which is 10 times $W_1$, as needed to provide $I_{D2} = 10 I_{D1}$. Since $Q_2$ is to operate at the edge of saturation,

$V_{DS2} = V_{OV}$

Thus,

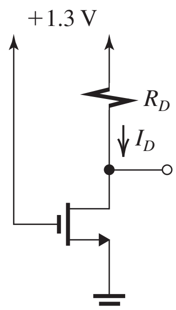
$V_{D2} = 0.25$ V

and

$$R_2 = \frac{V_{DD} - V_{D2}}{I_{D2}}$$

$$= \frac{1.8 - 0.25}{0.5} = 3.1 \text{ k}\Omega$$

**5.47**




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

$$= \frac{1}{2} \times 0.4 \times \frac{W}{L} (1.3 - 0.4)^2$$

$$= 0.162 \left(\frac{W}{L}\right)$$

$$V_D = 1.3 - I_D R_D = 1.3 - 0.162 \left(\frac{W}{L}\right) R_D$$

For the MOSFET to be at the edge of saturation, we must have

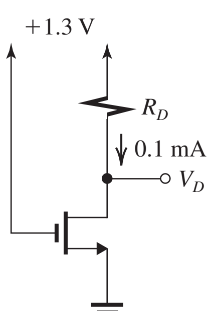
$V_D = V_{OV} = 1.3 - 0.4 = 0.9$

Thus

$$0.9 = 1.3 - 0.162 \left(\frac{W}{L}\right) R_D$$

$$\Rightarrow \left(\frac{W}{L}\right) R_D \simeq 2.5 \text{ k}\Omega \qquad \text{Q.E.D}$$

**5.48**




$V_{OV} = V_{GS} - V_t$

$= 1.3 - 0.4 = 0.9$

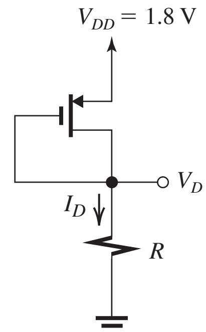
To operate at the edge of saturation, we must have

$V_D = V_{OV} = 0.9$ V

Thus,

$$R_D = \frac{1.3 - 0.9}{0.1} = 4 \text{ k}\Omega$$

**5.49**




$I_D = 180$ µA and $V_D = 1$ V

$$R = \frac{V_D}{I_D} = \frac{1}{0.18} = 5.6 \text{ k}\Omega$$

Transistor is operating in saturation with $|V_{OV}| = 1.8 - V_D - |V_t| = 1.8 - 1 - 0.5 = 0.3$ V:

$$I_D = \frac{1}{2} k_p' \frac{W}{L} |V_{OV}|^2$$

$$180 = \frac{1}{2} \times 100 \times \frac{W}{L} \times 0.3^2$$

$$\Rightarrow \frac{W}{L} = 40$$

$W = 40 \times 0.18 = 7.2$ µm

**5.50** Refer to Fig. P5.50. Both $Q_1$ and $Q_2$ are operating in saturation at $I_D = 0.5$ mA. For $Q_1$,

$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W_1}{L_1} V_{OV1}^2$$

$$0.5 = \frac{1}{2} \times 0.25 \times \frac{W_1}{L_1} (1 - 0.5)^2$$

$$\Rightarrow \frac{W_1}{L_1} = 16$$

$W_1 = 16 \times 0.25 = 4$ µm

For $Q_2$, we have

$$I_D = \frac{1}{2} \mu_n C_{ox} \left(\frac{W_2}{L_2}\right) V_{OV2}^2$$

$$0.5 = \frac{1}{2} \times 0.25 \times \frac{W_2}{L_2} (1.8 - 1 - 0.5)^2$$

$$\Rightarrow \frac{W_2}{L_2} = 44.4$$

$$W_2 = 44.4 \times 0.25 = 11.1$$

$$R = \frac{2.5 - 1.8}{0.5} = 1.4 \text{ k}\Omega$$

**5.51** Refer to the circuit in Fig. P5.51. All three transistors are operating in saturation with $I_D = 90\ \mu\text{A}$. For $Q_1$,

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W_1}{L_1}\ (V_{GS1} - V_t)^2$$

$$90 = \frac{1}{2} \times 90 \times \frac{W_1}{L_1}(0.8 - 0.5)^2$$

$$\Rightarrow \frac{W_1}{L_1} = 22.2$$

$$W_1 = 22.2 \times 0.5 = 11.1\ \mu\text{m}$$

For $Q_2$,

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W_2}{L_2}\ (V_{GS2} - V_t)^2$$

$$90 = \frac{1}{2} \times 90 \times \frac{W_2}{L_2}(1.5 - 0.8 - 0.5)^2$$

$$\Rightarrow \frac{W_2}{L_2} = 50$$

$$W_2 = 50 \times 0.5 = 25\ \mu\text{m}$$

For $Q_3$,

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W_3}{L_3}\ (V_{GS3} - V_t)^2$$

$$90 = \frac{1}{2} \times 90 \times \frac{W_3}{L_3}(2.5 - 1.5 - 0.5)^2$$

$$\Rightarrow \frac{W_3}{L_3} = 8$$

$$W_3 = 8 \times 0.5 = 4\ \mu\text{m}$$

**5.52** Refer to the circuits in Fig. 5.24 (page 282):

$$V_{GS} = 5 - 6I_D$$

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

$$= \frac{1}{2} \times 1.5 \times (5 - 6I_D - 1.5)^2$$

which results in the following quadratic equation in $I_D$:

$$36I_D^2 - 43.33I_D + 12.25 = 0$$

The physically meaningful root is

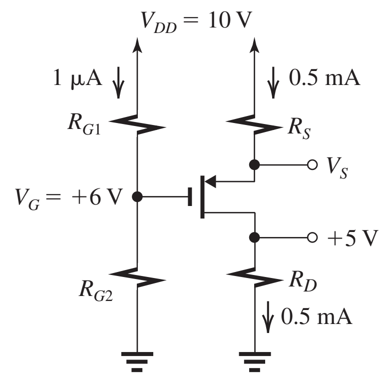
$$I_D = 0.45 \text{ mA}$$

This should be compared to the value of 0.5 mA found in Example 5.6. The difference of about 10% is relatively small, given the large variations in $k_n$ and $V_t$ (50% increase in each). The new value of $V_D$ is

$$V_D = V_{DD} - R_D I_D = 10 - 6 \times 0.45 = +7.3 \text{ V}$$

as compared to +7 V found in Example 5.6. We conclude that this circuit is quite tolerant to variations in device parameters.

**5.53**




Refer to the circuit in the figure above,

$$R_{G1} = \frac{V_{DD} - V_G}{1\ \mu\text{A}}$$

$$= \frac{10 - 6}{1} = 4 \text{ M}\Omega$$

$$R_{G2} = \frac{6}{1\ \mu\text{A}} = 6 \text{ M}\Omega$$

$$R_D = \frac{5 \text{ V}}{0.5 \text{ mA}} = 10 \text{ k}\Omega$$

To determine $V_S$, we use

$$I_D = \frac{1}{2}k_p'\left(\frac{W}{L}\right)(V_{SG} - |V_t|)^2$$

$$0.5 = \frac{1}{2} \times 4 \times (V_{SG} - 1.5)^2$$

$$\Rightarrow V_{SG} = 2 \text{ V}$$

Thus,

$$V_S = V_G + V_{SG} = 6 + 2 = 8 \text{ V}$$

$$R_S = \frac{10 - 8}{0.5} = 4 \text{ k}\Omega$$

**7.1** Coordinates of point A: $v_{GS} = V_t = 0.5$ V and $v_{DS} = V_{DD} = 5$ V.

To obtain the coordinates of point B, we first use Eq. (7.6) to determine $V_{GS}\big|_B$ as

$$V_{GS}\big|_B = V_t + \frac{\sqrt{2k_nR_DV_{DD}+1}-1}{k_nR_D}$$

$$= 0.5 + \frac{\sqrt{2\times 10\times 20\times 5+1}-1}{10\times 20}$$

$$= 0.5 + 0.22 = 0.72 \text{ V}$$

The vertical coordinate of point B is $V_{DS}\big|_B$,

$$V_{DS}\big|_B = V_{GS}\big|_B - V_t = V_{OV}\big|_B = 0.22 \text{ V}$$

**7.2** $V_{DS}\big|_B = V_{OV}\big|_B = 0.5$ V

Thus,

$$I_D\big|_B = \frac{1}{2}k_nV_{DS}^2\big|_B = \frac{1}{2}\times 5\times 0.5^2 = 0.625 \text{ mA}$$

The value of $R_D$ required can now be found as

$$R_D = \frac{V_{DD} - V_{DS}\big|_B}{I_D\big|_B}$$

$$= \frac{5-0.5}{0.625} = 7.2 \text{ k}\Omega$$

If the transistor is replaced with another having twice the value of $k_n$, then $I_D\big|_B$ will be twice as large and the required value of $R_D$ will be half that used before, that is, 3.6 kΩ.

**7.3** Bias point Q: $V_{OV} = 0.2$ V and $V_{DS} = 1$ V.

$$I_{DQ} = \frac{1}{2}k_nV_{OV}^2$$

$$= \frac{1}{2}\times 10\times 0.04 = 0.2 \text{ mA}$$

$$R_D = \frac{V_{DD}-V_{DS}}{I_{DQ}} = \frac{5-1}{0.2} = 20 \text{ k}\Omega$$

Coordinates of point B:

Equation (7.6):

$$V_{GS}\big|_B = V_t + \frac{\sqrt{2k_nR_DV_{DD}+1}-1}{k_nR_D}$$

$$= 0.5 + \frac{\sqrt{2\times 10\times 20\times 5+1}-1}{10\times 20}$$

$$= 0.5 + 0.22 = 0.72 \text{ V}$$

Equations (7.7) and (7.8):

$$V_{DS}\big|_B = \frac{\sqrt{2k_nR_DV_{DD}+1}-1}{k_nR_D} = 0.22 \text{ V}$$

$$A_v = -k_nR_DV_{OV}$$

$$= -10\times 20\times 0.2 = -40 \text{ V/V}$$

The lowest instantaneous voltage allowed at the output is $V_{DS}\big|_B = 0.22$ V. Thus the maximum allowable negative signal swing at the output is $V_{DSQ} - 0.22 = 1 - 0.22 = 0.78$ V. The corresponding peak input signal is

$$\hat{v}_{gs} = \frac{0.78 \text{ V}}{|A_v|} = \frac{0.78}{40} = 19.5 \text{ mV}$$

**7.4** From Eq. (7.18):

$$|A_{v\,\max}| = \frac{V_{DD} - V_{OV}\big|_B}{V_{OV}\big|_B/2}$$

$$14 = \frac{2 - V_{OV}\big|_B}{V_{OV}\big|_B/2}$$

$$\Rightarrow V_{OV}\big|_B = 0.25 \text{ V}$$

Now, using Eq. (7.15) at point B, we have

$$A_v\big|_B = -k_nV_{OV}\big|_BR_D$$

Thus,

$$-14 = -k_nR_D\times 0.25$$

$$\Rightarrow k_nR_D = 56$$

To obtain a gain of −12 V/V at point Q:

$$-12 = -k_nR_DV_{OV}\big|_Q$$

$$= -56V_{OV}\big|_Q$$

Thus,

$$V_{OV}\big|_Q = \frac{12}{56} = 0.214 \text{ V}$$

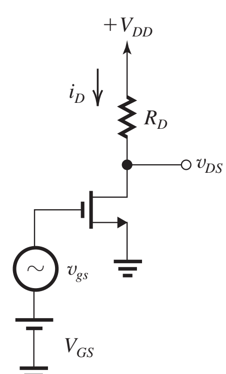
To obtain the required $V_{DS}\big|_Q$, we use Eq. (7.17),

$$A_v = -\frac{V_{DD} - V_{DS}\big|_Q}{V_{OV}\big|_Q/2}$$

$$-12 = -\frac{2 - V_{DS}\big|_Q}{0.214/2}$$

$$\Rightarrow V_{DS}\big|_Q = 0.714 \text{ V}$$

**7.5**



$V_{DD} = 5\text{ V}, \quad k_n' \frac{W}{L} = 1 \frac{\text{mA}}{\text{V}^2}$

$R_D = 24\text{ k}\Omega, \quad V_t = 1\text{ V}$

(a) Endpoints of saturation transfer segment:

Point A occurs at $V_{GS} = V_t = 1\text{ V}, i_D = 0$

Point A $= (1\text{ V}, 5\text{ V})\ (V_{GS}, V_{DS})$

Point B occurs at sat/triode boundary $(V_{GD} = V_t)$

$V_{GD} = 1\text{ V} \Rightarrow V_{GS} - [5 - i_D R_D] = 1$

$$V_{GS} - 5 + \left(\frac{1}{2}\right)(1)(24)\,[V_{GS} - 1]^2 - 1 = 0$$

$12V_{GS}^2 - 23V_{GS} + 6 = 0$

$V_{GS} = 1.605\text{ V}$

$i_D = 0.183\text{ mA} \quad V_{DS} = 0.608\text{ V}$

Point B $= (+1.61\text{ V}, 0.61\text{ V})$

(b) For $V_{OV} = V_{GS} - V_t = 0.5\text{ V}$, we have

$V_{GS} = 1.5\text{ V}$

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

$$= \frac{1}{2} \times 1(1.5 - 1)^2$$

$I_D = 0.125\text{ mA} \quad V_{DS} = +2.00\text{ V}$

Point Q $= (1.50\text{ V}, 2.00\text{ V})$

$A_v = -k_n V_{OV} R_D = -12\text{ V/V}$

(c) From part (a) above, the maximum instantaneous input signal while the transistor remains in saturation is 1.61 V and the corresponding output voltage is 0.61 V. Thus, the maximum amplitude of input sine wave is $(1.61 - 1.5) = 0.11$ V. That is, $v_{GS}$ ranges from $1.5 - 0.11 = 1.39$ V, at which

$$i_D = \frac{1}{2} \times 1 \times (1.39 - 1)^2 = 0.076\text{ mA}$$

and

$v_{DS} = 5 - 0.076 \times 24 = 3.175\text{ V}$

and $v_{GS} = 1.5 + 0.11 = 1.61$ V at which $v_{DS} = 0.61$ V.

Thus, the large-signal gain is

$$\frac{0.61 - 3.175}{1.61 - 1.39} = -11.7\text{ V/V}$$

whose magnitude is slightly less (−2.5%) than the incremental or small-signal gain (−12 V/V). This is an indication that the transfer characteristic is not a straight line.

**7.6** $R_D = 20\text{ k}\Omega$

$k_n' = 200\ \mu\text{A/V}^2$

$V_{RD} = 1.5\text{ V}$

$V_{GS} = 0.7\text{ V}$

$A_v = -10\text{ V/V}$

$A_v = -k_n V_{OV} R_D$

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

$$\frac{A_v}{V_{RD}} = \frac{-2}{V_{OV}} = \frac{-10}{1.5}$$

$\therefore V_{OV} = 0.30\text{ V}$

$V_t = V_{GS} - V_{OV} = 0.40\text{ V}$

$$k_n = \frac{A_v}{V_{OV} R_D} = \frac{-10}{-0.3 \times 20}$$

$= 1.67\text{ mA/V}^2$

$$k_n = k_n' \frac{W}{L} = 1.67\text{ mA/V}^2$$

$$\therefore \frac{W}{L} = 8.33$$

**7.7** At sat/triode boundary

$v_{GS}\big|_B = V_{GS} + \hat{v}_{gs}$

$v_{DS}\big|_B = V_{DS} - \hat{v}_o$

$(\hat{v}_o = \text{ max downward amplitude})$, we get

$$v_{DS}\big|_B = v_{GS}\big|_B - V_t = V_{GS} + \frac{\hat{v}_o}{|A_v|} - V_t$$

$= V_{DS} - \hat{v}_o$

$$V_{OV} + \frac{\hat{v}_o}{|A_v|} = V_{DS} - \hat{v}_o$$

$$\hat{v}_o = \frac{V_{DS} - V_{OV}}{1 + \frac{1}{|A_v|}} \qquad (1)$$

For $V_{DD} = 5\text{ V}, V_{OV} = 0.5\text{ V}$, and

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

$$A_v = \frac{-2(V_{DD} - V_{DS})}{V_{OV}}$$

and Eq. (1) to obtain

| $V_{DS}$ | $A_v$ | $\hat{v}_o$ | $\hat{v}_i$ |
|---|---|---|---|
| 1 V | −16 | 471 mV | 29.4 mV |
| 1.5 V | −14 | 933 mV | 66.7 mV |
| 2 V | −12 | 1385 mV | 115 mV |
| 2.5 V | −10 | 1818 mV | 182 mV |