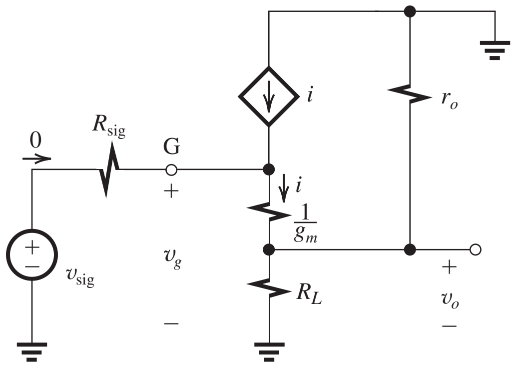
7.90



$v_g = v_{sig}$

Noting that r_o appears in effect in parallel with R_L, v_o is obtained as the ratio of the voltage divider formed by $(1/g_m)$ and $(R_L \parallel r_o)$,

$$G_v = \frac{v_o}{v_{sig}} = \frac{v_o}{v_g} = \frac{(R_L \parallel r_o)}{(R_L \parallel r_o) + \dfrac{1}{g_m}} \qquad \text{Q.E.D.}$$

With R_L removed,

$$G_v = \frac{r_o}{r_o + \dfrac{1}{g_m}} = 0.98 \tag{1}$$

With $R_L = 500\ \Omega$,

$$G_v = \frac{(500 \parallel r_o)}{(500 \parallel r_o) + \dfrac{1}{g_m}} = 0.49 \tag{2}$$

From Eq. (1), we have

$$\frac{1}{g_m} = \frac{r_o}{49}$$

Substituting in Eq. (2) and solving for r_o gives

$r_o = 25{,}000\ \Omega = 25\ \text{k}\Omega$

Thus

$$\frac{1}{g_m} = \frac{25{,}000}{49}\ \Omega$$

$\Rightarrow g_m = 1.96\ \text{mA/V}$

7.91 Adapting Eq. (7.114) gives

$$G_v = -\beta \frac{R_C \parallel R_L \parallel r_o}{R_{sig} + (\beta + 1)r_e}$$

$$= -\frac{R_C \parallel R_L \parallel r_o}{\dfrac{R_{sig}}{\beta} + \dfrac{\beta + 1}{\beta} r_e}$$

$$= -\frac{R_C \parallel R_L \parallel r_o}{\dfrac{R_{sig}}{\beta} + \dfrac{1}{g_m}}$$

Thus,

$$|G_v| = \frac{10 \parallel r_o}{0.1 + \dfrac{1}{g_m}} \tag{1}$$

where r_o and $\dfrac{1}{g_m}$ are in kilohms and are given by

$$r_o = \frac{V_A}{I_C} = \frac{25\ \text{V}}{I_C\ \text{mA}} \tag{2}$$

$$\frac{1}{g_m} = \frac{V_T}{I_C} = \frac{0.025\ \text{V}}{I_C\ \text{mA}} \tag{3}$$

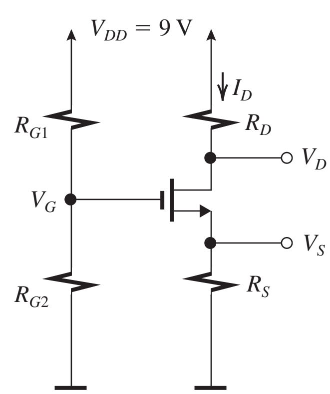
I_C **(mA)**	$1/g_m$ **(kΩ)**	r_o **(kΩ)**	$\lvert G_v \rvert$ **(V/V)**
0.1	0.250	250	27.5
0.2	0.125	125	41.2
0.5	0.050	50	55.6
1.0	0.025	25	57.1
1.25	0.020	20	55.6

Observe that initially $|G_v|$ increases as I_C is increased. However, above about 1 mA this trend reverses because of the effect of r_o. From the table we see that gain of 50 is obtained for I_C between 0.2 and 0.5 mA and also for I_C above 1.25 mA. Practically speaking, one normally uses the low value to minimize power dissipation. The required value of I_C is found by substituting for r_o and $1/g_m$ from Eqs. (2) and (3), respectively, in Eq. (1) and equating G_v to 50. The result (after some manipulations) is the quadratic equation.

$I_C^2 - 2.25 I_C + 0.625 = 0$

The two roots of this equation are $I_C = 0.325$ mA and 1.925 mA; our preferred choice is $I_C = 0.325$ mA.

7.92



$I_D = 1$ mA

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

$1 = \frac{1}{2} \times 2 \times V_{OV}^2$

$\Rightarrow V_{OV} = 1$ V

$V_{GS} = V_t + V_{OV} = 1 + 1 = 2$ V

Now, selecting $V_S = \frac{V_{DD}}{3} = 3$ V

$I_D R_S = 3$

$R_S = \frac{3}{1} = 3$ kΩ

Also,

$I_D R_D = \frac{V_{DD}}{3} = 3$ V

$\Rightarrow R_D = \frac{3}{1} = 3$ kΩ

$V_G = V_S + V_{GS}$

$= 3 + 2 = 5$ V

Thus the voltage drop across R_{G2}(5 V) is larger than that across R_{G1}(4 V). So we select

$R_{G2} = 22$ MΩ

and determine R_{G1} from

$\frac{R_{G1}}{R_{G2}} = \frac{4\text{ V}}{5\text{ V}}$

$\Rightarrow R_{G1} = 0.8 R_{G2} = 0.8 \times 22$

$= 17.6$ MΩ

Using only two significant figures, we have

$R_{G1} = 18$ MΩ

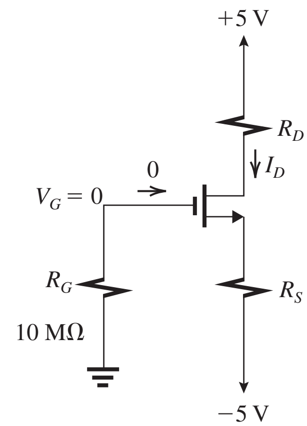
Note that this will cause V_G to deviate slightly from the required value of 5 V. Specifically,

$V_G = V_{DD} \frac{R_{G2}}{R_{G2} + R_{G1}}$

$= 9 \times \frac{22}{22 + 18} = 4.95$ V

It can be shown (after simple but somewhat tedious analysis) that the resulting I_D will be $I_D = 0.986$ mA, which is sufficiently close to the desired 1 mA. Since $V_D = V_{DD} - I_D R_D \simeq +6$ V and $V_G \simeq 5$ V, and the drain voltage can go down to $V_G - V_t = 4$ V, the drain voltage is 2 V above the value that causes the MOSFET to leave the saturation region.

7.93



For $I_D = 0.5$ mA

$0.5 = \frac{1}{2} k_n V_{OV}^2$

$= \frac{1}{2} \times 1 \times V_{OV}^2$

$\Rightarrow V_{OV} = 1$ V

$V_{GS} = V_t + V_{OV} = 1 + 1 = 2$ V

Since

$V_G = 0$ V, $\quad V_S = -V_{GS} = -2$ V

which leads to

$R_S = \frac{V_S - (-5)}{I_C} = \frac{-2 + 5}{0.5} = 6$ kΩ

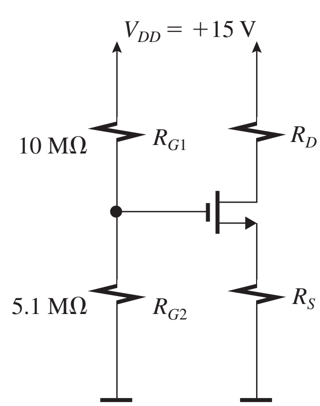
V_D is required to be halfway between cutoff (+5 V) and saturation ($0 - V_t = -1$ V). Thus

$V_D = +2$ V

and

$R_D = \frac{5 - 2}{0.5} = 6$ kΩ

7.94



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

$= 10 - 10 I_D$

(a) $V_t = 1$ V and $k_n = 0.5$ mA/V^2

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

$$I_D = \frac{1}{2} \times 0.5(10 - 10\, I_D - 1)^2$$

$$\Rightarrow I_D^2 - 1.84 I_D + 0.81 = 0$$

$I_D = 1.11$ mA or 0.73 mA

The first root results in $V_D = -0.11$ V, which is physically meaningless. Thus

$I_D = 0.73$ mA

$V_G = V_D = 10 - 10 \times 0.73 = 2.7$ V

(b) $V_t = 2$ V and $k_n = 1.25$ mA/V^2

$$I_D = \frac{1}{2} \times 1.25(10 - 10 I_D - 2)^2$$

$$\Rightarrow I_D^2 - 1.616 I_D + 0.64 = 0$$

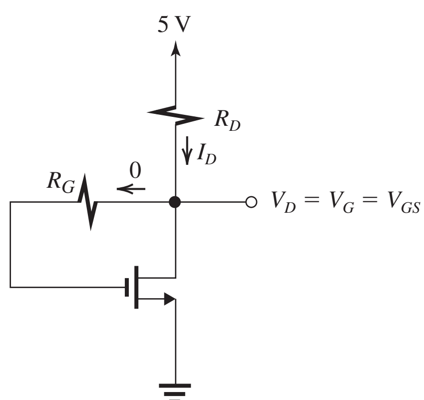
$I_D = 0.92$ mA or 0.695 mA

The first root can be shown to be physically meaningless, thus

$I_D = 0.695$ mA

$V_G = V_D = 10 - 10 \times 0.695 = 3.05$ V

7.102

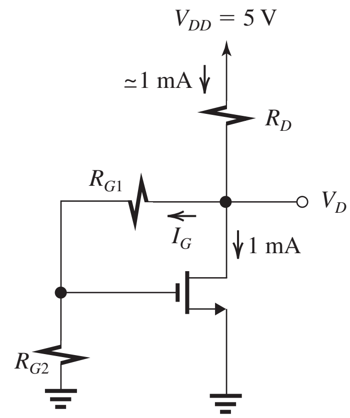


$$I_D = 0.2 = \frac{1}{2} \times 10(V_{GS} - V_t)^2$$

$$\Rightarrow V_{GS} = 1.2 \text{ V}$$

$$R_D = \frac{5 - 1.2}{0.2} = 19 \text{ k}\Omega$$

7.103



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

$$1 = \frac{1}{2} \times 8 V_{OV}^2$$

$$\Rightarrow V_{OV} = 0.5 \text{ V}$$

Since the transistor leaves the saturation region of operation when $v_D < V_{OV}$, we select

$V_D = V_{OV} + 2$

$V_D = 2.5$ V

Since $I_G \ll I_D$, we can write

$$R_D = \frac{V_{DD} - V_D}{I_D} = \frac{5 - 2.5}{1} = 2.5 \text{ k}\Omega$$

$V_{GS} = V_t + V_{OV} = 0.8 + 0.5 = 1.3$ V

Thus the voltage drop across R_{G2} is 1.3 V and that across R_{G1} is $(2.5 - 1.3) = 1.2$ V. Thus R_{G2} is the larger of the two resistances, and we select $R_{G2} = 22$ MΩ and find R_{G1} from

$$\frac{R_{G1}}{R_{G2}} = \frac{1.2}{1.3} \Rightarrow R_{G1} = 20.3 \text{ M}\Omega$$

Specifying all resistors to two significant digits, we have $R_D = 2.5$ kΩ, $R_{G1} = 22$ MΩ, and $R_{G1} = 20$ MΩ.

7.104 $\dfrac{R_{B1}}{R_{B1} + R_{B2}} \times 3 = 0.710$

$$\Rightarrow \frac{R_{B2}}{R_{B1}} = 3.225$$

Given that R_{B1} and R_{B2} are 1% resistors, the maximum and minimum values of the ratio R_{B2}/R_{B1} will be $3.225 \times 1.02 = 3.2895$ and $3.225 \times 0.98 = 3.1605$. The resulting V_{BE} will be 0.699 V and 0.721 V, respectively. Correspondingly, I_C will be

Thus,

$$R_1 = R_2 = R_E\left(\frac{V_{CC} - 2V_{BE}}{V_{CC}}\right)$$

For $V_{CC} = 10$ V and $V_{BE} = 0.7$ V,

$$R_1 = R_2 = R_E\left(\frac{10 - 1.4}{10}\right) = 0.86R_E$$

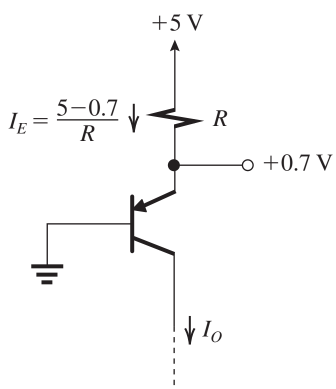
To obtain $I_O = 0.5$ mA,

$$0.5 = \frac{V_{CC}}{2R_E} = \frac{10}{2R_E}$$

$$\Rightarrow R_E = 10\ \text{k}\Omega$$

$$R_1 = R_2 = 8.6\ \text{k}\Omega$$

7.116



$$I_O = \alpha I_E \simeq 0.5\ \text{mA}$$

$$I_E = 0.5\ \text{mA}$$

$$\Rightarrow R = \frac{5 - 0.7}{0.5} = 8.6\ \text{k}\Omega$$

$$v_{C\max} = 0.7 - V_{EC\text{sat}} = 0.7 - 0.3$$

$$= +0.4\ \text{V}$$

7.117 Refer to the equivalent circuit in Fig. 7.55(b).

$$G_v = -\frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} g_m(R_D \parallel R_L \parallel r_o)$$

$$= -\frac{R_G}{R_G + R_{\text{sig}}} g_m(R_D \parallel R_L \parallel r_o)$$

$$= -\frac{10}{10 + 1} \times 3 \times (10 \parallel 20 \parallel 100)$$

$$= -17\ \text{V/V}$$

7.118 (a) Refer to Fig. P7.118. The dc circuit can be obtained by opening all coupling and bypass capacitors, resulting in the circuit shown in Fig. 1.

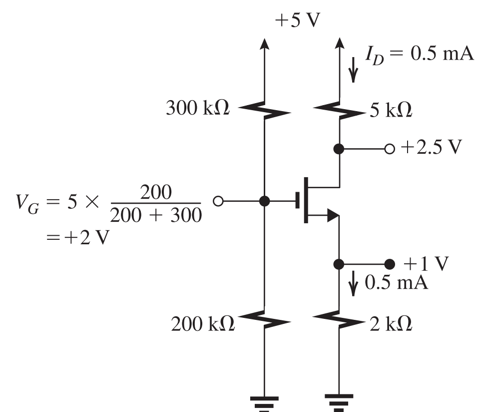


Figure 1

See analysis on figure.

$$V_{GS} = 2 - 1 = 1\ \text{V}$$

$$V_{OV} = V_{GS} - V_t = 1 - 0.7 = 0.3\ \text{V}$$

Since V_D at 2.5 V is 1.2 V higher than $V_S + V_{OV} = 1 + 0.3 = 1.3$ V, the transistor is

This figure belongs to Problem 7.118.

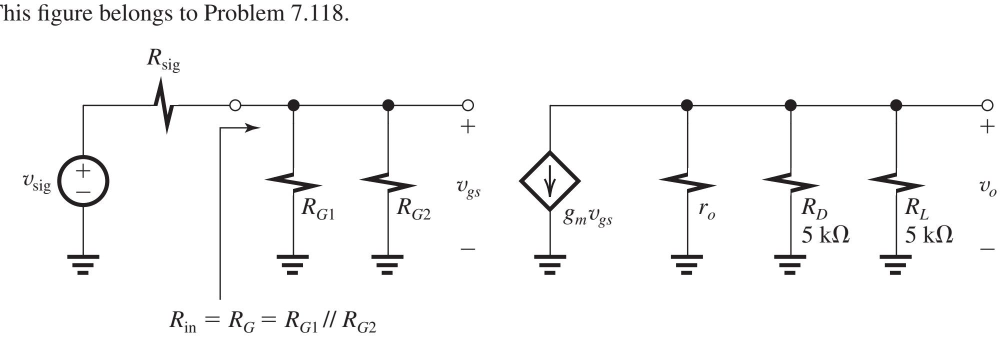


Figure 2

indeed operating in saturation. (Equivalent $V_D = 2.5$ V is higher than $V_G - V_t = 1.3$ V by 1.2 V.)

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

$$0.5 = \frac{1}{2}k_n \times 0.3^3$$

$$\Rightarrow k_n = 11.1 \text{ mA/V}^2$$

(b) The amplifier small-signal equivalent-circuit model is shown in Fig. 2.

$$R_{\text{in}} = R_{G1} \parallel R_{G2} = 300 \text{ k}\Omega \parallel 200 \text{ k}\Omega = 120 \text{ k}\Omega$$

$$g_m = \frac{2I_D}{V_{OV}} = \frac{2 \times 0.5}{0.3} = 3.33 \text{ mA/V}$$

$$r_o = \frac{V_A}{I_D} = \frac{50}{0.5} = 100 \text{ k}\Omega$$

$$G_v = -\frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} g_m (r_o \parallel R_D \parallel R_L)$$

$$= -\frac{120}{120 + 120} \times 3.33 \times (100 \parallel 5 \parallel 5)$$

$$= -4.1 \text{ V/V}$$

(c) $V_G = 2$ V, $\quad V_D = 2.5$ V

$$\hat{v}_{GS} = 2 + \hat{v}_{gs}, \quad \hat{v}_{DS} = 2.5 - |A_v|\hat{v}_{gs}$$

where

$$|A_v| = g_m (r_o \parallel R_D \parallel R_L) = 8.1 \text{ V/V}$$

To remain in saturation,

$$\hat{v}_{DS} \geq \hat{v}_{GS} - V_t$$

$$2.5 - 8.1\hat{v}_{gs} \geq 2 + \hat{v}_{gs} - 0.7$$

This is satisfied with equality at

$$\hat{v}_{gs} = \frac{2.5 - 1.3}{9.1} = 0.132 \text{ V}$$

The corresponding value of $\hat{v}_{\text{sig}}$ is

$$\hat{v}_{\text{sig}} = \hat{v}_{gs}\left(\frac{120 + 120}{120}\right) = 2 \times 0.132 = 0.264 \text{ V}$$

The corresponding amplitude at the output will be

$$|G_v|\hat{v}_{\text{sig}} = 4.1 \times 0.264 = 1.08 \text{ V}$$

(d) To be able to double $\hat{v}_{\text{sig}}$ without leaving saturation, we must reduce $\hat{v}_{gs}$ to half of what would be its new value; that is, we must keep $\hat{v}_{gs}$ unchanged. This in turn can be achieved by connecting an unbypassed R_s equal to $1/g_m$,

$$R_s = \frac{1}{3.33 \text{ mA/V}} = 300 \ \Omega$$

Since $\hat{v}_{gs}$ does not change, the output voltage also will not change, thus $\hat{v}_o = 1.08$ V.

7.119 Refer to Fig. P7.119.

(a) DC bias:

$$|V_{OV}| = 0.3 \text{ V} \Rightarrow \ V_{SG} = |V_{tp}| + |V_{OV}| = 1 \text{ V}$$

Since $V_G = 0$ V, $V_S = V_{SG} = +1$ V, and

$$I_D = \frac{2.5 - 1}{R_S} = 0.3 \text{ mA}$$

$$\Rightarrow R_S = \frac{1.5}{0.3} = 5 \text{ k}\Omega$$

(b) $G_v = -g_m R_D$

where

$$g_m = \frac{2I_D}{V_{OV}} = \frac{2 \times 0.3}{0.3} = 2 \text{ mA/V}$$

Thus,

$$-10 = -2R_D \Rightarrow R_D = 5 \text{ k}\Omega$$

(c) $v_G = 0$ V (dc) $+ v_{\text{sig}}$

$$v_{G\text{min}} = -\hat{v}_{\text{sig}}$$

$$\hat{v}_D = V_D + |G_v|\hat{v}_{\text{sig}}$$

where

$$V_D = -2.5 + I_D R_D = -2.5 + 0.3 \times 5 = -1 \text{ V}$$

To remain in saturation,

$$\hat{v}_D \leq \hat{v}_G + |V_{tp}|$$

$$-1 + 10\ \hat{v}_{\text{sig}} \leq -\hat{v}_{\text{sig}} + 0.7$$

Satisfying this constraint with equality gives

$$\hat{v}_{\text{sig}} = 0.154 \text{ V}$$

and the corresponding output voltage

$$\hat{v}_d = |G_v|\hat{v}_{\text{sig}} = 1.54 \text{ V}$$

(d) If $\hat{v}_{\text{sig}} = 50$ mV, then

$$V_D + |G_v|\hat{v}_{\text{sig}} = -\hat{v}_{\text{sig}} + |V_{tp}|$$

where

$$V_D = -2.5 + I_D R_D = -2.5 + 0.3R_D$$

and

$$|G_v| = g_m R_D = 2R_D$$

Thus

$$-2.5 + 0.3R_D + 2R_D\hat{v}_{\text{sig}} = -\hat{v}_{\text{sig}} + |V_{tp}|$$

$$-2.5 + 0.3R_D + 2R_D \times 0.05 = -0.05 + 0.7$$

$$0.4R_D = 3.15$$

$$\Rightarrow R_D = 7.875 \text{ k}\Omega$$

$$G_v = -g_m R_D = -2 \times 7.875 = -15.75 \text{ V/V}$$

7.120 Refer to Fig. P7.120.

$$R_{i2} = \frac{1}{g_{m2}} = 50\ \Omega$$

$$\Rightarrow g_{m2} = \frac{1}{50}\ \text{A/V} = 20\ \text{mA/V}$$

If Q_1 is biased at the same point as Q_2, then

$$g_{m1} = g_{m2} = 20\ \text{mA/V}$$

$$i_{d1} = g_{m1} \times 5\ (\text{mV})$$

$$= 20 \times 0.005 = 0.1\ \text{mA}$$

$$v_{d1} = i_{d1} \times 50\ \Omega$$

$$= 0.1 \times 50 = 5\ \text{mV}$$

$$v_o = i_{d1} R_D = 1\ \text{V}$$

$$R_D = \frac{1\ \text{V}}{0.1\ \text{mA}} = 10\ \text{k}\Omega$$

7.121 (a) DC bias: Refer to the circuit in Fig. P7.121 with all capacitors eliminated:

R_{in} at gate $= R_G = 10\ \text{M}\Omega$

$V_G = 0$, thus $V_S = -V_{GS}$, where V_{GS} can be obtained from

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

$$0.4 = \frac{1}{2} \times 5 \times V_{OV}^2$$

$$\Rightarrow V_{OV} = 0.4\ \text{V}$$

$$V_{GS} = V_t + 0.4 = 0.8 + 0.4 = 1.2\ \text{V}$$

$$V_S = -1.2\ \text{V}$$

$$R_S = \frac{-1.2 - (-5)}{0.4} = 9.5\ \text{k}\Omega$$

To remain in saturation, the minimum drain voltage must be limited to $V_G - V_t = 0 - 0.8 = -0.8$ V. Now, to allow for 0.8-V negative signal swing, we must have

$$V_D = 0\ \text{V}$$

and

$$R_D = \frac{5 - 0}{0.4} = 12.5\ \text{k}\Omega$$

(b) $g_m = \dfrac{2I_D}{V_{OV}} = \dfrac{2 \times 0.4}{0.4} = 2\ \text{mA/V}$

$$r_o = \frac{V_A}{I_D} = \frac{40}{0.4} = 100\ \text{k}\Omega$$

(c) If terminal Z is connected to ground, the circuit becomes a CS amplifier,

$$G_v = -\frac{v_y}{v_{\text{sig}}} = \frac{R_G}{R_G + R_{\text{sig}}} \times -g_m(r_o \parallel R_D \parallel R_L)$$

$$= -\frac{10}{10+1} \times 2 \times (100 \parallel 12.5 \parallel 10)$$

$$= -9.6\ \text{V/V}$$

(d) If terminal Y is grounded, the circuit becomes a CD or source-follower amplifier:

$$\frac{v_z}{v_x} = \frac{(R_S \parallel r_o)}{(R_S \parallel r_o) + \dfrac{1}{g_m}}$$

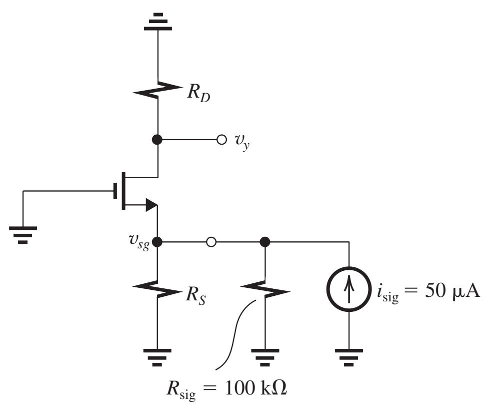
$$= \frac{(9.5 \parallel 100)}{(9.5 \parallel 100) + \dfrac{1}{2}} = 0.946\ \text{V/V}$$

Looking into terminal Z, we see R_o:

$$R_o = R_S \parallel r_o \parallel \frac{1}{g_m}$$

$$= 9.5 \parallel 100 \parallel \frac{1}{2} = 473\ \Omega$$

(e) If X is grounded, the circuit becomes a CG amplifier.



The figure shows the circuit prepared for signal calculations.

$$v_{sg} = i_{\text{sig}} \times \left[R_{\text{sig}} \parallel R_S \parallel \frac{1}{g_m} \right]$$

$$= 50 \times 10^{-3}(\text{mA}) \left[100 \parallel 9.5 \parallel \frac{1}{2} \right] (\text{k}\Omega)$$

$$= 0.024\ \text{V}$$

$$v_y = (g_m R_D) v_{sg}$$

$$= (2 \times 12.5) \times 0.024 = 0.6\ \text{V}$$

7.122 (a) Refer to the circuit of Fig. P7.122(a):

$$A_{vo} \equiv \frac{v_{o1}}{v_i} = \frac{10}{10 + \dfrac{1}{g_m}} = \frac{10}{10 + \dfrac{1}{10}} = 0.99\ \text{V/V}$$

$$R_o = \frac{1}{g_m} \parallel 10\ \text{k}\Omega = 0.1 \parallel 10 = 99\ \Omega$$