resistance of the transistor;

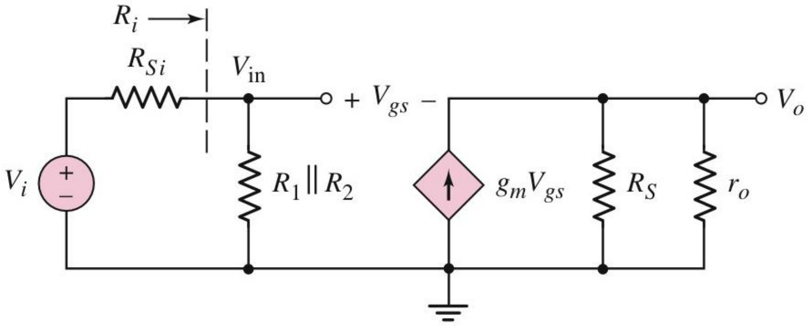
$$
r_o = \frac{1}{\lambda I_D} = \frac{1}{0.015\times 1.5\times 10^{-3}} = 44.44\ \mathrm{k\Omega}
$$

MOSFET Basic Amplifier Configurations

Common-drain — Example 4 – *Solution (cont'd)*

The small-signal voltage of the amplifier is;

$$A_v = \frac{(R_S \| r_o)}{1/g_m + (R_S \| r_o)} \left(\frac{R_i}{R_{Si} + R_i} \right)$$



$$= \frac{(3.33 \| 44.44)}{1/2.45 \times 10^{-3} + (3.33 \| 44.44)} \left(\frac{119 \| 281}{0.2 + 119 \| 281} \right)$$

$$\boxed{A_v = 0.882 \text{ V/V}}$$

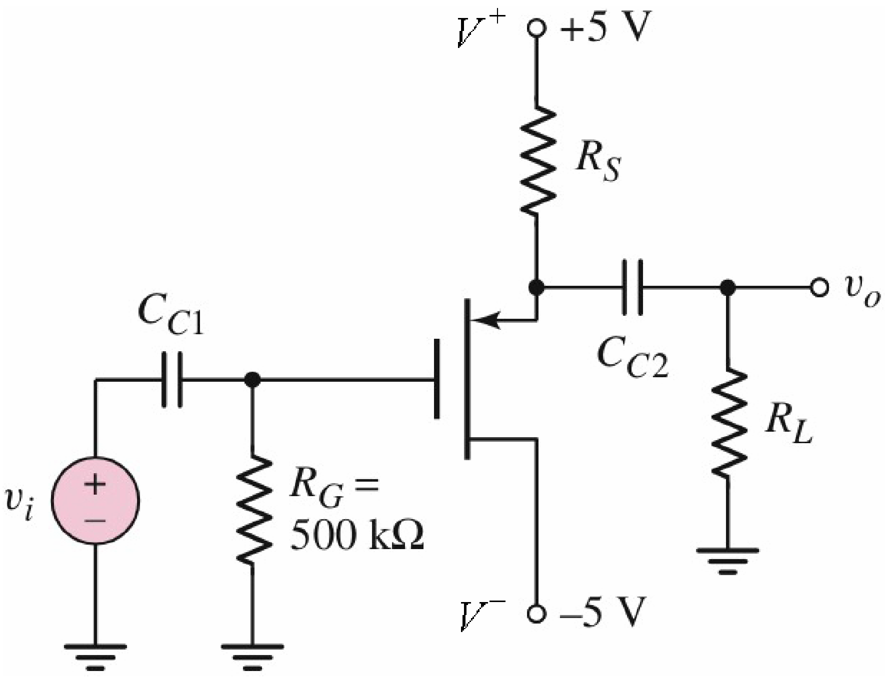
MOSFET Basic Amplifier Configurations

Common-drain Example 5

The transistor in the figure has the following parameters;

$$V_{TP} = -2\text{ V},\ \ K_p = 2\text{ mA/V}^2,$$

$$\text{and } \lambda = 0.02\text{ V}^{-1}$$



Design the circuit such that I_{DQ} = 3 mA.

Determine the open-circuit small-signal **voltage gain** and **output resistance**

What value of R_L will result in a 10% reduction in gain?

MOSFET Basic Amplifier Configurations

Common-drain | Example 5 – *Solution*

Since I_D = 3 mA;

$$V_S = 5 - 3\times10^{-3} R_S$$

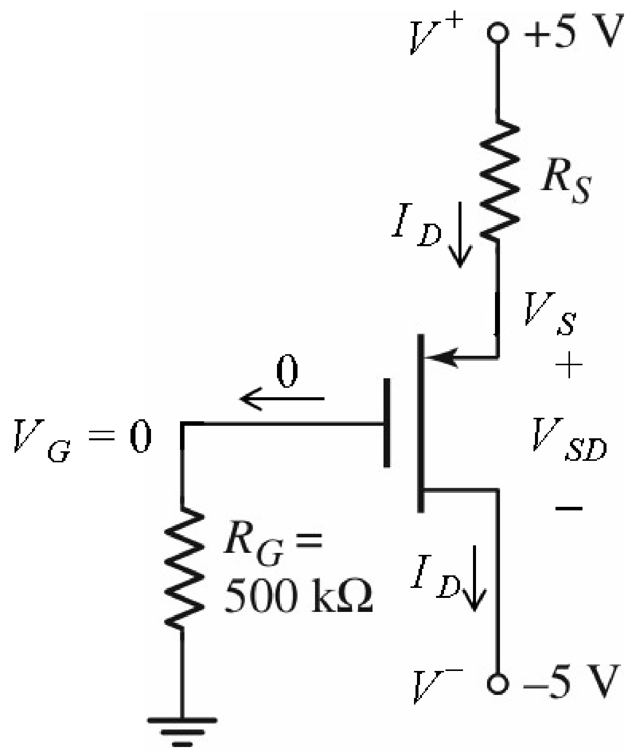
Because G is at ground potential, we have;

$$V_{SG} = V_S = 5 - 3\times10^{-3} R_S$$

The equation for the drain current is;

$$I_D = K_p \left(V_{SG} + V_{TP}\right)^2$$

The circuit under dc condition



Substituting values;

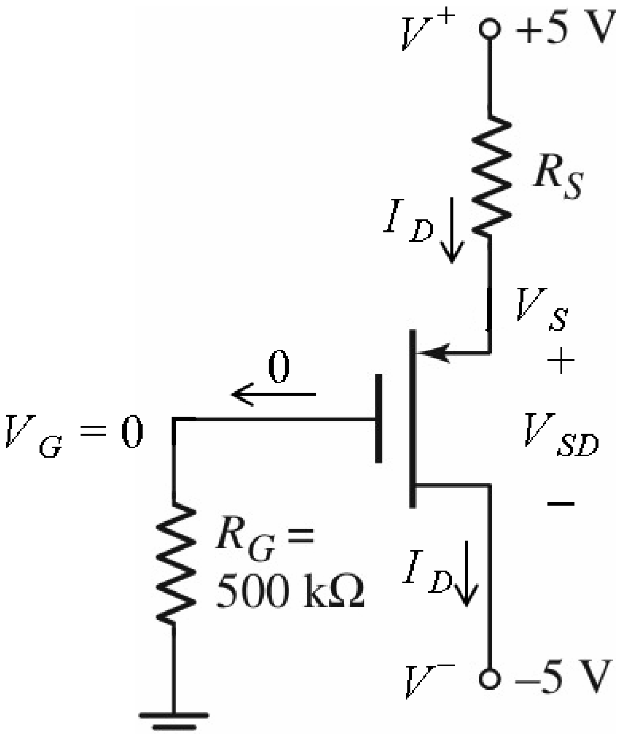
$$3 = 2\left(5 - 3\times10^{-3} R_S - 2\right)^2$$

Or;

$$R_S = \frac{3 \pm \sqrt{1.5}}{3} \times 10^3$$

The above equation gives us two values;

$R_S = 1.41\ \mathrm{k\Omega}$ or $R_S = 592\ \Omega$



For $R_S = 1.41\ \mathrm{k\Omega}$

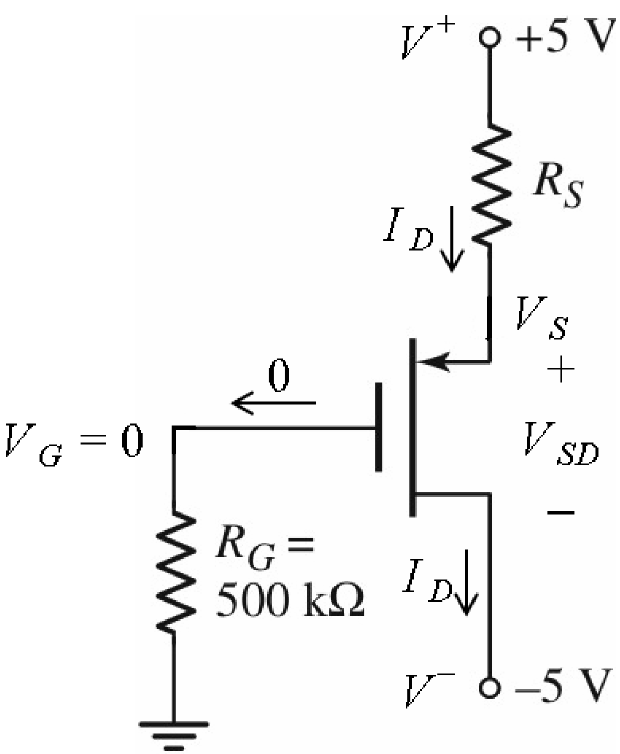
$$V_{SG} = 5 - 3\times10^{-3}\times1.41\times10^{3}$$
$$= 0.77\ \mathrm{V}$$

(unrealistic because $V_{SG} < |V_{TP}|$

For $R_S = 592\ \Omega$

$$V_{SG} = 5 - 3\times10^{-3}\times0.592\times10^{3}$$
$$= 3.24\ \mathrm{V}$$

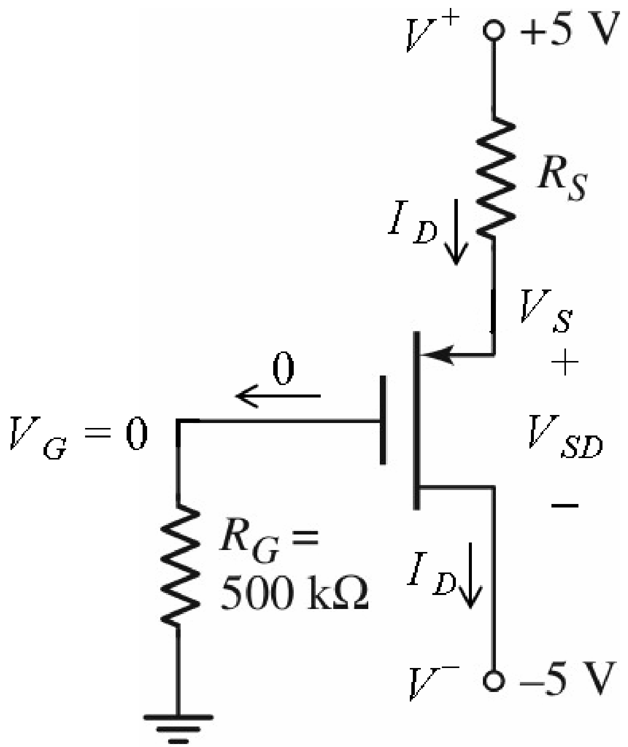
(acceptable)



The transconductance is;

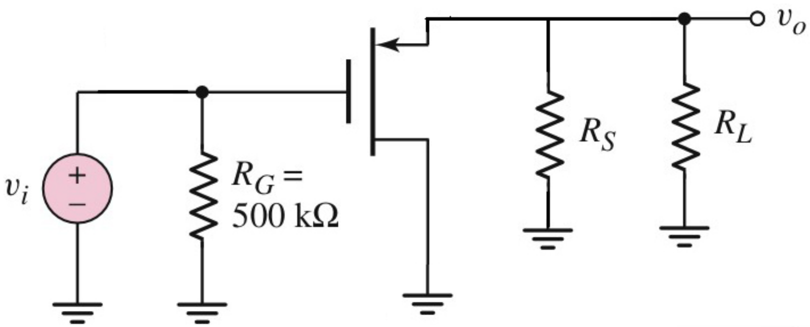
$$g_m = 2K_p(V_{SG} + V_{TP})$$
$$= 2 \times 2 \times 10^{-3}(3.24 - 2)$$
$$= 4.96\,\text{mA/V}$$

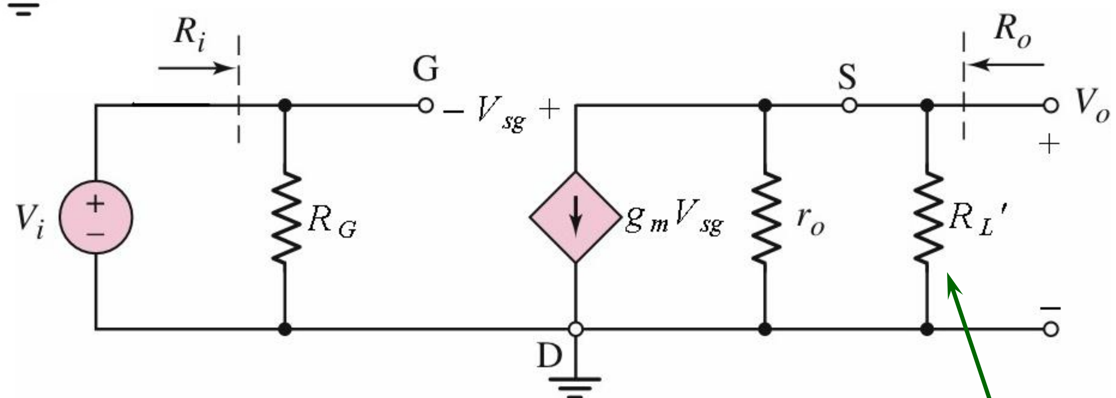
$$r_o = \frac{1}{\lambda I_D} = \frac{1}{0.02 \times 3 \times 10^{-3}}$$
$$= 16.6\,\text{k}\Omega$$



Common-drain

Example 5 – *Solution (cont'd)*

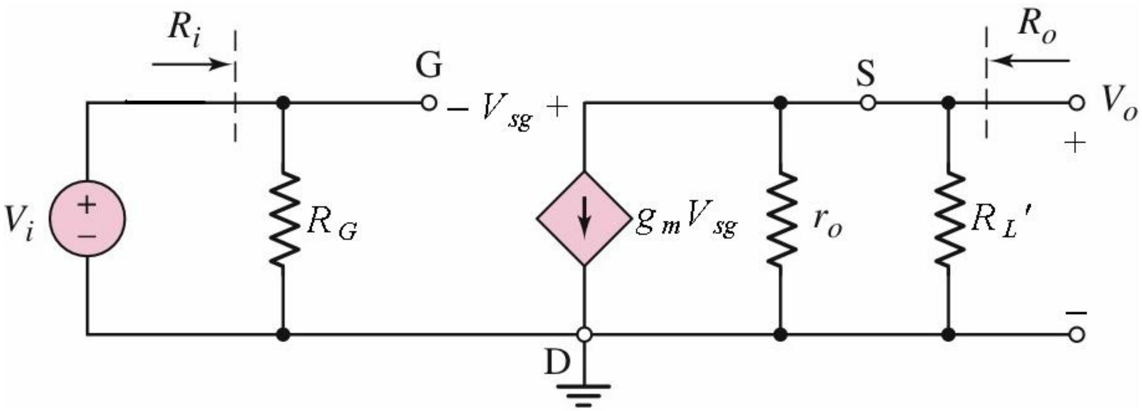




$$R_L' = R_S \| R_L$$

$$V_o = -g_m V_{sg} \left(r_o \| R_L' \right) \Rightarrow V_{sg} = -\frac{V_o}{g_m \left(r_o \| R_L' \right)}$$

Example 5 – *Solution (cont'd)*



$$V_i = -V_{sg} + V_o = \frac{V_o}{g_m\left(r_o \| R_L'\right)} + V_o = \left[\frac{1 + g_m\left(r_o \| R_L'\right)}{g_m\left(r_o \| R_L'\right)}\right] V_o$$

$$A_v = \frac{V_o}{V_i} = \left[\frac{g_m\left(r_o \| R_L'\right)}{1 + g_m\left(r_o \| R_L'\right)}\right]$$

MOSFET Basic Amplifier Configurations

Common-drain Example 5 – *Solution (cont'd)*

$$A_v = \frac{V_o}{V_i} = \left[\frac{g_m \left(r_o \| R_L' \right)}{1 + g_m \left(r_o \| R_L' \right)} \right]$$

$$\left. \begin{aligned} g_m &= 4.96\ \mathrm{mA/V} \\ r_o &= 16.7\ \mathrm{k\Omega} \end{aligned} \right\}$$ (As calculated previously)

$$\left. \begin{aligned} R_L' = R_S \| R_L &= R_S \\ &= 0.592\ \mathrm{k\Omega} \end{aligned} \right\}$$ (Since $R_L = \infty$ – open circuit)

The open-circuit small-signal voltage gain is;

$$A_v(\text{open-circuit}) = \left[\frac{4.96\times10^{-3}\times592}{1+4.96\times10^{-3}\times592}\right]$$

$$A_v(\text{open-circuit}) = 0.746 \text{ V/V}$$

The voltage gain after a reduction of 10% is;

$$A_v' = 0.9A_v(\text{open-circuit})$$
$$= 0.9\times0.746$$
$$= 0.671 \text{ V/V}$$

Substituting for A_v in the equation;

$$A_v = \frac{V_o}{V_i} = \left[\frac{g_m \left(r_o \| R_L{}' \right)}{1 + g_m \left(r_o \| R_L{}' \right)} \right]$$

we have;

$$0.671 = \left[\frac{g_m \left(r_o \| R_L{}' \right)}{1 + g_m \left(r_o \| R_L{}' \right)} \right]$$

Substituting the value for g_m gives us;

$$0.671 = \left[\frac{4.96\times10^{-3}\left(r_o \| R_L'\right)}{1+4.96\times10^{-3}\left(r_o \| R_L'\right)} \right]$$

Solving the above equation, we obtain;

$$r_o \| R_L' = \frac{1}{2.432\times10^{-3}} = 411\Omega$$

This equation may be written as;

$$\frac{r_o R_L'}{r_o + R_L'} = 411\ \Omega$$

Or;

$$R_L' = \frac{411\, r_o}{r_o - 411}$$

Substituting values;

$$R_L' = \frac{411 \times 16.7 \times 10^3}{16.7 \times 10^3 - 411} = 421\ \Omega$$

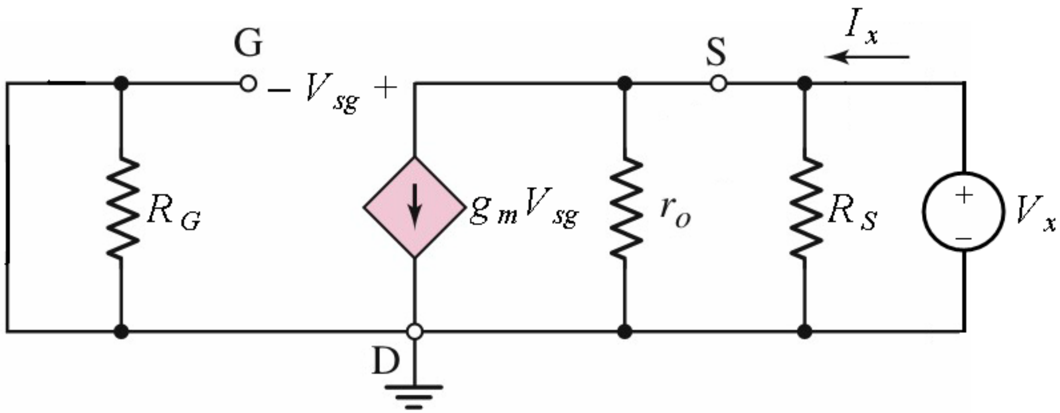
$$R_L' = \frac{R_S R_L}{R_S + R_L} = 421\ \Omega$$

$$R_L' = \frac{R_S R_L}{R_S + R_L} = 421\ \Omega$$

Solving the equation for RL gives us;

$$R_L = 1.46\ \text{k}\Omega$$

Example 5 – *Solution (cont'd)*



Using the equivalent circuit above, the output resistance R_o is given by the expression;

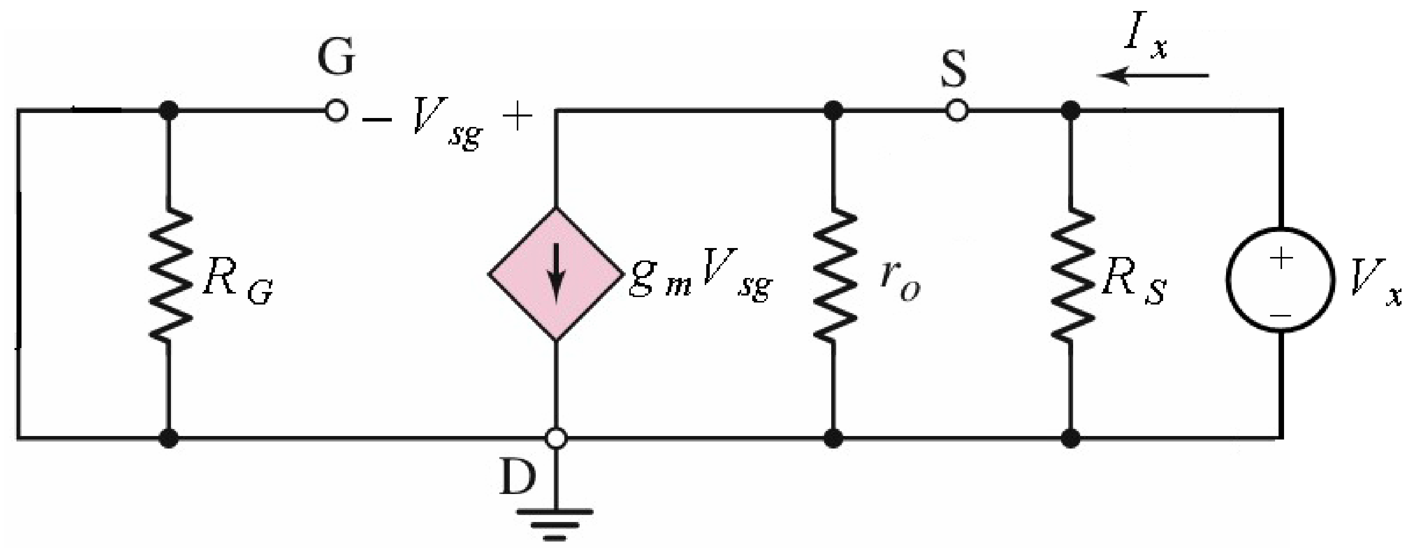
$$\frac{1}{R_o} = \left(g_m + \frac{1}{R_S} + \frac{1}{r_o} \right)$$

Example 5 – *Solution (cont'd)*

Substituting values;

$$\frac{1}{R_o} = \left(4.96\times10^{-3} + \frac{1}{0.592\times10^{3}} + \frac{1}{16.7\times10^{3}}\right)$$

$$= 6.709\times10^{-3}$$

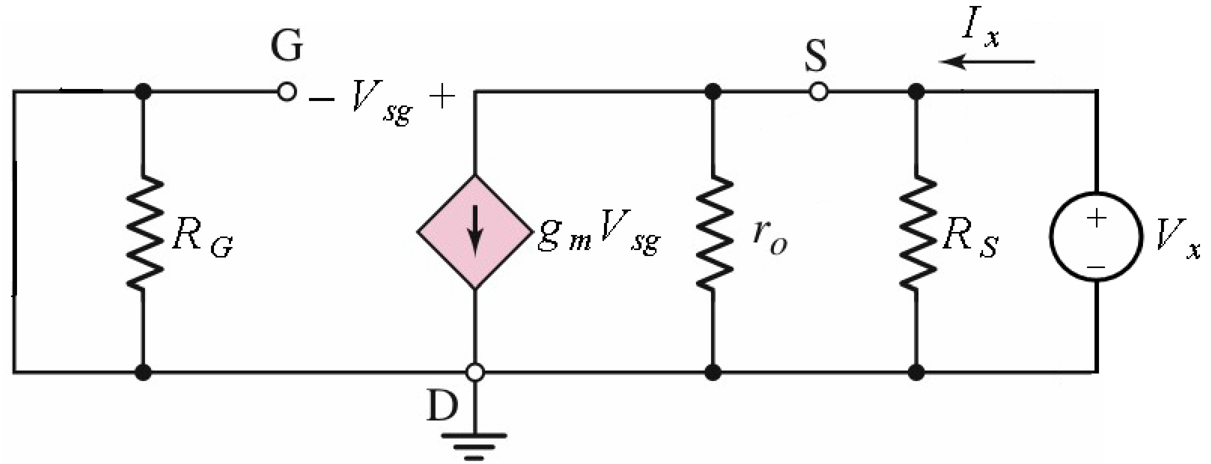


Example 5 - *Solution (cont'd)*

The output resistance is;

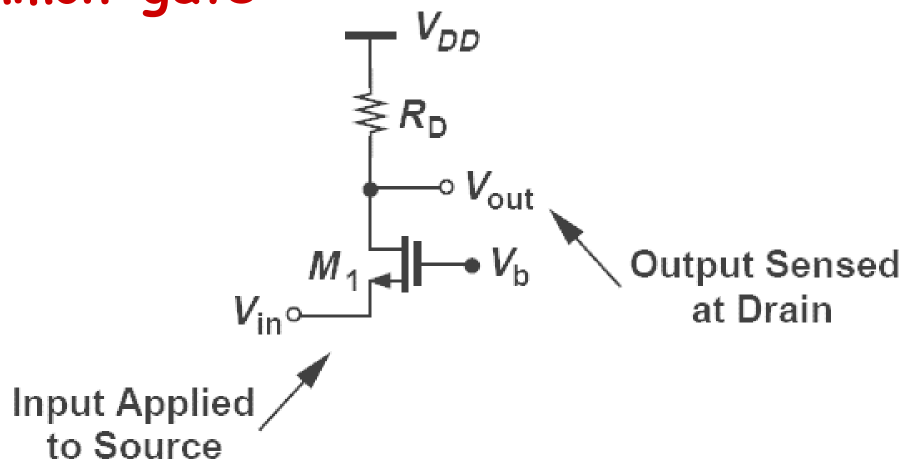
$$R_o = \frac{1}{6.709 \times 10^3}$$

$$R_o = 149\ \Omega$$



Common-gate

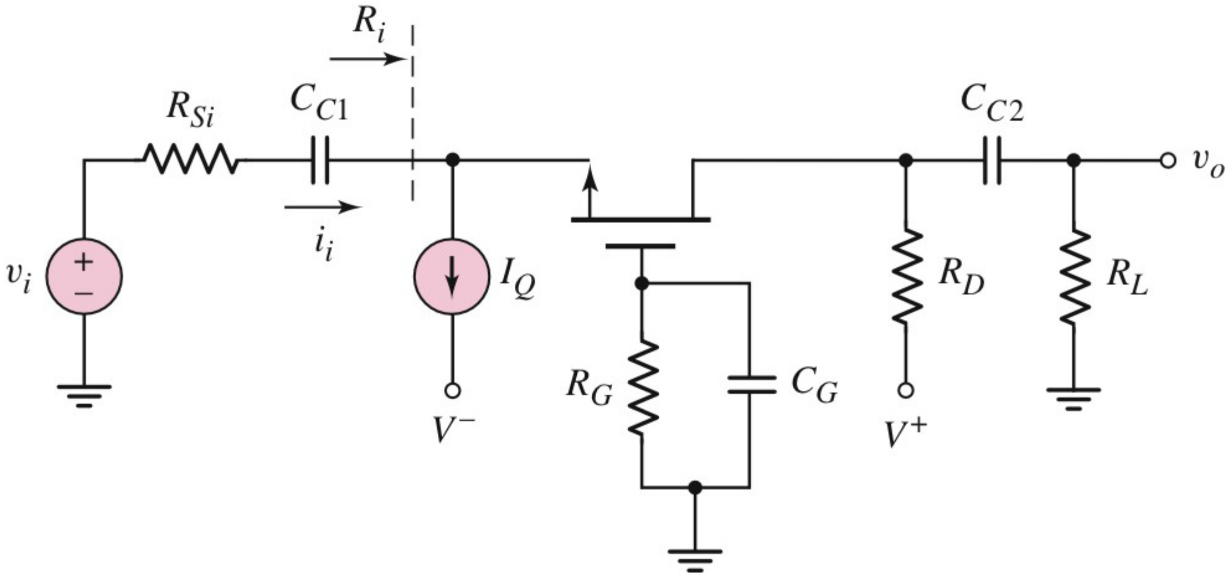
The input signal is applied to the source and gate terminal is grounded. The output is taken between the drain and gate terminals. The gate is therefore common to both the input and output and hence the name "**common-gate**"



MOSFET Basic Amplifier Configurations

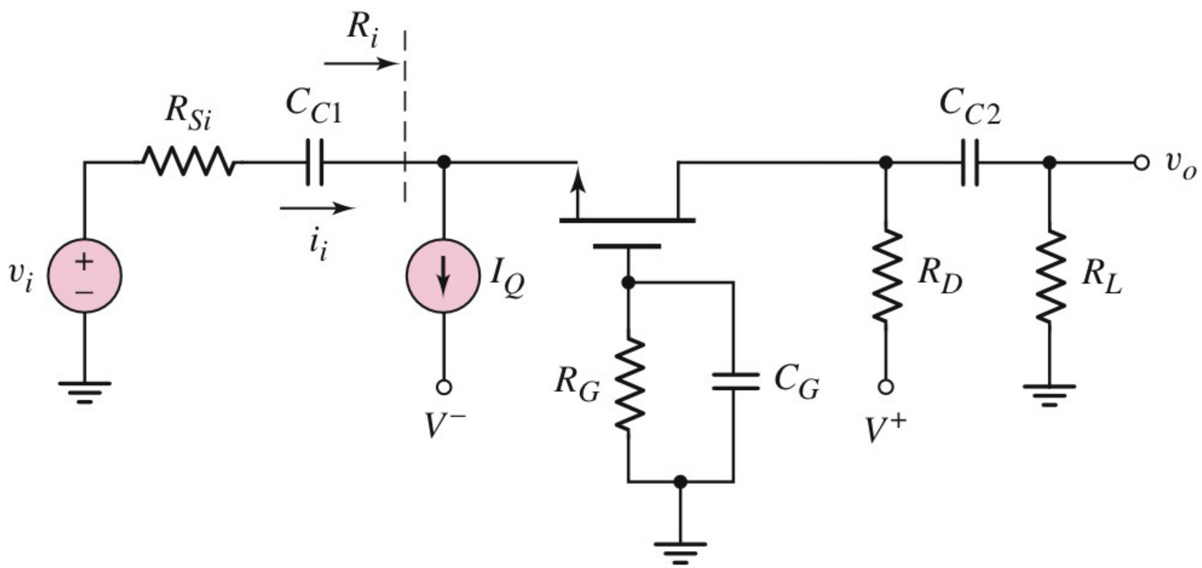
Common-gate

C_{C1} and C_{C2} are the coupling capacitors for input and output respectively. In the following figure, the DC bias current is obtained from the current source I_Q.



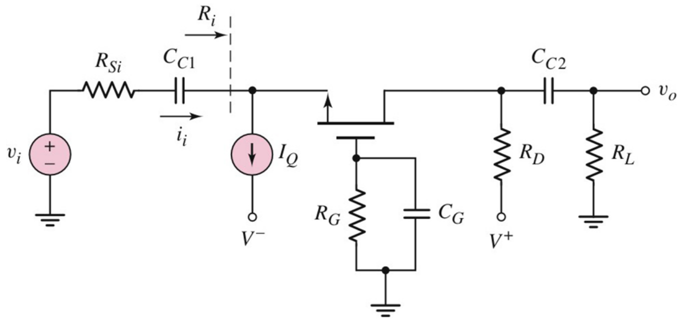
Common-gate

The dc analysis is the same as that of previous configurations.

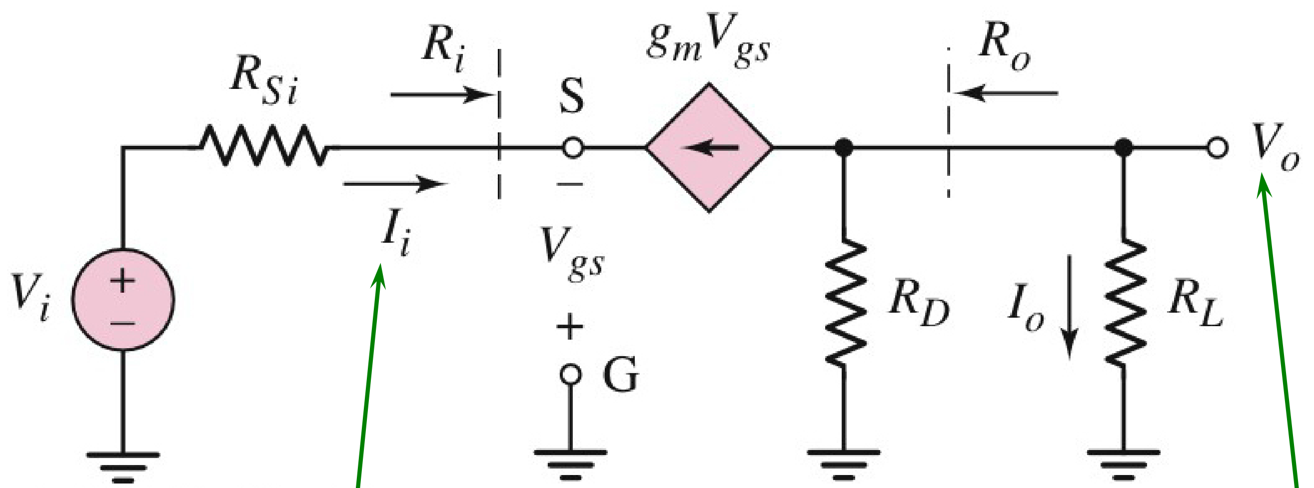


MOSFET Basic Amplifier Configurations

Common-gate – small-signal voltage gain



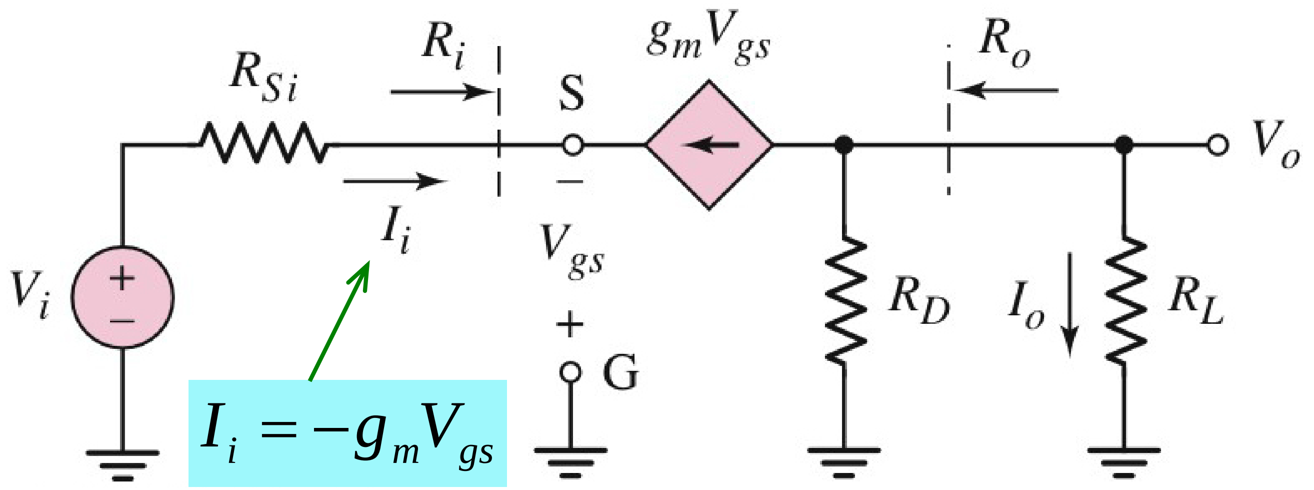
The gains can be determined using the following equivalent circuit;



$$I_i = -g_m V_{gs}$$

$$V_o = -g_m V_{gs} \left(R_D \| R_L \right)$$

Common-gate – small-signal voltage gain



Applying KVL at the input, we obtain;

$$V_i = I_i R_{Si} + V_{sg} = I_i R_{Si} - V_{gs}$$

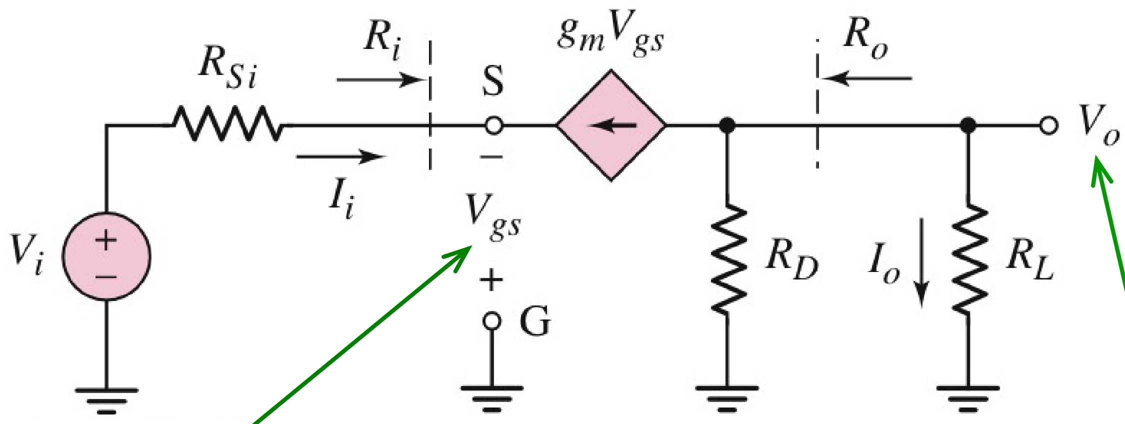
Substituting for I_i, we obtain; $V_i = -g_m V_{gs} R_{Si} - V_{gs}$

Common-gate – small-signal voltage gain

$$V_i = -g_m V_{gs} R_{Si} - V_{gs}$$

Re-arranging, gives us;

$$V_{gs} = \frac{-V_i}{1 + g_m R_{Si}}$$



$$V_{gs} = \frac{-V_i}{\left(1 + g_m R_{Si}\right)}$$

$$V_o = -g_m V_{gs}\left(R_D \| R_L\right)$$

Common-gate – small-signal voltage gain

Substituting for V_{gs} in the expression for V_o, we obtain;

$$V_o = -g_m\left(\frac{-V_i}{\left(1+g_m R_{Si}\right)}\right)\left(R_D \| R_L\right)$$

$$V_{gs} = \frac{-V_i}{\left(1+g_m R_{Si}\right)}$$

$$V_o = -g_m V_{gs}\left(R_D \| R_L\right)$$

The small-signal voltage gain is;

$$A_v = \frac{V_o}{V_i} = \frac{g_m\left(R_D \| R_L\right)}{1+g_m R_{Si}}$$

Common-gate – input resistance

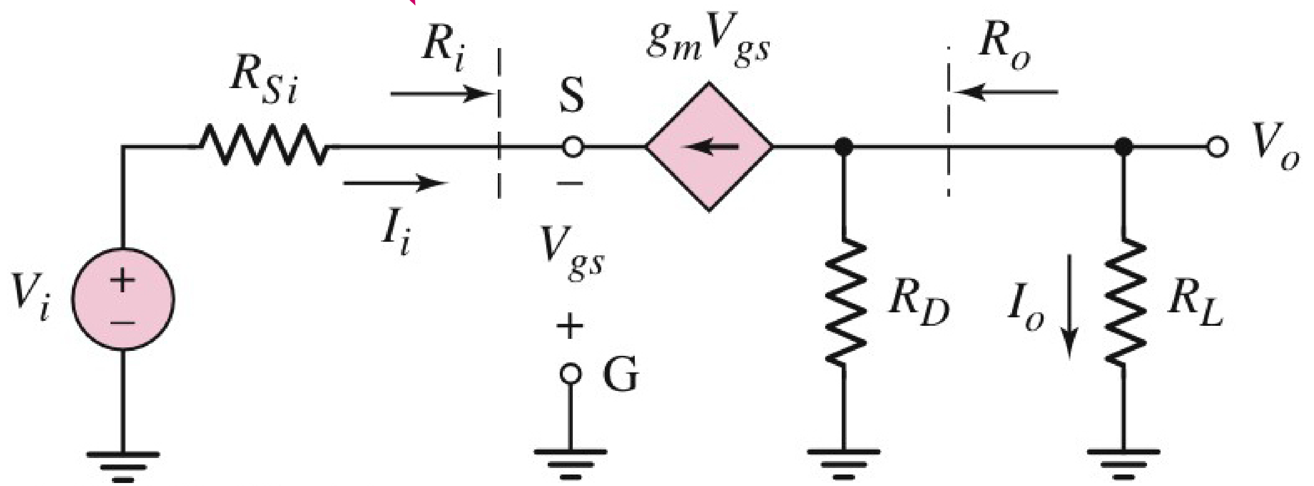
From the equivalent circuit;

$$R_i = \frac{-V_{gs}}{I_i}$$

Since; $I_i = -g_m V_{gs}$

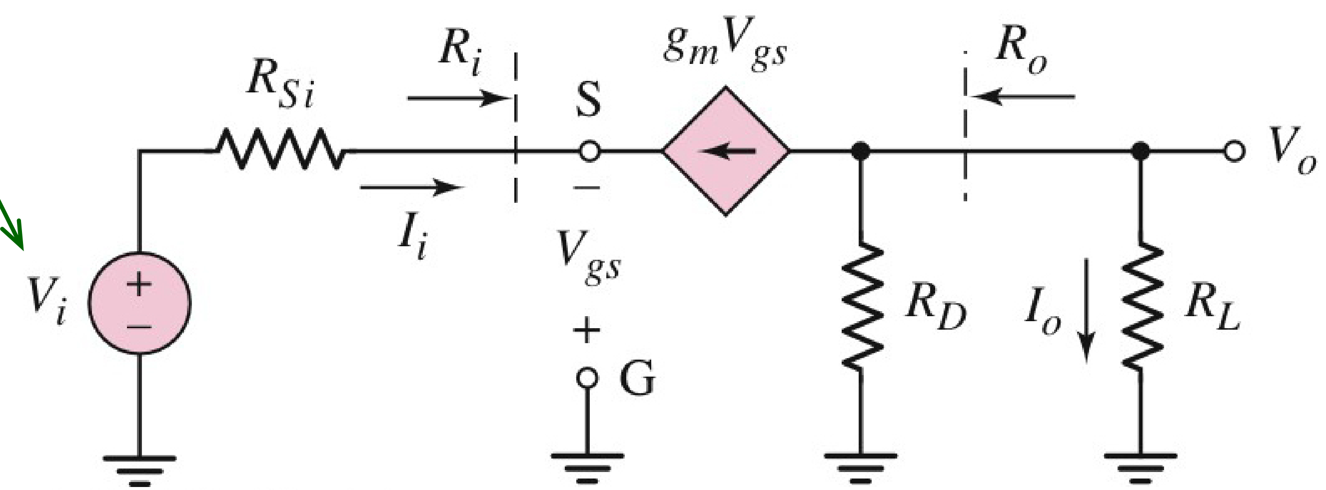
the input resistance becomes;

$$\boxed{R_i = \frac{1}{g_m}}$$

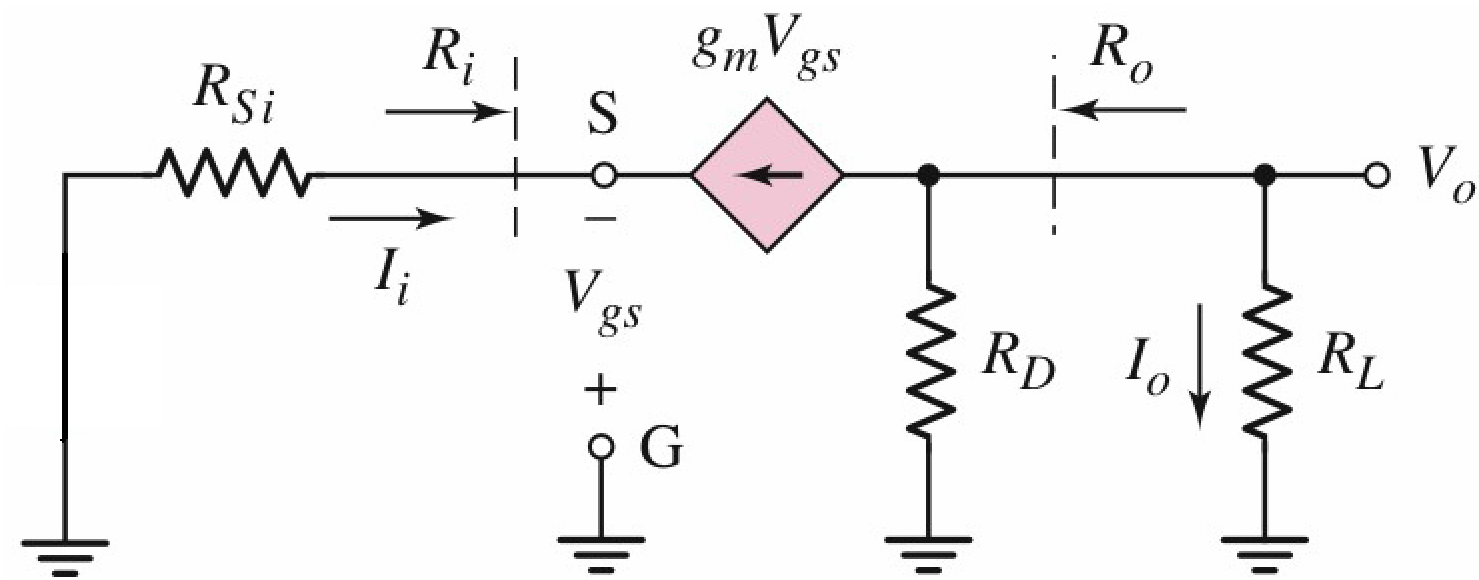


Common-gate – output resistance

The output resistance may be found by setting $V_i = 0$



Common-gate – output resistance



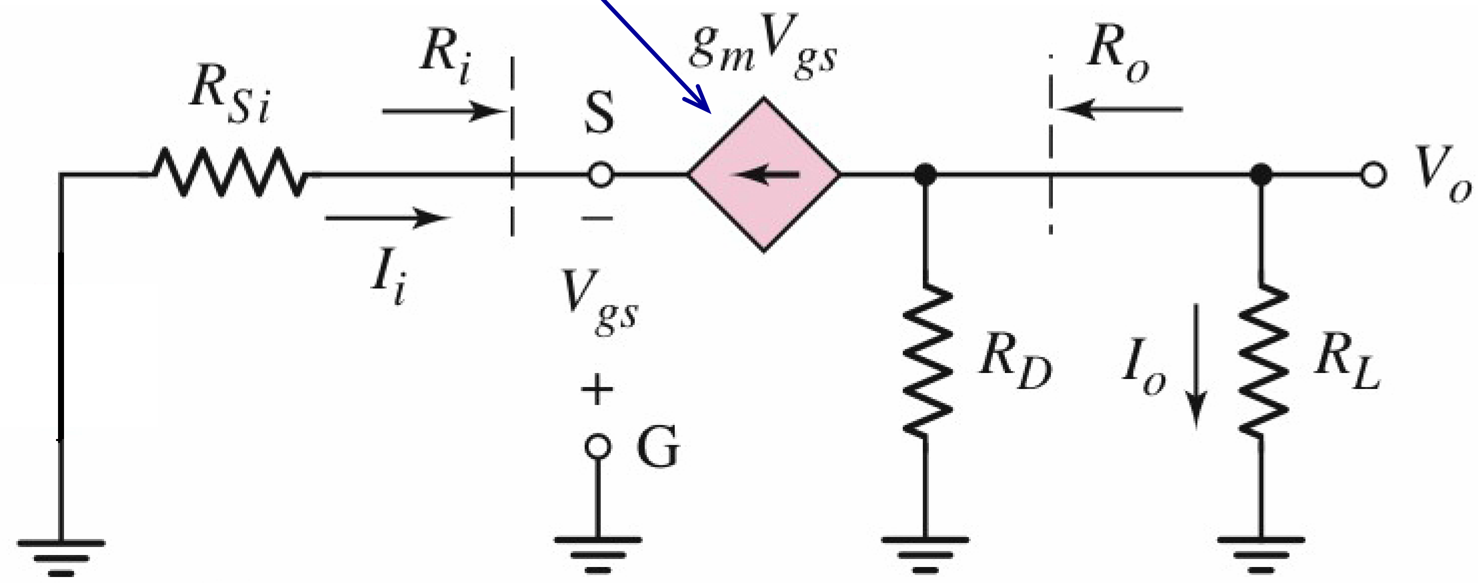
When V_i is set to zero;

$$V_{gs} = -g_m V_{gs} R_{Si}$$

which only holds if $V_{gs} = 0$

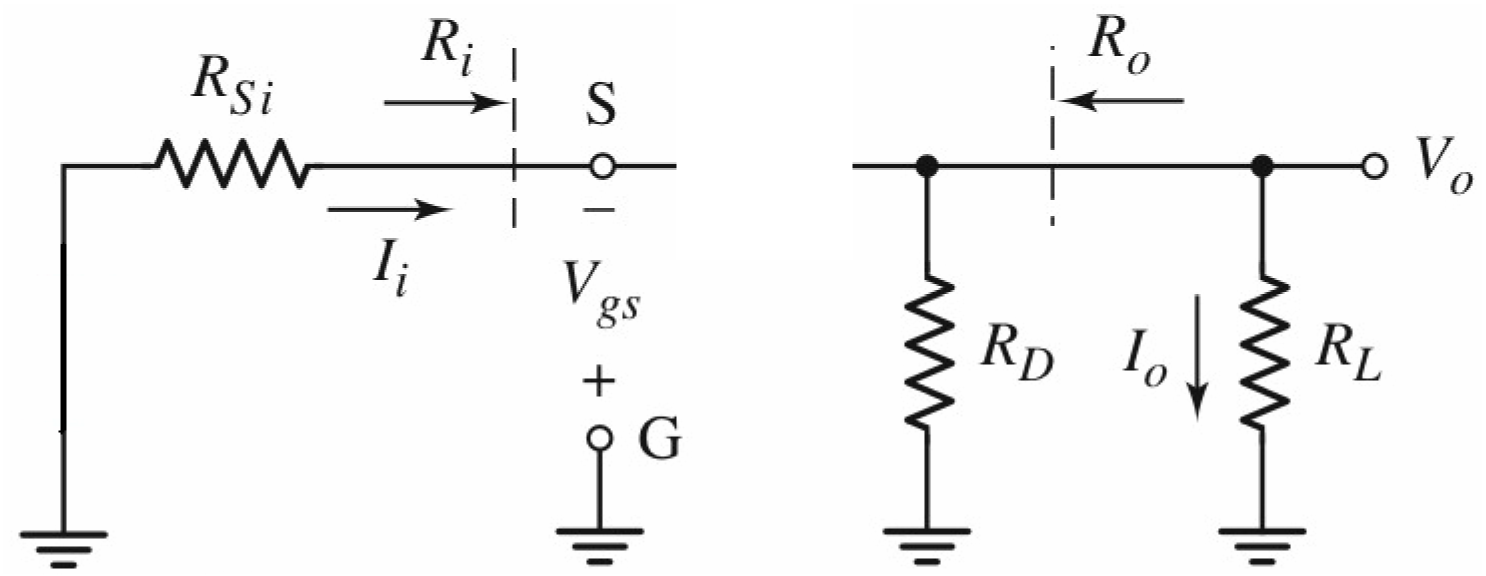
Common-gate – output resistance

When V_{gs} = 0, the controlled current source $g_m V_{gs}$ is open



Common-gate – output resistance

The equivalent circuit becomes as shown below;



Hence the output resistance is;

$$R_o = R_D$$

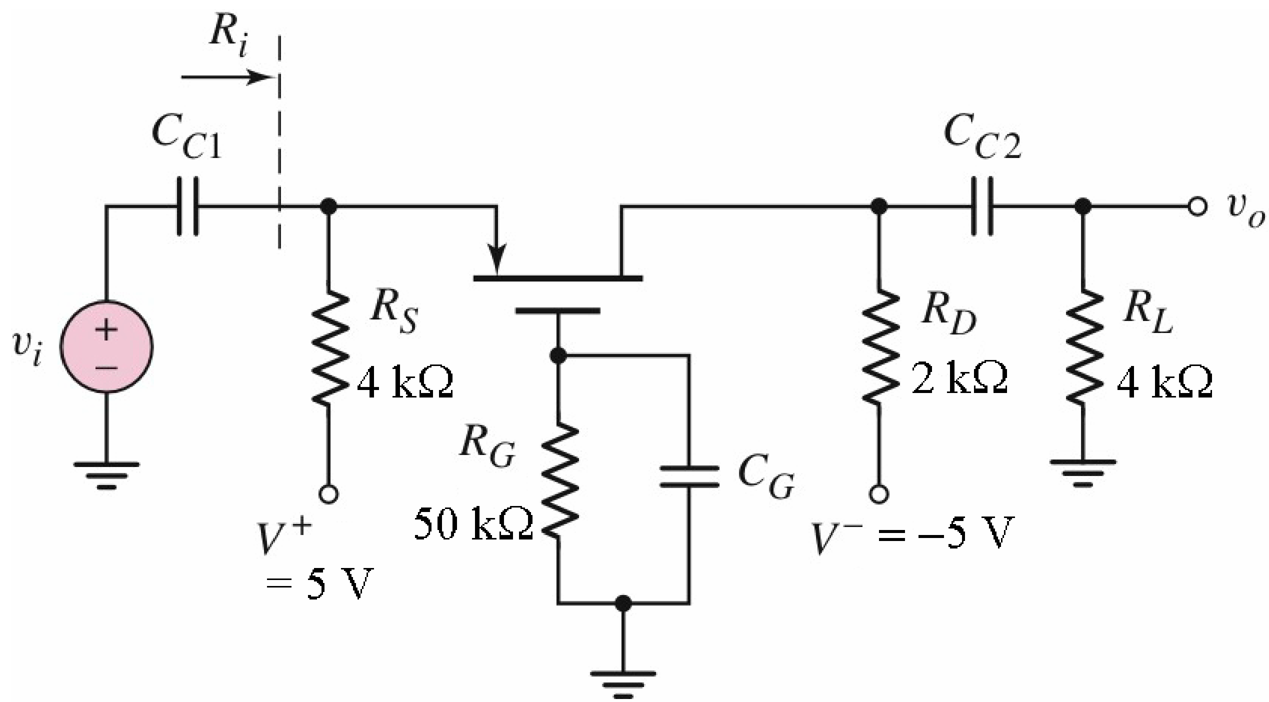
The transistor parameters in the following figure are;

$$K_p = 1\,\mathrm{mA/V^2},\ V_{TP} = -0.8\,\mathrm{V},\ \lambda = 0$$

(a) Draw the small-signal equivalent

(b) Determine the small-signal voltage gain A_v.

(c) Find the input resistance R_i.



Example 6 - *Solution*

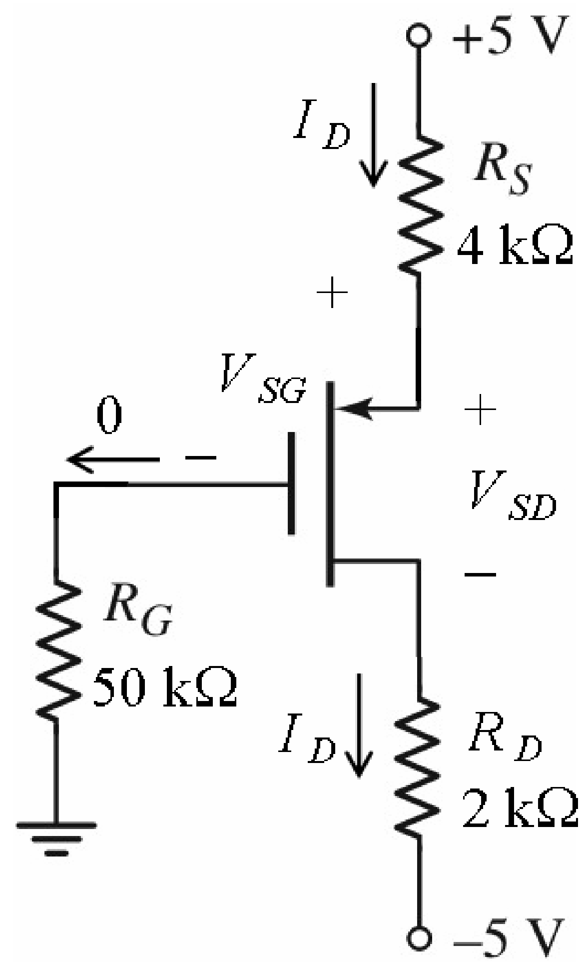
DC analysis

May be performed using the dc equivalent circuit shown.

$$I_D = K_p\left(V_{SG} + V_{TP}\right)^2$$

$$= 10^{-3}\left(V_{SG} - 0.8\right)^2$$

$$I_D = 10^{-3}\left(V_{SG}^2 - 1.6V_{SG} + 0.64\right)$$

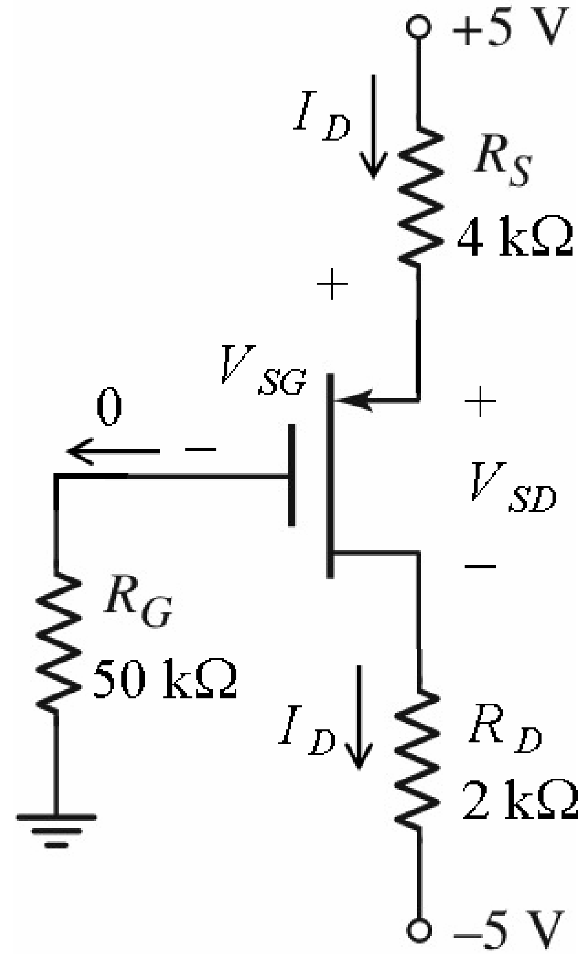


From the dc equivalent circuit;

$$V_{SG} = V_S = 5 - I_D R_S$$
$$= 5 - 4\times 10^3 I_D$$

Rearranging, we have;

$$I_D = (1.25 - 0.25V_{SG})10^{-3}$$



Example 6 – *Solution (cont'd)*

Substituting for I_D;

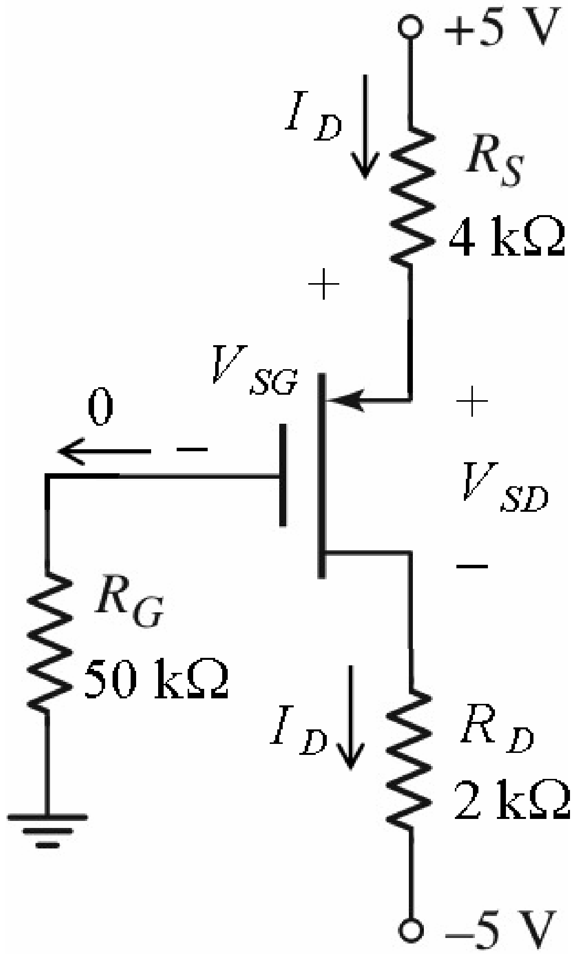
$$1.25 - 0.25V_{SG} = V_{SG}^2 - 1.6V_{SG} + 0.64$$

or;

$$V_{SG}^2 - 1.35V_{SG} - 0.61 = 0$$

Solving the equation, we have;

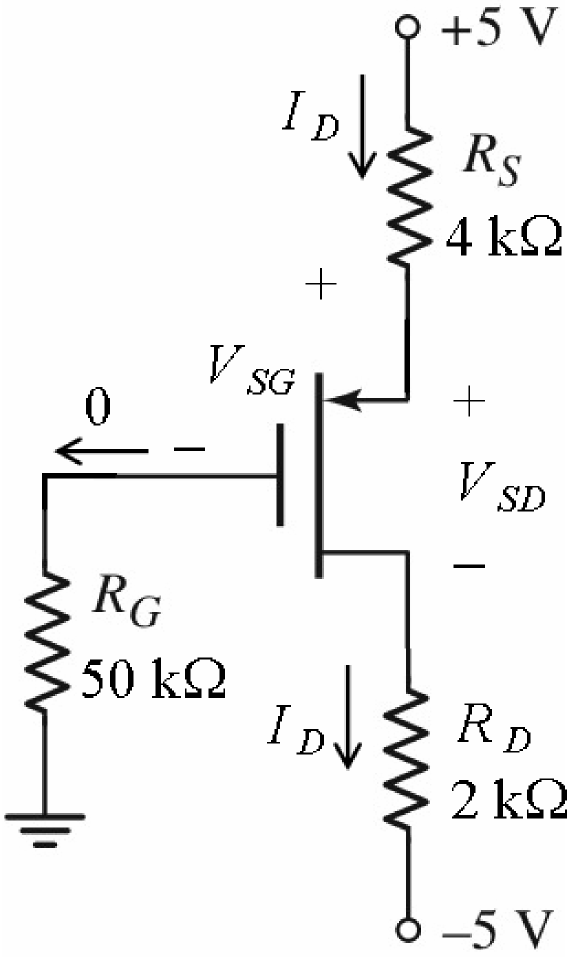
$$V_{SG} = 1.71\ \text{V}$$



Example 6 - *Solution (cont'd)*

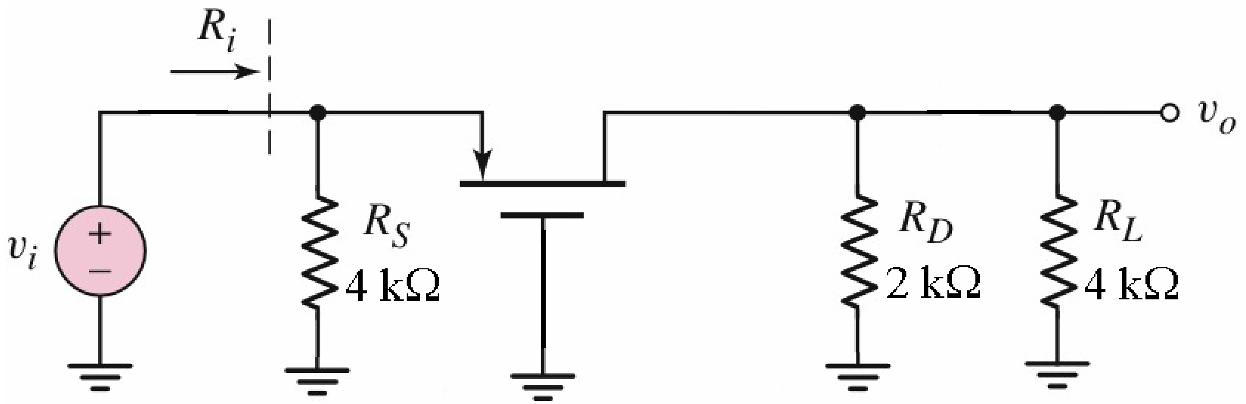
The transconductance is;

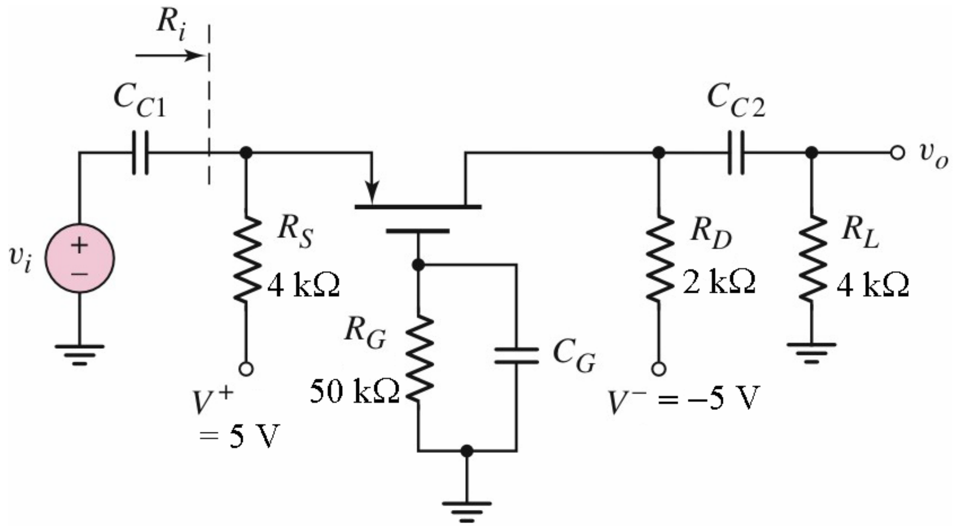
$$g_m = 2K_p\left(V_{SG} + V_{TP}\right)$$
$$= 2\times10^{-3}\left(1.71 - 0.8\right)$$
$$= 1.81\,\mathrm{mA/V}$$



Example 6 – *Solution (cont'd)*

The ac equivalent circuit is as follows;

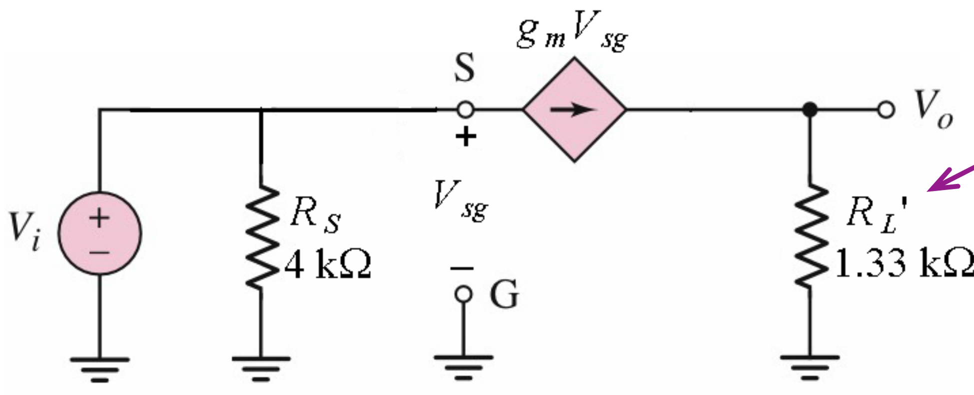


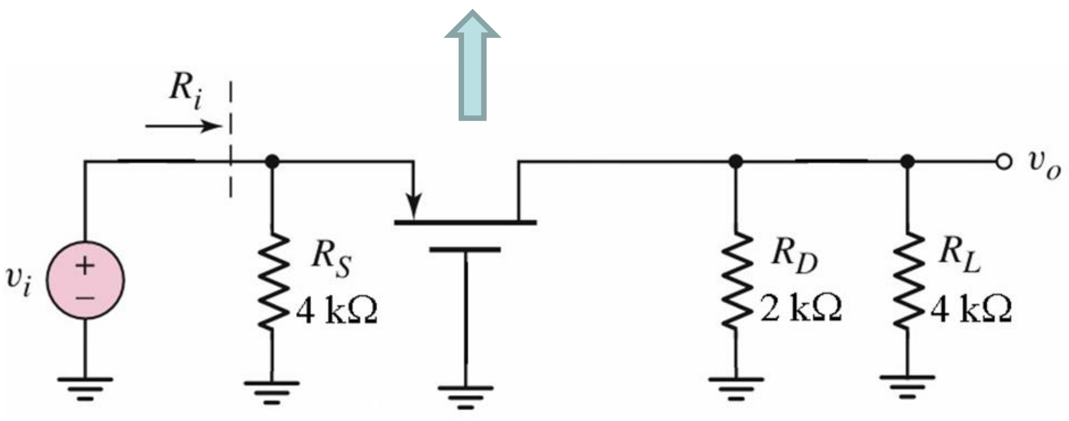


Common-gate Example 6 – *Solution (cont'd)*

Replacing the transistor with its small-signal model, we have the following circuit;

$$R_L' = R_D \| R_L = 2 \| 4 = 1.33\,\text{k}\Omega$$

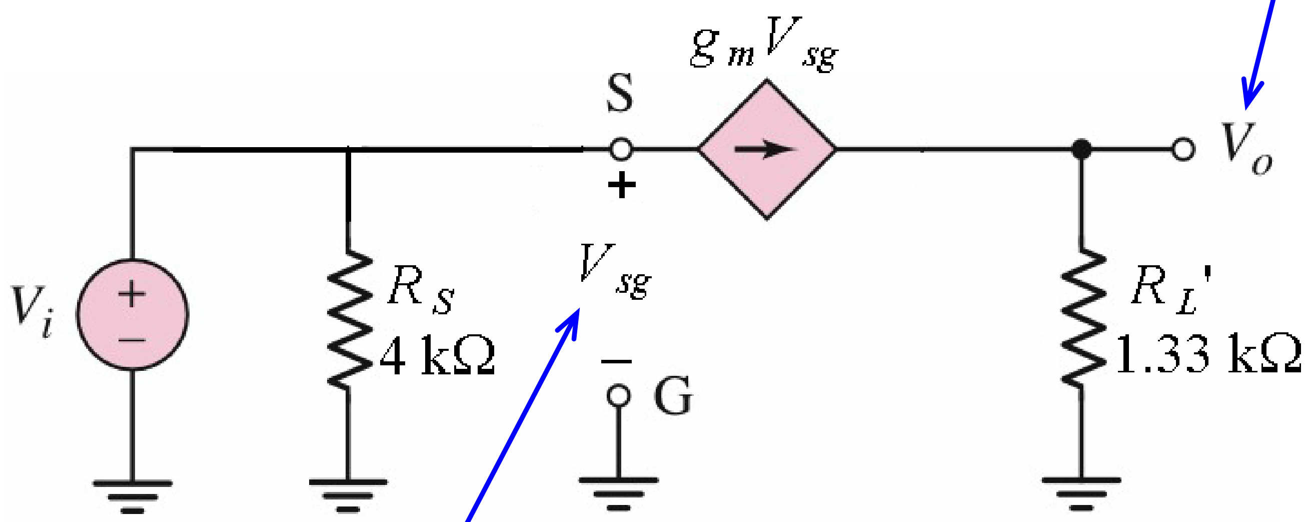




Common-gate

Example 6 – *Solution (cont'd)*

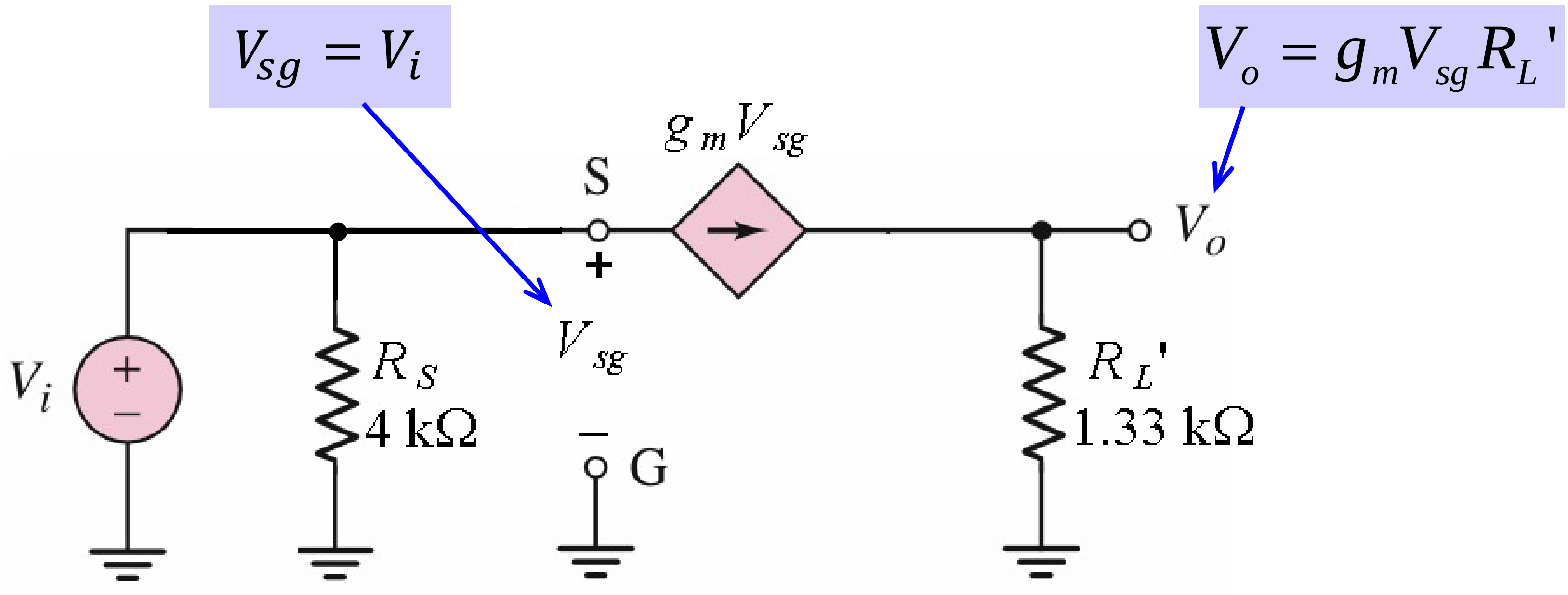
$$V_o = g_m V_{sg} R_L'$$



$$V_{sg} = V_i$$

MOSFET Basic Amplifier Configurations

Common-gate — Example 6 – *Solution* (cont'd)



$$V_o = g_m V_{sg} R_L' = g_m V_i R_L'$$

The small-signal voltage gain is $A_v = \dfrac{V_o}{V_i} = g_m R_L'$

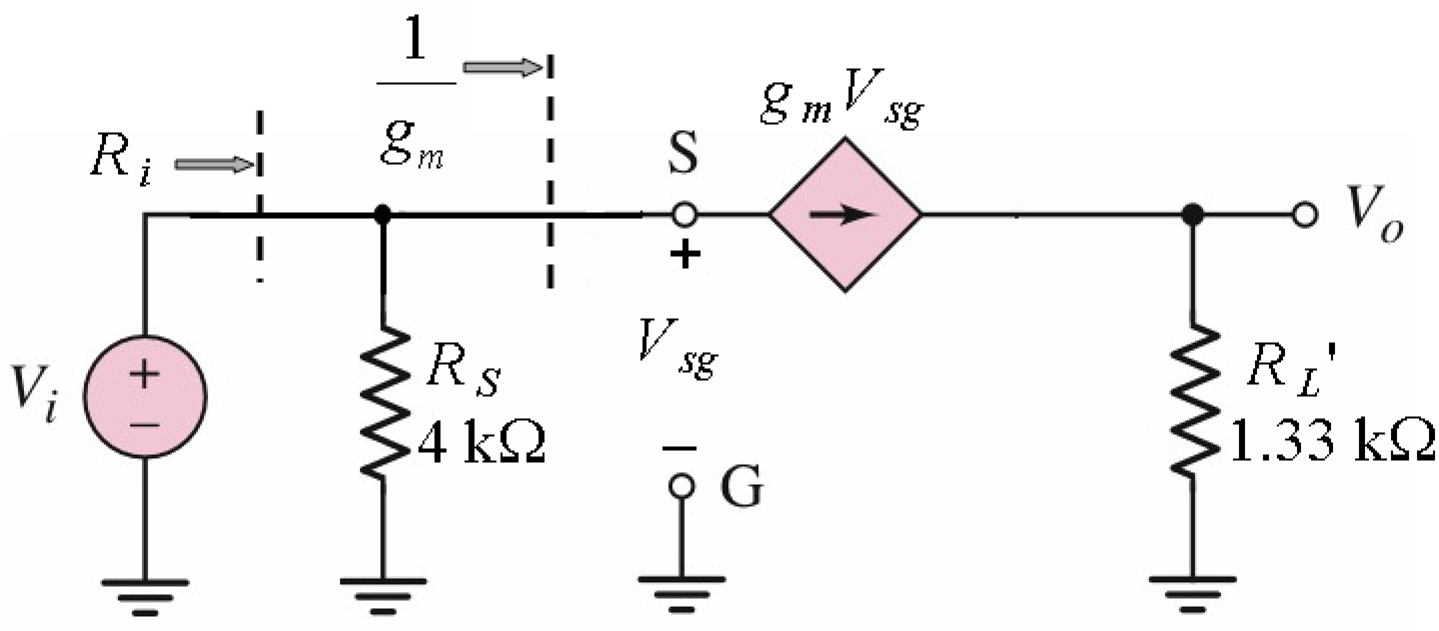
Example 6 - *Solution (cont'd)*

Substituting values;

$$\boxed{A_v = 1.81 \times 1.33 = 2.41}$$

Common-gate

Example 6 – *Solution (cont'd)*



The input resistance is;

$$R_i = R_S \left\| \frac{1}{g_m} \right. = 4 \left\| \frac{1}{1.81\times10^{-3}} \right. = 0.485\,\text{k}\Omega$$