Ex: 7.1 Refer to Fig. 7.2(a) and 7.2(b).

Coordinates of point A: V_t and V_{DD}; thus 0.4 V and 1.8 V. To determine the coordinates of point B, we use Eqs. (7.7) and (7.8) as follows:

$$V_{OV}\big|_B = \frac{\sqrt{2k_n R_D V_{DD} + 1} - 1}{k_n R_D}$$

$$= \frac{\sqrt{2 \times 4 \times 17.5 \times 1.8 + 1} - 1}{4 \times 17.5}$$

$$= 0.213 \text{ V}$$

Thus,

$$V_{GS}\big|_B = V_t + V_{OV}\big|_B = 0.4 + 0.213 = 0.613 \text{ V}$$

and

$$V_{DS}\big|_B = V_{OV}\big|_B = 0.213 \text{ V}$$

Thus, coordinates of B are 0.613 V and 0.213 V. At point C, the MOSFET is operating in the triode region, thus

$$i_D = k_n\left[(v_{GS}\big|_C - V_t)v_{DS}\big|_C - \frac{1}{2}v_{DS}^2\big|_C\right]$$

If $v_{DS}\big|_C$ is very small,

$$i_D \simeq k_n(v_{GS}\big|_C - V_t)v_{DS}\big|_C$$

$$= 4(1.8 - 0.4)v_{DS}\big|_C$$

$$= 5.6v_{DS}\big|_C, \text{ mA}$$

But

$$i_D = \frac{V_{DD} - v_{DS}\big|_C}{R_D} \simeq \frac{V_{DD}}{R_D} = \frac{1.8}{17.5} = 0.1 \text{ mA}$$

Thus, $v_{DS}\big|_C = \dfrac{0.1}{5.6} = 0.018 \text{ V} = 18 \text{ mV}$, which is indeed very small, as assumed.

Ex: 7.2 Refer to Example 7.1 and Fig. 7.4(a).

Design 1:

$$V_{OV} = 0.2 \text{ V}, \; V_{GS} = 0.6 \text{ V}$$

$$I_D = 0.8 \text{ mA}$$

Now,

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

Thus,

$$-10 = -0.4 \times 10 \times 0.2 \times R_D$$

$$\Rightarrow R_D = 12.5 \text{ k}\Omega$$

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

$$= 1.8 - 12.5 \times 0.08 = 0.8 \text{ V}$$

Design 2:

$$R_D = 17.5 \text{ k}\Omega$$

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

$$-10 = -0.4 \times 10 \times V_{OV} \times 17.5$$

Thus,

$$V_{OV} = 0.14 \text{ V}$$

$$V_{GS} = V_t + V_{OV} = 0.4 + 0.14 = 0.54 \text{ V}$$

$$I_D = \frac{1}{2}k_n'\left(\frac{W}{L}\right)V_{OV}^2$$

$$= \frac{1}{2} \times 0.4 \times 10 \times 0.14^2 = 0.04 \text{ mA}$$

$$R_D = 17.5 \text{ k}\Omega$$

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

$$= 1.8 - 17.5 \times 0.04 = 1.1 \text{ V}$$

Ex: 7.3

$$A_v = -\frac{I_C R_C}{V_T}$$

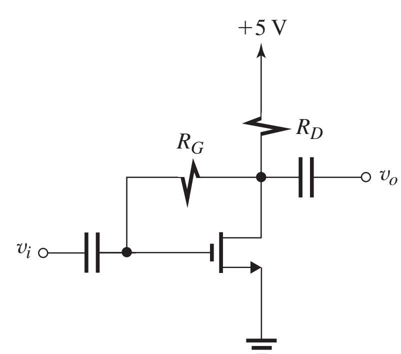
$$-320 = -\frac{1 \times R_C}{0.025} \Rightarrow R_C = 8 \text{ k}\Omega$$

$$V_C = V_{CC} - I_C R_C$$

$$= 10 - 1 \times 8 = 2 \text{ V}$$

Since the collector voltage is allowed to decrease to +0.3 V, the largest negative swing allowed at the output is 2 − 0.3 = 1.7 V. The corresponding input signal amplitude can be found by dividing 1.7 V by the gain magnitude (320 V/V), resulting in 5.3 mV.

Ex: 7.4



Refer to the solution of Example 7.3. From Eq. (7.47), $A_v \equiv \dfrac{v_o}{v_i} = -g_m R_D$ (note that R_L is absent).

Thus,

$$g_m R_D = 25$$

Substituting for $g_m = k_n V_{OV}$, we have

$$k_n V_{OV} R_D = 25$$

where $k_n = 1\ \text{mA/V}^2$, thus

$$V_{OV}R_D = 25 \quad (1)$$

Next, consider the bias equation

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

Thus,

$$V_t + V_{OV} = V_{DD} - R_D I_D$$

Substituting $V_t = 0.7$ V, $V_{DD} = 5$ V, and

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

we obtain

$$0.7 + V_{OV} = 5 - \frac{1}{2}V_{OV}^2 R_D \quad (2)$$

Equations (1) and (2) can be solved to obtain

$$V_{OV} = 0.319\ \text{V}$$

and

$$R_D = 78.5\ \text{k}\Omega$$

The dc current I_D can be now found as

$$I_D = \frac{1}{2}k_n V_{OV}^2 = 50.9\ \mu\text{A}$$

To determine the required value of R_G we use Eq. (7.48), again noting that R_L is absent:

$$R_{\text{in}} = \frac{R_G}{1 + g_m R_D}$$

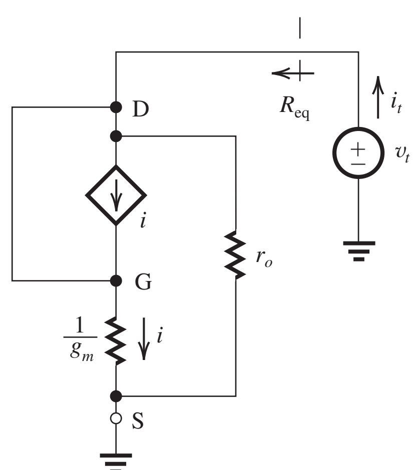
$$0.5\ \text{M}\Omega = \frac{R_G}{1 + 25}$$

$$\Rightarrow R_G = 13\ \text{M}\Omega$$

Finally, the maximum allowable input signal $\hat{v}_i$ can be found as follows:

$$\hat{v}_i = \frac{V_t}{|A_v| + 1} = \frac{0.7\ \text{V}}{25 + 1} = 27\ \text{mV}$$

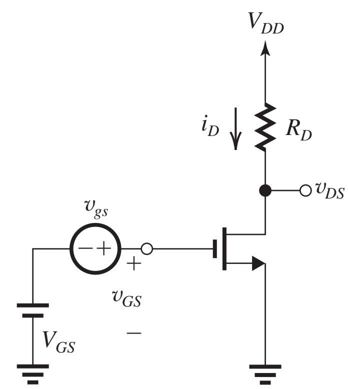
Ex: 7.5



$$i_t = \frac{v_t}{r_o} + i = \frac{v_t}{r_o} + g_m v_t$$

$$\therefore R_{\text{eq}} = \frac{v_t}{i_t} = r_o \| \frac{1}{g_m}$$

Ex: 7.6



$$V_{DD} = 5\ \text{V}$$

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

$$V_t = 1\ \text{V}$$

$$\lambda = 0$$

$$k_n' = 20\ \mu\text{A/V}^2$$

$$R_D = 10\ \text{k}\Omega$$

$$\frac{W}{L} = 20$$

(a) $V_{GS} = 2\ \text{V} \Rightarrow V_{OV} = 1\ \text{V}$

$$I_D = \frac{1}{2}k_n' \frac{W}{L} V_{OV}^2 = 200\ \mu\text{A}$$

$$V_{DS} = V_{DD} - I_D R_D = +3\ \text{V}$$

(b) $g_m = k_n' \frac{W}{L} V_{OV} = 400\ \mu\text{A/V} = 0.4\ \text{mA/V}$

(c) $A_v = \frac{v_{ds}}{v_{gs}} = -g_m R_D = -4\ \text{V/V}$

(d) $v_{gs} = 0.2 \sin\omega t$ V

$$v_{ds} = -0.8 \sin\omega t\ \text{V}$$

$$v_{DS} = V_{DS} + v_{ds} \Rightarrow 2.2\ \text{V} \le v_{DS} \le 3.8\ \text{V}$$

(e) Using Eq. (7.28), we obtain

$$i_D = \frac{1}{2}k_n(V_{GS} - V_t)^2 + k_n(V_{GS} - V_t)v_{gs} + \frac{1}{2}k_n v_{gs}^2$$

$$i_D = 200 + 80 \sin\omega t + 8 \sin^2\omega t,\ \mu\text{A}$$

$= [200 + 80\sin\omega t + (4 - 4\ \cos 2\omega t)]$

$= 204 + 80\sin\omega t - 4\cos 2\omega t, \mu A$

I_D shifts by 4 μA.

Thus,

$$2HD = \frac{\hat{i}_{2\omega}}{\hat{i}_{\omega}} = \frac{4\ \mu A}{80\ \mu A} = 0.05\ (5\%)$$

Ex: 7.7

(a) $g_m = \dfrac{2I_D}{V_{OV}}$

$$I_D = \frac{1}{2}k_n'\frac{W}{L}V_{OV}^2 = \frac{1}{2} \times 60 \times 40 \times (1.5 - 1)^2$$

$I_D = 300\ \mu A = 0.3$ mA, $V_{OV} = 0.5$ V

$$g_m = \frac{2 \times 0.3}{0.5} = 1.2\ \text{mA/V}$$

$$r_o = \frac{V_A}{I_D} = \frac{15}{0.3} = 50\ k\Omega$$

(b) $I_D = 0.5$ mA $\Rightarrow g_m = \sqrt{2\ \mu_n C_{ox}\dfrac{W}{L}I_D}$

$$= \sqrt{2 \times 60 \times 40 \times 0.5 \times 10^3}$$

$g_m = 1.55$ mA/V

$$r_o = \frac{V_A}{I_D} = \frac{15}{0.5} = 30\ k\Omega$$

Ex: 7.8

$I_D = 0.1$ mA, $g_m = 1$ mA/V, $k_n' = 50\ \mu A/V^2$

$$g_m = \frac{2I_D}{V_{OV}} \Rightarrow V_{OV} = \frac{2 \times 0.1}{1} = 0.2\ V$$

$$I_D = \frac{1}{2}k_n'\frac{W}{L}V_{OV}^2 \Rightarrow \frac{W}{L} = \frac{2I_D}{k_n' V_{OV}^2}$$

$$= \frac{2 \times 0.1}{\dfrac{50}{1000} \times 0.2^2} = 100$$

Ex: 7.9

$$g_m = \mu_n C_{ox}\frac{W}{L}V_{OV}$$

Same bias conditions, so same V_{OV} and also same L and g_m for both PMOS and NMOS.

$$\mu_n C_{ox} W_n = \mu_p C_{ox} W_p \Rightarrow \frac{\mu_p}{\mu_n} = 0.4 = \frac{W_n}{W_p}$$

$$\Rightarrow \frac{W_p}{W_n} = 2.5$$

Ex: 7.10

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

$$= \frac{1}{2} \times 60 \times \frac{16}{0.8} \times\ (1.6 - 1)^2$$

$I_D = 216\ \mu A$

$$g_m = \frac{2I_D}{|V_{OV}|} = \frac{2 \times 216}{1.6 - 1} = 720\ \mu A/V$$

$= 0.72$ mA/V

$$\lambda = 0.04 \Rightarrow V_A' = \frac{1}{\lambda} = \frac{1}{0.04} = 25\ V/\mu m$$

$$r_o = \frac{V_A' \times L}{I_D} = \frac{25 \times 0.8}{0.216} = 92.6\ k\Omega$$

Ex: 7.11

$$g_m r_o = \frac{2I_D}{V_{OV}} \times \frac{V_A}{I_D} = \frac{2V_A}{V_{OV}}$$

$V_A' \times L = V_A$

$$L = 0.8\ \mu m \Rightarrow g_m r_o = \frac{2 \times 12.5 \times 0.8}{0.2}$$

$= 100$ V/V

Ex: 7.12

Given: $g_m = \left.\dfrac{\partial i_C}{\partial v_{BE}}\right|_{i_C = I_C}$

where $I_C = I_S e^{V_{BE}/V_T}$

$$\frac{\partial i_C}{\partial v_{BE}} = \frac{I_S e^{V_{BE}/V_T}}{V_T} = \frac{I_C}{V_T}$$

Thus,

$$g_m = \frac{I_C}{V_T}$$

Ex: 7.13

$$g_m = \frac{I_C}{V_T} = \frac{0.5\ \text{mA}}{25\ \text{mV}} = 20\ \text{mA/V}$$

Ex: 7.14

$I_C = 0.5$ mA (constant)

$\beta = 50 \qquad \beta = 200$

$$g_m = \frac{I_C}{V_T} = \frac{0.5\ \text{mA}}{25\ \text{mV}}$$

$= 20$ mA/V $\qquad = 20$ mA/V

$$I_B = \frac{I_C}{\beta} = \frac{0.5}{50} = \frac{0.5}{200}$$

$= 10\ \mu A \qquad = 2.5\ \mu A$

$$r_\pi = \frac{\beta}{g_m} = \frac{50}{20} = \frac{200}{20}$$

$= 2.5\ k\Omega \qquad = 10\ k\Omega$

Ex: 7.15

$\beta = 100 \quad I_C = 1\text{ mA}$

$g_m = \dfrac{1\text{ mA}}{25\text{ mV}} = 40\text{ mA/V}$

$r_e = \dfrac{V_T}{I_E} = \dfrac{\alpha V_T}{I_C} \simeq \dfrac{25\text{ mV}}{1\text{ mA}} = 25\ \Omega$

$r_\pi = \dfrac{\beta}{g_m} = \dfrac{100}{40} = 2.5\text{ k}\Omega$

Ex: 7.16

$g_m = \dfrac{I_C}{V_T} = \dfrac{1\text{ mA}}{25\text{ mV}} = 40\text{ mA/V}$

$A_v = \dfrac{v_{ce}}{v_{be}} = -g_m R_C$

$= -40 \times 10$

$= -400\text{ V/V}$

$V_C = V_{CC} - I_C R_C$

$= 15 - 1 \times 10 = 5\text{ V}$

$v_C(t) = V_C + v_c(t)$

$= (V_{CC} - I_C R_C) + A_v v_{be}(t)$

$= (15 - 10) - 400 \times 0.005 \sin\omega t$

$= 5 - 2 \sin\omega t$

$i_B(t) = I_B + i_b(t)$

where

$I_B = \dfrac{I_C}{\beta} = \dfrac{1\text{ mA}}{100} = 10\ \mu\text{A}$

and $i_b(t) = \dfrac{g_m v_{be}(t)}{\beta}$

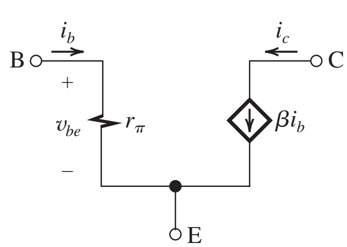
$= \dfrac{40 \times 0.005 \sin\omega t}{100}$

$= 2 \sin\omega t,\ \mu\text{A}$

Thus,

$i_B(t) = 10 + 2 \sin\omega t,\ \mu\text{A}$

Ex: 7.17



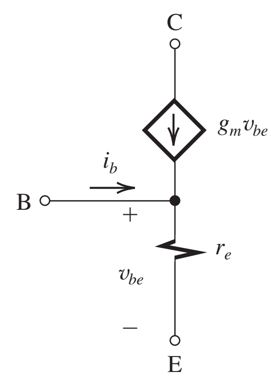
$i_c = \beta i_b = \beta \dfrac{v_{be}}{r_\pi}$

$= \left(\dfrac{\beta}{r_\pi}\right) v_{be} = g_m v_{be}$

$i_e = i_b + \beta i_b = (\beta + 1) i_b = (\beta + 1) \dfrac{v_{be}}{r_\pi}$

$= \dfrac{v_{be}}{r_\pi(\beta + 1)} = \dfrac{v_{be}}{r_e}$

Ex: 7.18



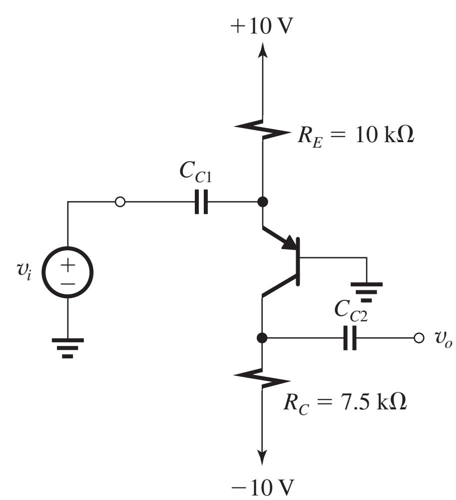
$i_b = \dfrac{v_{be}}{r_e} - g_m v_{be}$

$= v_{be}\left(\dfrac{1}{r_e} - g_m\right)$

$= v_{be}\left(\dfrac{1}{r_{\pi/\beta+1}} - \dfrac{\beta}{r_\pi}\right)$

$= v_{be}\left(\dfrac{\beta + 1}{r_\pi} - \dfrac{\beta}{r_\pi}\right) = \dfrac{v_{be}}{r_\pi}$

Ex: 7.19



$$I_E = \frac{10 - 0.7}{10} = 0.93 \text{ mA}$$

$$I_C = \alpha I_E = 0.99 \times 0.93$$

$$= 0.92 \text{ mA}$$

$$V_C = -10 + I_C R_C$$

$$= -10 + 0.92 \times 7.5 = -3.1 \text{ V}$$

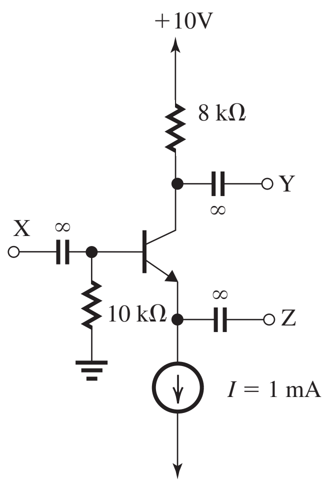
$$A_v = \frac{v_o}{v_i} = \frac{\alpha R_C}{r_e}$$

where $r_e = \dfrac{25 \text{ mV}}{0.93 \text{ mA}} = 26.9\ \Omega$

$$A_v = \frac{0.99 \times 7.5 \times 10^3}{26.9} = 276.2 \text{ V/V}$$

For $\hat{v}_i = 10$ mV, $\hat{v}_o = 276.2 \times 10 = 2.76$ V

Ex: 7.20



$$I_E = 1 \text{ mA}$$

$$I_C = \frac{100}{101} \times 1 = 0.99 \text{ mA}$$

$$I_B = \frac{1}{101} \times 1 = 0.0099 \text{ mA}$$

(a) $V_C = 10 - 8 \times 0.99 = 2.08 \simeq 2.1$ V

$$V_B = -10 \times 0.0099 = -0.099 \simeq -0.1 \text{ V}$$

$$V_E = -0.1 - 0.7 = -0.8 \text{ V}$$

(b) $g_m = \dfrac{I_C}{V_T} = \dfrac{0.99}{0.025} \simeq 40$ mA/V

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{40} \simeq 2.5 \text{ k}\Omega$$

$$r_o = \frac{V_A}{I_C} = \frac{100}{0.99} = 101 \simeq 100 \text{ k}\Omega$$

(c) $R_{\text{sig}} = 2$ kΩ $\quad R_B = 10$ kΩ $\quad r_\pi = 2.5$ kΩ

$$g_m = 40 \text{ mA/V}$$

$R_C = 8$ kΩ $\quad R_L = 8$ kΩ $\quad r_o = 100$ kΩ

$$\frac{V_y}{V_{\text{sig}}} = \frac{V_\pi}{V_{\text{sig}}} \times \frac{V_y}{V_\pi}$$

$$= \frac{R_B \| r_\pi}{(R_B \| r_\pi) + R_{\text{sig}}} \times -g_m (R_C \| R_L \| r_o)$$

$$= \frac{10 \| 2.5}{(10 \| 2.5) + 2} \times -40(8 \| 8 \| 100)$$

$$-0.5 \times 40 \times 3.846 = -77 \text{ V/V}$$

If r_o is negelected, $\dfrac{V_y}{V_{\text{sig}}} = -80$, for an error of 3.9%.

Ex: 7.21

$$g_m = \frac{2I_D}{V_{OV}} = \frac{2 \times 0.25}{0.25} = 2 \text{ mA/V}$$

$$R_{\text{in}} = \infty$$

$$A_{vo} = -g_m R_D = -2 \times 20 = -40 \text{ V/V}$$

$$R_o = R_D = 20 \text{ k}\Omega$$

$$A_v = A_{vo} \frac{R_L}{R_L + R_o} = -40 \times \frac{20}{20 + 20}$$

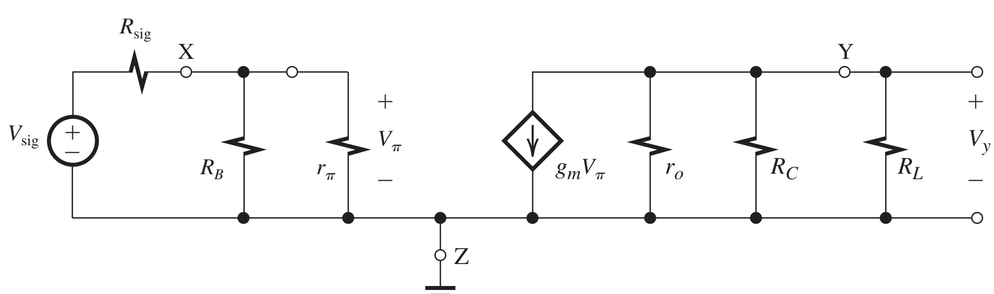
$$= -20 \text{ V/V}$$

$$G_v = A_v = -20 \text{ V/V}$$

$$\hat{v}_i = 0.1 \times 2V_{OV} = 0.2 \times 2 \times 0.25 = 0.05 \text{ V}$$

$$\hat{v}_o = 0.05 \times 20 = 1 \text{ V}$$

This figure belongs to Exercise 7.20c.



Ex: 7.22

$I_C = 0.5$ mA

$$g_m = \frac{I_C}{V_T} = \frac{0.5 \text{ mA}}{0.025 \text{ V}} = 20 \text{ mA/V}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{20} = 5 \text{ k}\Omega$$

$$R_{\text{in}} = r_\pi = 5 \text{ k}\Omega$$

$$A_{vo} = -g_m R_C = -20 \times 10 = -200 \text{ V/V}$$

$$R_o = R_C = 10 \text{ k}\Omega$$

$$A_v = A_{vo} \frac{R_L}{R_L + R_o} = -200 \times \frac{5}{5 + 10}$$

$$= -66.7 \text{ V/V}$$

$$G_v = \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} A_v = \frac{5}{5+5} \times -66.7$$

$$= -33.3 \text{ V/V}$$

$$\hat{v}_\pi = 5 \text{ mV} \Rightarrow \hat{v}_{\text{sig}} = 2 \times 5 = 10 \text{ mV}$$

$$\hat{v}_o = 10 \times 33.3 = 0.33 \text{ V}$$

Although a larger fraction of the input signal reaches the amplifier input, linearity considerations cause the output signal to be in fact smaller than in the original design!

Ex: 7.23 Refer to the solution to Exercise 7.21. If $\hat{v}_{\text{sig}} = 0.2$ V and we wish to keep $\hat{v}_{gs} = 50$ mV, then we need to connect a resistance $R_s = \dfrac{3}{g_m}$ in the source lead. Thus,

$$R_s = \frac{3}{2 \text{ mA/V}} = 1.5 \text{ k}\Omega$$

$$G_v = A_v = -\frac{R_D \| R_L}{\dfrac{1}{g_m} + R_s}$$

$$= -\frac{20 \| 20}{0.5 + 1.5} = -5 \text{ V/V}$$

$$\hat{v}_o = G_v \hat{v}_{\text{sig}} = 5 \times 0.2 = 1 \text{ V (unchanged)}$$

Ex: 7.24

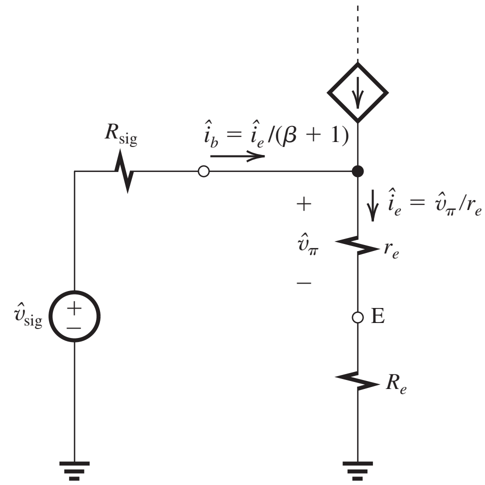
From the following figure we see that

$$\hat{v}_{\text{sig}} = \hat{i}_b R_{\text{sig}} + \hat{v}_\pi + \hat{i}_e R_e$$

$$= \frac{i_e}{\beta + 1} R_{\text{sig}} + \hat{v}_\pi + \hat{i}_e R_e$$

$$= \frac{\hat{v}_\pi}{(\beta + 1) r_e} R_{\text{sig}} + \hat{v}_\pi + \frac{\hat{v}_\pi}{r_e} R_e$$

$$\hat{v}_{\text{sig}} = \hat{v}_\pi \left(1 + \frac{R_e}{r_e} + \frac{R_{\text{sig}}}{r_\pi}\right) \qquad \text{Q.E.D}$$



For $I_C = 0.5$ mA and $\beta = 100$,

$$r_e = \frac{V_T}{I_E} = \frac{\alpha V_T}{I_C} = \frac{0.99 \times 25}{0.5} \simeq 50 \ \Omega$$

$$r_\pi = (\beta + 1) r_e \simeq 5 \text{ k}\Omega$$

For $\hat{v}_{\text{sig}} = 100$ mV, $R_{\text{sig}} = 10$ kΩ and with $\hat{v}_\pi$ limited to 10 mV, the value of R_e required can be found from

$$100 = 10\left(1 + \frac{R_e}{50} + \frac{10}{5}\right)$$

$$\Rightarrow R_e = 350 \ \Omega$$

$$R_{\text{in}} = (\beta + 1)(r_e + R_e) = 101 \times (50 + 350)$$

$$= 40.4 \text{ k}\Omega$$

$$G_v = -\beta \frac{R_C \| R_L}{R_{\text{sig}} + (\beta + 1)(r_e + R_e)}$$

$$= -100 \frac{10}{10 + 101 \times 0.4} = -19.8 \text{ V/V}$$

Ex: 7.25

$$\frac{1}{g_m} = R_{\text{sig}} = 100 \ \Omega$$

$$\Rightarrow g_m = \frac{1}{0.1 \text{ k}\Omega} = 10 \text{ mA/V}$$

But

$$g_m = \frac{2I_D}{V_{OV}}$$

Thus,

$$10 = \frac{2I_D}{0.2}$$

$$\Rightarrow I_D = 1 \text{ mA}$$

$$G_v = \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} \times g_m R_D$$

$$= 0.5 \times 10 \times 2 = 10 \text{ V/V}$$

Ex: 7.26

$I_C = 1 \text{ mA}$

$r_e = \dfrac{V_T}{I_E} \simeq \dfrac{V_T}{I_C} = \dfrac{25 \text{ mV}}{1 \text{ mA}} = 25\ \Omega$

$R_{\text{in}} = r_e = 25\ \Omega$

$A_{vo} = g_m R_C = 40 \times 5 = 200 \text{ V/V}$

$R_o = R_C = 5 \text{ k}\Omega$

$A_v = A_{vo} \dfrac{R_L}{R_L + R_o} = 200 \times \dfrac{5}{5+5} = 100 \text{ V/V}$

$G_v = \dfrac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} \times A_v$

$= \dfrac{25}{25 + 5000} \times 100 = 0.5 \text{ V/V}$

Ex: 7.27

$R_{\text{in}} = r_e = 50\ \Omega$

$\Rightarrow I_E = \dfrac{V_T}{r_e} = \dfrac{25 \text{ mV}}{50\ \Omega} = 0.5 \text{ mA}$

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

$G_v = \dfrac{R_C \| R_L}{r_e + R_{\text{sig}}}$

$40 = \dfrac{R_C \| R_L}{(50 + 50)\Omega}$

$R_C \| R_L = 4 \text{ k}\Omega$

Ex: 7.28 Refer to Fig. 7.41(c).

$R_o = 100\ \Omega$

Thus,

$\dfrac{1}{g_m} = 100\ \Omega \Rightarrow g_m = 10 \text{ mA/V}$

But

$g_m = \dfrac{2 I_D}{V_{OV}}$

Thus,

$I_D = \dfrac{10 \times 0.25}{2} = 1.25 \text{ mA}$

$\hat{v}_o = \hat{v}_i \times \dfrac{R_L}{R_L + R_o} = 1 \times \dfrac{1}{1 + 0.1} = 0.91 \text{ V}$

$\hat{v}_{gs} = \hat{v}_i \dfrac{\dfrac{1}{g_m}}{\dfrac{1}{g_m} + R_L} = 1 \times \dfrac{0.1}{0.1 + 1} = 91 \text{ mV}$

Ex: 7.29

$R_o = 200\ \Omega$

$\dfrac{1}{g_m} = 200\ \Omega$

$\Rightarrow g_m = 5 \text{ mA/V}$

But

$gm = k_n' \left(\dfrac{W}{L}\right) V_{OV}$

Thus,

$5 = 0.4 \times \dfrac{W}{L} \times 0.25$

$\Rightarrow \dfrac{W}{L} = 50$

$I_D = \dfrac{1}{2} k_n' \dfrac{W}{L} V_{OV}^2$

$= \dfrac{1}{2} \times 0.4 \times 50 \times 0.25^2$

$= 0.625 \text{ mA}$

$R_L = 1 \text{ k}\Omega$ to $10 \text{ k}\Omega$

Correspondingly,

$G_v = \dfrac{R_L}{R_L + R_o} = \dfrac{R_L}{R_L + 0.2}$

will range from

$G_v = \dfrac{1}{1 + 0.2} = 0.83 \text{ V/V}$

to

$G_v = \dfrac{10}{10 + 0.2} = 0.98 \text{ V/V}$

Ex: 7.30

$I_C = 5 \text{ mA}$

$r_e = \dfrac{V_T}{I_E} \simeq \dfrac{V_T}{I_C} = \dfrac{25 \text{ mV}}{5 \text{ mA}} = 5\ \Omega$

$R_{\text{sig}} = 10 \text{ k}\Omega \quad R_L = 1 \text{ k}\Omega$

$R_{\text{in}} = (\beta + 1)\ (r_e + R_L)$

$= 101 \times (0.005 + 1)$

$= 101.5 \text{ k}\Omega$

$G_{vo} = 1 \text{ V/V}$

$R_{\text{out}} = r_e + \dfrac{R_{\text{sig}}}{\beta + 1}$

$= 5 + \dfrac{10{,}000}{101} = 104\ \Omega$

$G_v = \dfrac{R_L}{R_L + r_e + \dfrac{R_{\text{sig}}}{\beta + 1}} = \dfrac{R_L}{R_L + R_{\text{out}}}$

$= \dfrac{1}{1 + 0.104} = 0.91 \text{ V/V}$

$$v_\pi = v_{\text{sig}} \frac{r_e}{r_e + R_L + \dfrac{R_{\text{sig}}}{\beta+1}}$$

$$\hat{v}_{\text{sig}} = \hat{v}_\pi \left[1 + \frac{R_L}{r_e} + \frac{R_{\text{sig}}}{(\beta+1)\ r_e}\right]$$

$$\hat{v}_{\text{sig}} = 5\left[1 + \frac{1000}{5} + \frac{10{,}000}{101 \times 5}\right] = 1.1 \text{ V/V}$$

Correspondingly,

$$\hat{v}_o = G_v \times 1.1 = 0.91 \times 1.1 = 1 \text{ V}$$

Ex: 7.31

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

$$0.5 = \frac{1}{2} \times 1 (V_{GS} - 1)^2$$

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

If $V_t = 1.5$ V, then

$$I_D = \frac{1}{2} \times 1 \times (2 - 1.5)^2 = 0.125 \text{ mA}$$

$$\Rightarrow \frac{\Delta I_D}{I_D} = \frac{0.125 - 0.5}{0.5} = -0.75 = -75\%$$

Ex: 7.32

$$R_D = \frac{V_{DD} - V_D}{I_D} = \frac{5-2}{0.5} = 6 \text{ k}\Omega$$

$$\to R_D = 6.2 \text{ k}\Omega$$

$$I_D = \frac{1}{2} k_n' \frac{W}{L} V_{OV}^2 \Rightarrow 0.5 = \frac{1}{2} \times 1 \times V_{OV}^2$$

$$\Rightarrow V_{OV} = 1 \text{ V}$$

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

$$\Rightarrow V_S = -2 \text{ V}$$

$$R_S = \frac{V_S - V_{SS}}{I_D} = \frac{-2 - (-5)}{0.5} = 6 \text{ k}\Omega$$

$$\to R_S = 6.2 \text{ k}\Omega$$

If we choose $R_D = R_S = 6.2$ kΩ, then I_D will change slightly:

$$I_D = \frac{1}{2} \times 1 \times (V_{GS} - 1)^2. \text{ Also}$$

$$V_{GS} = -V_S = 5 - R_S I_D$$

$$2I_D = (4 - 6.2I_D)^2$$

$$\Rightarrow 38.44 I_D^2 - 51.6 I_D^2 + 16 = 0$$

$$\Rightarrow I_D = 0.49 \text{ mA},\ 0.86 \text{ mA}$$

$I_D = 0.86$ results in $V_S > 0$ or $V_S > V_G$, which is not acceptable. Therefore $I_D = 0.49$ mA and

$$V_S = -5 + 6.2 \times 0.49 = -1.96 \text{ V}$$

$$V_D = 5 - 6.2 \times 0.49 = +1.96 \text{ V}$$

R_G should be selected in the range of 1 MΩ to 10 MΩ to have low current.

Ex: 7.33

$$I_D = 0.5 \text{ mA} = \frac{1}{2} k_n' \frac{W}{L} V_{OV}^2$$

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

$$\Rightarrow V_{OV} = 1 \text{ V} \Rightarrow V_{GS} = 1 + 1 = 2 \text{ V}$$

$$= V_D \Rightarrow R_D = \frac{5-2}{0.5} = 6 \text{ k}\Omega$$

$\Rightarrow R_D = 6.2$ kΩ (standard value). For this R_D we have to recalculate I_D:

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

$$= \frac{1}{2}(V_{DD} - R_D I_D - 1)^2$$

$$(V_{GS} = V_D = V_{DD} - R_D I_D)$$

$$I_D = \frac{1}{2}(4 - 6.2 I_D)^2 \Rightarrow I_D \cong 0.49 \text{ mA}$$

$$V_D = 5 - 6.2 \times 0.49 = 1.96 \text{ V}$$

Ex: 7.34 Refer to Example 7.12.

(a) For design 1, $R_E = 3$ kΩ, $R_1 = 80$ kΩ, and $R_2 = 40$ kΩ. Thus, $V_{BB} = 4$ V.

$$I_E = \frac{V_{BB} - V_{BE}}{R_E + \dfrac{R_1 \| R_2}{\beta + 1}}$$

For the nominal case, $\beta = 100$ and

$$I_E = \frac{4 - 0.7}{3 + \dfrac{40 \| 80}{101}} = 1.01 \simeq 1 \text{ mA}$$

For $\beta = 50$,

$$I_E = \frac{4 - 0.7}{3 + \dfrac{40 \| 80}{51}} = 0.94 \text{ mA}$$

For $\beta = 150$,

$$I_E = \frac{4 - 0.7}{3 + \dfrac{40 \| 80}{151}} = 1.04 \text{ mA}$$

Thus, I_E varies over a range approximately 10% of the nominal value of 1 mA.

(b) For design 2, $R_E = 3.3$ kΩ, $R_1 = 8$ kΩ, and $R_2 = 4$ kΩ. Thus, $V_{BB} = 4$ V. For the nominal case, $\beta = 100$ and

$$I_E = \frac{4-0.7}{3.3+\dfrac{4\|8}{101}} = 0.99 \simeq 1 \text{ mA}$$

For $\beta = 50$,

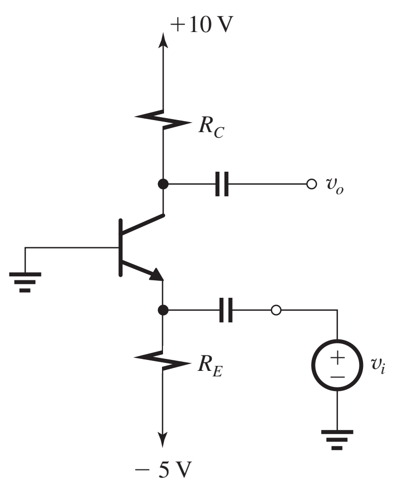
$$I_E = \frac{4-0.7}{3.3+\dfrac{4\|8}{51}} = 0.984 \text{ mA}$$

For $\beta = 150$,

$$I_E = \frac{4-0.7}{3.3+\dfrac{4\|8}{151}} = 0.995 \text{ mA}$$

Thus, I_E varies over a range of 1.1% of the nominal value of 1 mA. Note that lowering the resistances of the voltage divider considerably decreases the dependence on the value of β, a highly desirable result obtained at the expense of increased current and hence power dissipation.

Ex: 7.35 Refer to Fig. 7.53. Since the circuit is to be used as a common-base amplifier, we can dispense with R_B altogether and ground the base; thus $R_B = 0$. The circuit takes the form shown in the figure below.



To establish $I_E = 1$mA,

$$I_E = \frac{5 - V_{BE}}{R_E}$$

$$1 \text{ mA} = \frac{5-0.7}{R_E}$$

$$\Rightarrow R_E = 4.3 \text{ k}\Omega$$

The voltage gain $\dfrac{v_o}{v_i} = g_m R_C$, where $g_m = \dfrac{I_C}{V_T} =$ 40 mA/V. To maximize the voltage gain, we select R_C as large as possible, consistent with obtaining a ±2-V signal swing at the collector.

To maintain active-mode operation at all times, the collector voltage should not be allowed to fall below the value that causes the CBJ to become forward biased, namely, −0.4 V. Thus, the lowest possible dc voltage at the collector is −0.4 V + 2V = +1.6 V. Correspondingly,

$$R_C = \frac{10-1.6}{I_C} \simeq \frac{10-1.6}{1 \text{ mA}} = 8.4 \text{ k}\Omega$$

Ex: 7.36 Refer to Fig. 7.54. For $I_E = 1$ mA and $V_C = 2.3$ V,

$$I_E = \frac{V_{CC} - V_C}{R_C}$$

$$1 = \frac{10-2.3}{R_C}$$

$$\Rightarrow R_C = 7.7 \text{ k}\Omega$$

Now, using Eq. (7.147), we obtain

$$I_E = \frac{V_{CC} - V_{BE}}{R_C + \dfrac{R_B}{\beta+1}}$$

$$1 = \frac{10-0.7}{7.7+\dfrac{R_B}{101}}$$

$$\Rightarrow R_B = 162 \text{ k}\Omega$$

Selecting standard 5% resistors (Appendix J), we use

$$R_B = 160 \text{ k}\Omega \quad \text{and} \quad R_C = 7.5 \text{ k}\Omega$$

The resulting value of I_E is found as

$$I_E = \frac{10-0.7}{7.5+\dfrac{160}{101}} = 1.02 \text{ mA}$$

and the collector voltage will be

$$V_C = V_{CC} - I_E R_C = 2.3 \text{ V}$$

Ex: 7.37 Refer to Fig. 7.55(b).

$V_S = 3.5$ and $I_D = 0.5$ mA; thus

$$R_S = \frac{V_S}{I_D} = \frac{3.5}{0.5} = 7 \text{ k}\Omega$$

$V_{DD} = 15$ V and $V_D = 6$ V; thus

$$R_D = \frac{V_{DD} - V_D}{I_D} = \frac{15-6}{0.5 \text{ mA}} = 18 \text{ k}\Omega$$

To obtain V_{OV}, we use

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

$$0.5 = \frac{1}{2} \times 4 V_{OV}^2$$

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

Thus,

$$V_{GS} = V_t + V_{OV} = 1 + 0.5 = 1.5 \text{ V}$$

We now can obtain the dc voltage required at the gate,

$$V_G = V_S + V_{GS} = 3.5 + 1.5 = 5 \text{ V}$$

Using a current of 2 μA in the voltage divider, we have

$$R_{G2} = \frac{5 \text{ V}}{2 \ \mu\text{A}} = 2.5 \text{ M}\Omega$$

The voltage drop across R_{G1} is 10 V, thus

$$R_{G1} = \frac{10 \text{ V}}{2 \ \mu\text{A}} = 5 \text{ M}\Omega$$

This completes the bias design. To obtain g_m and r_o, we use

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

$$r_o = \frac{V_A}{I_D} = \frac{100}{0.5} = 200 \text{ k}\Omega$$

Ex: 7.38 Refer to Fig. 7.55(a) and (c) and to the values found in the solution to Exercise 7.37 above.

$$R_{\text{in}} = R_{G1} \| R_{G2} = 5 \| 2.5 = 1.67 \text{ M}\Omega$$

$$R_o = R_D \| r_o = 18 \| 200 = 16.5 \text{ k}\Omega$$

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

$$= -\frac{1.67}{1.67 + 0.1} \times 2 \times (200 \| 18 \| 20)$$

$$= -17.1 \text{ V/V}$$

Ex: 7.39 To reduce v_{gs} to half its value, the unbypassed R_s is given by

$$R_s = \frac{1}{g_m}$$

From the solution to Exercise 7.37 above, $g_m = 2$ mA/V. Thus

$$R_s = \frac{1}{2} = 0.5 \text{ k}\Omega$$

Neglecting r_o, G_v is given by

$$G_v = -\frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} \times -\frac{R_D \| R_L}{\dfrac{1}{g_m} + R_s}$$

$$= -\frac{1.67}{1.67 + 0.1} \times \frac{18 \| 20}{0.5 + 0.5}$$

$$= -8.9 \text{ V/V}$$

Ex: 7.40 Refer to Fig. 7.56(a). For $V_B = 5$ V and 50-μA current through R_{B2}, we have

$$R_{B2} = \frac{5 \text{ V}}{0.05 \text{ mA}} = 100 \text{ k}\Omega$$

The base current is

$$I_B = \frac{I_E}{\beta + 1} \simeq \frac{0.5 \text{ mA}}{100} = 5 \ \mu\text{A}$$

The current through R_{B1} is

$$I_{R_{B1}} = I_B + I_{R_{B2}} = 5 + 50 = 55 \ \mu\text{A}$$

Since the voltage drop across R_{B1} is $V_{CC} - V_B = 10$ V, the value of R_{B1} can be found from

$$R_{B1} = \frac{10 \text{ V}}{0.055 \ \mu\text{A}} = 182 \text{ k}\Omega$$

The value of R_E can be found from

$$I_E = \frac{V_B - V_{BE}}{R_E}$$

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

The value of R_C can be found from

$$V_C = V_{CC} - I_C R_C$$

$$6 = 15 - 0.99 \times 0.5 \times R_C$$

$$R_C \simeq 18 \text{ k}\Omega$$

This completes the bias design. The values of g_m, r_π, and r_o can be found as follows:

$$g_m = \frac{I_C}{V_T} \simeq \frac{0.5 \text{ mA}}{0.025 \text{ V}} = 20 \text{ mA/V}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{20} = 5 \text{ k}\Omega$$

$$r_o = \frac{V_A}{I_C} \simeq \frac{100}{0.5} = 200 \text{ k}\Omega$$

Ex: 7.41 Refer to Fig. 7.56(b) and to the solution of Exercise 7.40 above.

$$R_{\text{in}} = R_{B1} \| R_{B2} \| r_\pi$$

$$= 182 \| 100 \| 5 = 4.64 \text{ k}\Omega$$

$$R_o = R_C \| r_o = 18 \| 200 = 16.51 \text{ k}\Omega$$

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

$$G_v = -\frac{4.64}{4.64 + 10} \times 20 \times (18 \| 20 \| 200)$$

$$= -57.3 \text{ V/V}$$

Ex: 7.42 Refer to the solutions of Exercises 7.40 and 7.41 above. With R_e included (i.e., left unbypassed), the input resistance becomes [refer to Fig. 7.57(b)]

$R_{\text{in}} = R_{B1} \| R_{B2} \| [(\beta + 1)(r_e + R_e)]$

Thus,

$10 = 182 \| 100 \| [101(0.05 + R_e)]$

where we have substituted $r_e = \dfrac{V_T}{I_E} = \dfrac{25}{0.5} = 50\ \Omega$. The value of R_e is found from the equation above to be

$R_e = 67.7\ \Omega$

The overall voltage gain can be found from

$$G_v = -\alpha \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} \frac{R_C \| R_L}{r_e + R_e}$$

$$G_v = -0.99 \times \frac{10}{10 + 10} \frac{18 \| 20}{0.05 + 0.0677}$$

$= -39.8$ V/V

Ex: 7.43 Refer to Fig. 7.58.

$R_{\text{in}} = 50\ \Omega = r_e \| R_E \simeq r_e$

$r_e = 50\ \Omega = \dfrac{V_T}{I_E}$

$\Rightarrow I_E = 0.5$ mA

$I_C = \alpha I_E \simeq I_E = 0.5$ mA

$V_C = V_{CC} - R_C I_C$

For $V_C = 1$ V and $V_{CC} = 5$ V, we have

$1 = 5 - R_C \times 0.5$

$\Rightarrow R_C = 8$ kΩ

To obtain the required value of R_E, we note that the voltage drop across it is $(V_{EE} - V_{BE}) = 4.3$ V. Thus,

$R_E = \dfrac{4.3}{0.5} = 8.6$ kΩ

$$G_v = \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} g_m (R_C \| R_L)$$

$$= \frac{50\ \Omega}{50\ \Omega + 50\ \Omega} \times 20(8 \| 8)$$

$= 40$ V/V

$\hat{v}_o = 40 \hat{v}_{\text{sig}} = 40 \times 10\ \text{mV} = 0.4\ \text{V}$

Ex: 7.44 Refer to Fig. 7.59. Consider first the bias design of the circuit in Fig. 7.59(a). Since the required $I_E = 1$ mA, the base current

$I_B = \dfrac{I_E}{\beta + 1} = \dfrac{1}{101} \simeq 0.01$ mA. For a dc voltage drop across R_B of 1 V, we obtain

$R_B = \dfrac{1\ \text{V}}{0.01\ \text{mA}} = 100$ kΩ

The result is a base voltage of –1 V and an emitter voltage of –1.7 V. The required value of R_E can now be determined as

$$R_E = \frac{-1.7 - (-5)}{I_E} = \frac{3.3}{1\ \text{mA}} = 3.3\ \text{k}\Omega$$

$R_{\text{in}} = R_B \| [(\beta + 1)[r_e + (R_E \| r_o \| R_L)]$

where $r_o = \dfrac{V_A}{I_C} = \dfrac{100\ \text{V}}{1\ \text{mA}} = 100$ kΩ

$R_{\text{in}} = 100 \| (100 + 1)[0.025 + (3.3 \| 100 \| 1)]$

$= 44.3$ kΩ

$$\frac{v_i}{v_{\text{sig}}} = \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} = \frac{44.3}{44.3 + 50} = 0.469\ \text{V/V}$$

$$\frac{v_o}{v_i} = \frac{R_E \| r_o \| R_L}{r_e + (R_E \| r_o \| R_L)} = 0.968\ \text{V/V}$$

$$G_v \equiv \frac{v_o}{v_{\text{sig}}} = 0.469 \times 0.968 = 0.454\ \text{V/V}$$

$$R_{\text{out}} = r_o \| R_E \| \left[r_e + \frac{R_B \| + R_{\text{sig}}}{\beta + 1} \right]$$

$$= 100 \| 3.3 \| \left[0.025 + \frac{100 \| 50}{101} \right]$$

$= 320\ \Omega$

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,

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

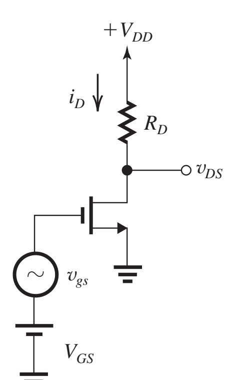
To obtain the required $V_{DS}\big|_Q$, we use Eq. (7.17),

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

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

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

7.5



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

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

(a) Endpoints of saturation transfer segment:

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

Point A = (1 V, 5 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 V, 0.61 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 V, 2.00 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

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

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

$\left(\hat{v}_o = \text{ max downward amplitude}\right)$, 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

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

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

and Eq. (1) to obtain

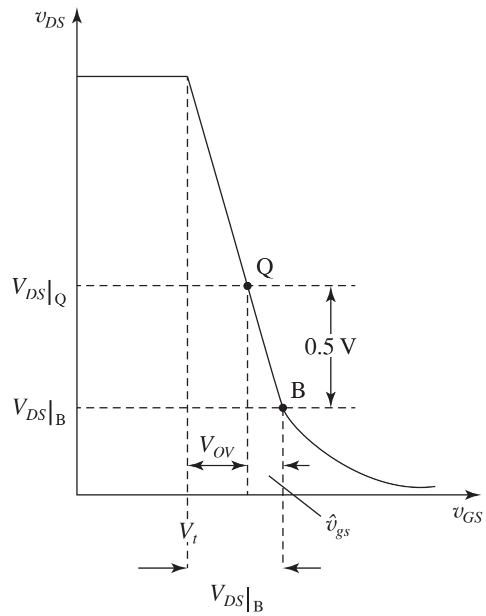
V_{DS}	A_v	$\hat{v}_o$	$\hat{v}_i$
1 V	−16	471 mV	29.4 mV
1.5 V	−14	933 mV	66.7 mV
2 V	−12	1385 mV	115 mV
2.5 V	−10	1818 mV	182 mV

For $V_{DS} = 1$ V, $A_v = -16 = -k_n V_{OV} R_D$

$\therefore R_D = 32$ kΩ

$I_D R_D = 4$ V, $I_D = 0.125$ mA

7.8



To obtain maximum gain while allowing for a −0.5-V signal swing at the output, we bias the MOSFET at point Q where

$$V_{DS}\big|_Q = V_{DS}\big|_B + 0.5 \text{ V} \qquad (1)$$

as indicated in the figure above. Now, $V_{DS}\big|_B$ is given by Eq. (7.8) [together with Eq. (7.7)],

$$V_{DS}\big|_B = \frac{\sqrt{2k_n R_D V_{DD} + 1} - 1}{k_n R_D} \qquad (2)$$

From the figure we see that

$$V_{DS}\big|_B = V_{OV} + \hat{v}_{gs}$$

where $V_{OV} = 0.2$ V (given) and

$$\hat{v}_{gs} = \frac{0.5 \text{ V}}{|A_v|}$$

$$= \frac{0.5}{k_n R_D V_{OV}} = \frac{0.5}{k_n R_D \times 0.2} = \frac{2.5}{k_n R_D} \qquad (3)$$

Thus,

$$V_{DS}\big|_B = 0.2 + \frac{2.5}{k_n R_D}$$

Substituting for $V_{DS}\big|_B$ from Eq. (2), we obtain

$$\frac{\sqrt{2k_n R_D V_{DD} + 1} - 1}{k_n R_D} = 0.2 + \frac{2.5}{k_n R_D}$$

Substituting $V_{DD} = 5$ V, rearranging the equation to obtain a quadratic equation in $k_n R_D$, and solving the resulting quadratic equation results in

$$k_n R_D = 213.7$$

which can be substituted into Eq. (2) to obtain

$$V_{DS}\big|_B = 0.212 \text{ V}$$

The value of V_{DS} at the bias point can now be found from Eq. (1) as

$$V_{DS}\big|_Q = 0.212 + 0.5 = 0.712 \text{ V}$$

(b) The gain achieved can be found as

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

$$= -213.7 \times 0.2 = -42.7 \text{ V/V}$$

$$\hat{v}_{gs} = \frac{0.5}{|A_v|} = \frac{0.5}{42.7} = 11.7 \text{ mV}$$

(c) $I_D = 100$ μA

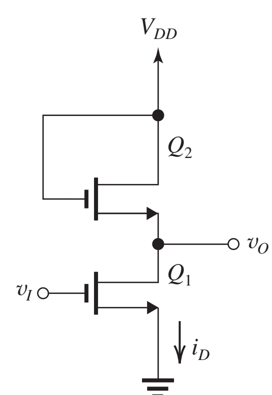
$$R_D = \frac{V_{DD} - V_{DS}\big|_Q}{I_D}$$

$$= \frac{5 - 0.712}{0.1} = 42.88 \text{ k}\Omega$$

(d) $k_n = \dfrac{213.7}{42.88} = 4.98$ mA/V^2

$$\frac{W}{L} = \frac{4.98}{0.2} = 24.9$$

7.9



given $V_{t1} = V_{t2} = V_t$

For Q_2, $i_D = \dfrac{1}{2} k_n' \left(\dfrac{W}{L}\right)_2 [\, V_{DD} - v_O - V_t \,]^2$

For Q_1, $i_D = \dfrac{1}{2} k_n' \left(\dfrac{W}{L}\right)_1 [\, v_I - V_t \,]^2$

For $V_t \le v_I \le v_O + V_t$,

equate i_{D1} and i_{D2}

$$\left(\frac{W}{L}\right)_2 [\,V_{DD} - v_O + V_t\,]^2$$

$$= \left(\frac{W}{L}\right)_1 [\,v_I - V_t\,]^2$$

$$[\,V_{DD} - v_O - V_t\,] = \sqrt{\frac{(W/L)_1}{(W/L)_2}} \cdot [\,v_I - V_t\,]$$

$$v_O = V_{DD} - V_t + V_t\sqrt{\frac{(W/L)_1}{(W/L)_2}}$$

$$-v_I\sqrt{\frac{(W/L)_1}{(W/L)_2}}$$

For $\sqrt{\dfrac{(W/L)_1}{(W/L)_2}} = \sqrt{\dfrac{\left(\dfrac{50}{0.5}\right)}{\left(\dfrac{5}{0.5}\right)}} = \sqrt{10}$,

$$A_v = -\sqrt{10} = -3.16 \text{ V/V}$$

7.10 Refer to Fig. 7.6.

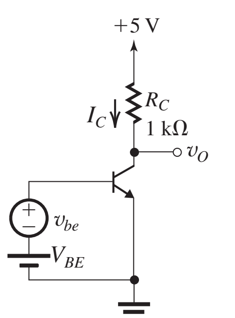
$$A_v = -\frac{V_{CC} - V_{CE}}{V_T}$$

$$= -\frac{5-1}{0.025} = -160 \text{ V/V}$$

The transistor enters saturation when $v_{CE} \leq 0.3$ V, thus the maximum allowable output voltage swing is $1 - 0.3 = 0.7$ V. The corresponding maximum input signal permitted $\hat{v}_{be}$ is

$$\hat{v}_{be} = \frac{0.7 \text{ V}}{|A_v|} = \frac{0.7}{160} = 4.4 \text{ mV}$$

7.11



For $I_C = 0.5$ mA, we have

$$A_v = -\frac{I_C R_C}{V_T} = -\frac{0.5}{0.025} = -20 \text{ V/V}$$

$$V_{CE} = V_{CC} - I_C R_C$$

$$= 5 - 0.5 = 4.5 \text{ V}$$

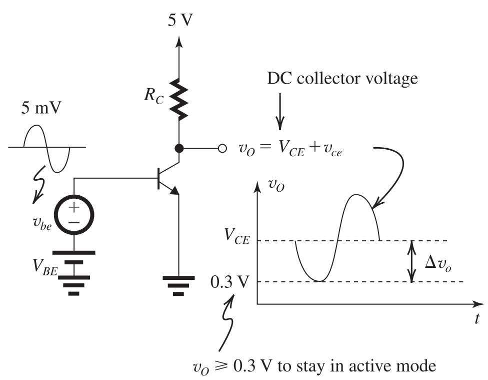
$$\max +\Delta v_O = 5 - 4.5 = 0.5 \text{ V}$$

$$\max -\Delta v_O = 4.5 - 0.3 = 4.2 \text{ V}$$

Similarly →

I_C (mA)	V_{CE} (V)	A_v (V/V)	POS Δv_O (V)	Neg Δv_O (V)
0.5	4.5	–20	0.5	4.2
1.0	4.0	–40	1.0	3.7
2.5	2.5	–100	2.5	2.2
4.0	1.0	–160	4.0	0.7
4.5	0.5	–180	4.5	0.2

7.12



$$A_v = -\frac{I_C R_C}{V_T} = -\frac{V_{CC} - V_{CE}}{V_T}$$

On the verge of satuation

$$V_{CE} - \hat{v}_{ce} = 0.3 \text{ V}$$

For linear operation, $v_{ce} = A_v v_{be}$

$$V_{CE} - |A_v \hat{v}_{be}| = 0.3$$

$$(5 - I_C R_C) - |A_v| \times 5 \times 10^{-3} = 0.3$$

But

$$|A_v| = \frac{I_C R_C}{V_T}$$

Thus,

$$I_C R_C = |A_v| V_T$$

and

$$5 - |A_v| V_T - |A_v| \times 5 \times 10^{-3} = 0.3$$

$$|A_v|(0.025 + 0.005) = 5 - 0.3$$

$|A_v| = 156.67$. Note A_V is negative.

$$\therefore A_v = -156.67 \text{ V/V}$$

Now we can find the dc collector voltage. Referring to the sketch of the output voltage, we see that

$$V_{CE} = 0.3 + |A_v|\,0.005 = 1.08 \text{ V}$$

7.13 To determine $|A_{v\,\max}|$, we use Eq. (7.23),

$$|A_{v\,\max}| = \frac{V_{CC} - 0.3}{V_T}$$

Then, for $V_{CE} = \dfrac{V_{CC}}{2}$ we obtain

$$|A_v| = \frac{V_{CC} - \dfrac{V_{CC}}{2}}{V_T}$$

$$= \frac{V_{CC}}{2V_T}$$

Finally, if a negative-going output signal swing of 0.4 is required, the transistor must be biased at $V_{CE} = 0.4 + 0.3 = 0.7$ V and the gain achieved becomes

$$|A_v| = \frac{V_{CC} - 0.7}{V_T}.$$

The results are as follows:

V_{CC}	**1.0**	**1.5**	**2.0**	**3.0 (V)**
$V_{CC} - 0.3$	0.7	1.2	1.7	2.7 (V)
$\|A_{v\max}\|$	28	48	68	108 (V/V)
$V_{CC}/2$	0.5	0.75	1.0	1.5 (V)
$\|A_v\|$	20	30	40	60 (V/V)
$V_{CC} - 0.7$	0.3	0.8	1.3	2.3 (V)
$\|A_v\|$	12	32	52	92 (V/V)

7.14 To obtain an output signal of peak amplitude P volts and maximum gain, we bias the transistor at

$$V_{CE} = V_{CE\text{sat}} + P$$

The resulting gain will be

$$A_v = -\frac{V_{CC} - V_{CE}}{V_T}$$

which results in V_{CC} of

$$V_{CC} = V_{CE} + |A_v| V_T$$

Thus the minimum required V_{CC} will be

$$V_{CC\min} = V_{CE\text{sat}} + P + |A_v| V_T$$

but we have to make sure that the amplifier can support a positive peak amplitude of P, that is,

$$|A_v| V_T \geq P$$

In the results obtained, tabulated below, $V_{CE\text{sat}} = 0.3$ V and V_{CC} is the nearest 0.5 V to $V_{CC\min}$.

Case	A_v **(V/V)**	P **(V)**	$\|A_v\| V_T$	$V_{CC\min}$	V_{CC}
a	−20	0.2	0.5	1.0	1.0
b	−50	0.5	1.25	2.05	2.5
c	−100	0.5	2.5	3.3	3.5
d	−100	1.0	2.5	3.8	4.0
e	−200	1.0	5.0	6.3	6.5
f	−500	1.0	12.5	13.8	14.0
g	−500	2.0	12.5	14.8	15.0

7.15 See figure below

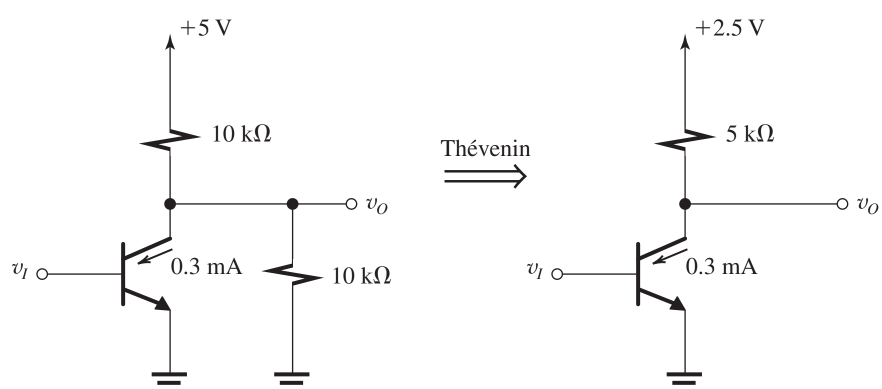
$$A_v = -\frac{I_C R_C}{V_T} = -\frac{0.3 \times 5}{0.025} = -60 \text{ V/V}$$

7.16 (a) See figure on next page

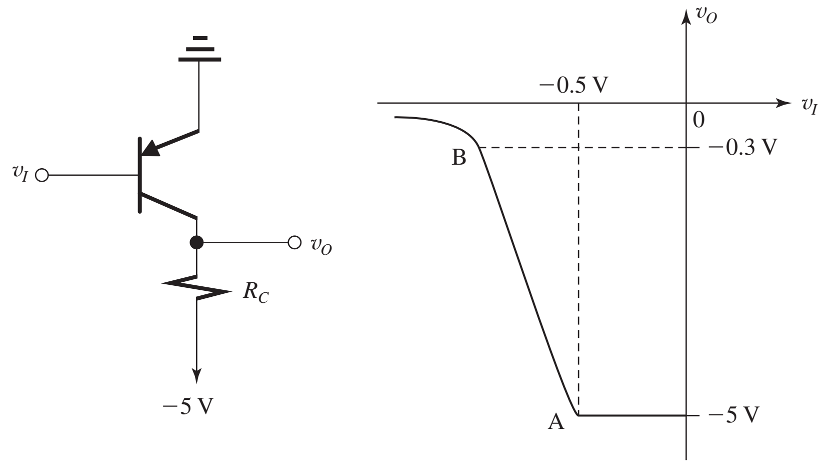
(b) See figure on next page

Note that in part (b) the graph is shifted right by +5 V and up by +5 V.

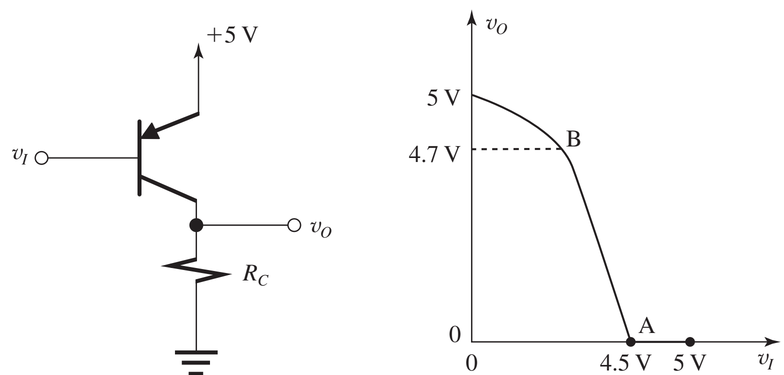
This figure belongs to Problem 7.15.



This figure belongs to Problem 7.16(a).



This figure belongs to Problem 7.16(b).



7.17 $i_C = I_S e^{v_{BE}/V_T}\left(1 + \dfrac{v_{CE}}{V_A}\right)$

$$I_C = I_S e^{V_{BE}/V_T}\left(1 + \frac{V_{CE}}{V_A}\right)$$

$$v_{CE} = V_{CC} - R_C i_C$$

$$V_{CE} = V_{CC} - R_C I_C$$

$$A_v = \left.\frac{dv_{CE}}{dv_{BE}}\right|_{v_{BE}=V_{BE},\ v_{CE}=V_{CE}}$$

$$= -R_C I_S\left(1 + \frac{V_{CE}}{V_A}\right)e^{V_{BE}/V_T}\left(\frac{1}{V_T}\right)$$

$$-R_C I_S e^{V_{BE}/V_T}\left(\frac{dv_{CE}}{dv_{BE}}\right)\left(\frac{1}{V_A}\right)$$

$$= -R_C I_C \frac{1}{V_T} - R_C \frac{I_C}{1 + \dfrac{V_{CE}}{V_A}}\left(\frac{1}{V_A}\right)A_v$$

Thus,

$$A_v = \frac{-I_C R_C / V_T}{1 + \dfrac{I_C R_C}{V_A + V_{CE}}} \qquad \text{Q.E.D}$$

Substituting $I_C R_C = V_{CC} - V_{CE}$, we obtain

$$A_v = -\frac{(V_{CC} - V_{CE})/V_T}{\left[1 + \dfrac{V_{CC} - V_{CE}}{V_A + V_{CE}}\right]} \qquad \text{Q.E.D}$$

For $V_{CC} = 5$ V, $V_{CE} = 3$ V, and $V_A = 100$ V,

$$A_v \text{ (without the Early effect)} = -\frac{5 - 3}{0.025}$$

$$= -80 \text{ V/V}$$

$$A_v \text{ (with the Early effect)} = \frac{-80}{1 + \dfrac{2}{100 + 3}}$$

$$= -78.5 \text{ V/V}$$

7.18 $I_C = \dfrac{V_{CC} - V_{CE}}{R_C} = \dfrac{5 - 2}{1} = 3$ mA

$$A_v = -\frac{V_{CC} - V_{CE}}{V_T} = -\frac{3}{0.025} = -120 \text{ V/V}$$

Using the small-signal voltage gain with $\Delta v_{BE} = +5$ mV, we have

$$\Delta v_O = A_v \times \Delta v_{BE} = -120 \times 5 \text{ mV} = -0.6 \text{ V}$$

Using the exponential characteristic yields

$i_C = I_C e^{v_{BE}/V_T}$

$= 3 \times e^{5/25} = 3.66$ mA

Thus, $\triangle i_C = 0.66$ mA and

$\triangle v_O = - \triangle i_C R_C$

$= -0.66 \times 1 = -0.66$ V

Repeating for $\triangle v_{BE} = -5$ mV as follows.

Using the small-signal voltage gain:

$\triangle v_O = -120 \times -5 = +0.6$ V

Using the exponential characteristic:

$i_C = I_C e^{v_{BE}/V_T}$

$= 3 \times e^{-5/25} = 2.46$ mA

Thus, $\triangle i_C = 2.46 - 3 = -0.54$ mA and $\triangle v_O = 0.54 \times 1 = 0.54$ V

Δv_{BE}	Δv_O(exp)	Δv_O(linear)
+5 mV	−660 mV	−600 mV
−5 mV	+540 mV	+600 mV

Thus, using the small-signal approximation underestimates $|\triangle v_O|$ for positive $\triangle v_{BE}$ by about 10% and overestimates $|\triangle v_O|$ for negative $\triangle v_{BE}$ by about 10%.

7.19 (a) Using Eq. (7.23) yields

$$|A_{v\,\max}| = \frac{V_{CC} - 0.3}{V_T} = \frac{3 - 0.3}{0.025} = 108 \text{ V/V}$$

(b) Using Eq. (7.22) with $A_v = -60$ yields

$$-60 = -\frac{V_{CC} - V_{CE}}{V_T} = -\frac{3 - V_{CE}}{0.025}$$

$\Rightarrow V_{CE} = 1.5$ V

(c) $I_C = 0.5$ mA

$I_C R_C = V_{CC} - V_{CE} = 3 - 1.5 = 1.5$ V

$$R_C = \frac{1.5}{0.5} = 3 \text{ k}\Omega$$

(d) $I_C = I_S e^{V_{BE}/V_T}$

$0.5 \times 10^{-3} = 10^{-15} e^{V_{BE}/0.025}$

$\Rightarrow V_{BE} = 0.673$ V

(e) Assuming linear operation around the bias point, we obtain

$v_{ce} = A_v \times v_{be}$

$= -60 \times 5 \sin \omega t = -300 \sin \omega t$, mV

$= -0.3 \sin \omega t$, V

(f) $i_c = \dfrac{-v_{ce}}{R_C} = 0.1 \sin \omega t$, mA

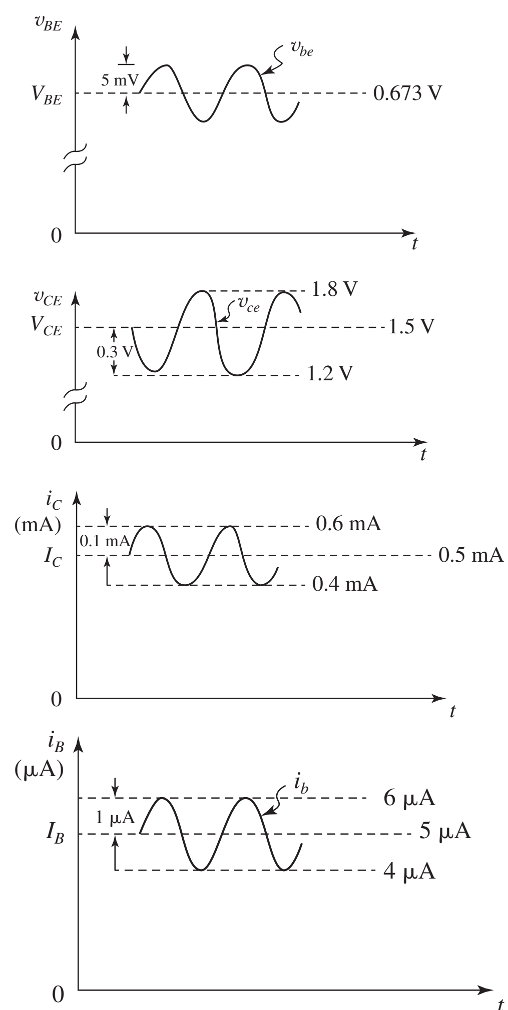
(g) $I_B = \dfrac{I_C}{\beta} = \dfrac{0.5 \text{ mA}}{100} = 0.005$ mA

$$i_b = \frac{i_c}{\beta} = \frac{0.1}{100} \sin \omega t = 0.001 \sin \omega t, \text{ mA}$$

(h) Small-signal input resistance $\equiv \dfrac{\hat{v}_{be}}{\hat{v}_b}$

$$= \frac{5 \text{ mV}}{0.001 \text{ mA}} = 5 \text{ k}\Omega$$

(i)



7.20 $A_v = -\left(\frac{I_C}{V_T}\right)R_C$

But

$$A_v \equiv \frac{\triangle v_O}{\triangle v_{BE}} = \frac{-\triangle i_C R_C}{\triangle v_{BE}} = -g_m R_C$$

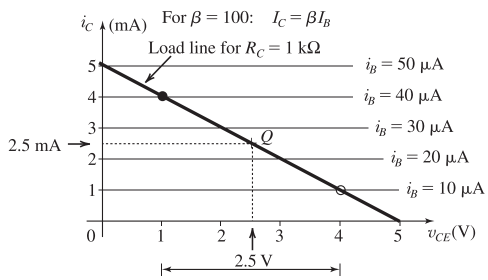
Thus,

$g_m = I_C/V_T$

For a transistor biased at $I_C = 0.5$ mA, we have

$$g_m = \frac{0.5}{0.025} = 20 \text{ mA/V}$$

7.21



Peak-to-peak v_C swing $= 4 - 1 = 3$ V

For point Q at $V_{CC}/2 = 2.5$ V, we obtain

$V_{CE} = 2.5$ V, $\quad I_C = 2.5$ mA

$I_B = 25$ µA

$$I_B = \frac{V_{BB} - 0.7}{R_B} = 25 \text{ µA}$$

$\Rightarrow V_{BB} = I_B R_B + 0.7 = 2.5 + 0.7 = 3.2$ V

7.22 See the graphical construction that follows. For this circuit:

$V_{CC} = 10$ V, $\qquad \beta = 100$,

$R_C = 1$ kΩ, $\qquad V_A = 100$ V,

$I_B = 50$ µA (dc bias),

At $v_{CE} = 0$, $i_C = \beta i_B$

$\therefore I_C = 50 \times 100$

$= 5$ mA (dc bias)

Given the base bias current of 50 mA, the dc or bias point of the collector current I_C, and voltage V_{CE} can be found from the intersection of the load line and the transistor line L_1 of $i_B = 50$ µA. Specifically:

Eq. of $L_1 \Rightarrow i_C = I_C\,(1 + v_{CE}/V_A)$

$= 5\,(1 + v_{CE}/100)$

$= 5 + 0.05 v_{CE}$

Load line $\Rightarrow i_C = \dfrac{V_{CC} - v_{CE}}{R_C} = 10 - v_{CE}$

$\therefore 10 - v_{CE} = 5 + 0.05 v_{CE}$

$V_{CE} = v_{CE} = 4.76$ V

$I_C = i_C = 10 - v_{CE} = 5.24$ mA

Now for a signal of 30-µA peak superimposed on $I_B = 50$ µA, the operating point moves along the load line between points N and M. To obtain the coordinates of point M, we solve the load line and line L_2 to find the intersection M, and the load line and line L_3 to find N:

For point M:

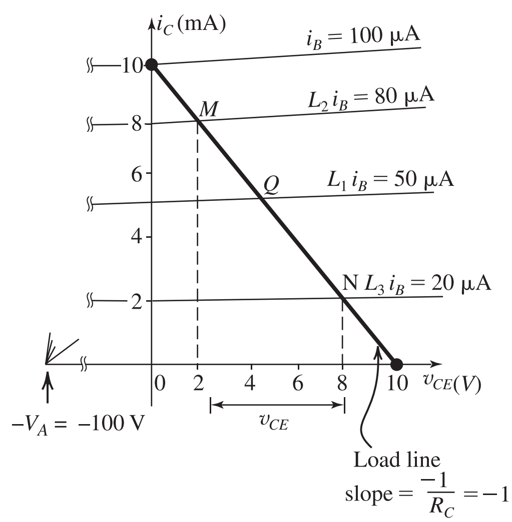
$i_C = 8 + (8/100)v_{CE}$ and $i_C = 10 - v_{CE}$

$\therefore i_C\big|_M = 8.15$ mA, $\quad v_{CE}\big|_M = 1.85$ V

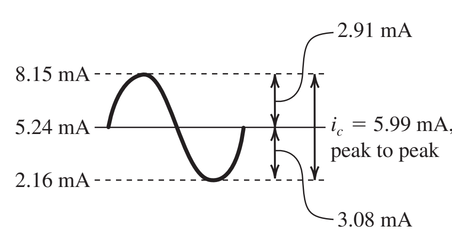
For point N:

$i_C = 2 + 0.02 v_{CE}$ and $i_C = 10 - v_{CE}$

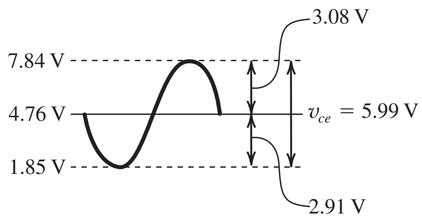
$v_{CE}\big|_N = 7.84$ V, $\quad i_C\big|_N = 2.16$ mA



Thus the collector current varies as follows:



And the collector voltage varies as follows:



7.23 Substituting $v_{gs} = V_{gs} \sin \omega t$ in Eq. (7.28),

$$i_D = \frac{1}{2}k_n(V_{GS} - V_t)^2 + k_n(V_{GS} - V_t)V_{gs} \sin \omega t$$

$$+\frac{1}{2}k_n V_{gs}^2 \sin^2 \omega t$$

$$= \frac{1}{2}k_n(V_{GS} - V_t)^2 + k_n(V_{GS} - V_t)V_{gs} \sin \omega t$$

$$+\frac{1}{2}k_n V_{gs}^2 (\frac{1}{2} - \frac{1}{2} \cos 2\,\omega t)$$

Second-harmonic distortion

$$= \frac{\frac{1}{4}k_n V_{gs}^2}{k_n(V_{GS} - V_t)V_{gs}} \times 100$$

$$= \frac{1}{4}\frac{V_{gs}}{V_{OV}} \times 100 \qquad \text{Q.E.D}$$

For $V_{gs} = 10$ mV, to keep the second-harmonic distortion to less than 1%, the minimum overdrive voltage required is

$$V_{OV} = \frac{1}{4} \times \frac{0.01 \times 100}{1} = 0.25 \text{ V}$$

7.24 $I_D = \frac{1}{2}k_n V_{OV}^2 = \frac{1}{2} \times 10 \times 0.2^2 = 0.2$ mA

$v_{GS} = V_{GS} + v_{gs}$, where $v_{gs} = 0.02$ V

$v_{OV} = 0.2 + 0.02 = 0.22$ V

$i_D = \frac{1}{2}k_n v_{OV}^2 = \frac{1}{2} \times 10 \times 0.22^2 = 0.242$ mA

Thus,

$i_d = 0.242 - 0.2 = 0.042$ mA

For

$v_{gs} = -0.02$ V, $\quad v_{OV} = 0.2 - 0.02 = 0.18$ V

$i_D = \frac{1}{2}k_n v_{OV}^2 = \frac{1}{2} \times 10 \times 0.18^2 = 0.162$ mA

Thus,

$i_d = 0.2 - 0.162 = 0.038$ mA

Thus, an estimate of g_m can be obtained as follows:

$$g_m = \frac{0.042 + 0.038}{0.04} = 2 \text{ mA/V}$$

Alternatively, using Eq. (7.33), we can write

$g_m = k_n V_{OV} = 10 \times 0.2 = 2$ mA/V

which is an identical result.

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

$= \frac{1}{2} \times 5(0.6 - 0.4)^2 = 0.1$ mA

$V_{DS} = V_{DD} - I_D R_D = 1.8 - 0.1 \times 10 = 0.8$ V

(b) $g_m = k_n V_{OV} = 5 \times 0.2 = 1$ mA/V

(c) $A_v = -g_m R_D = -1 \times 10 = -10$ V/V

(d) $\lambda = 0.1\ \text{V}^{-1}, \quad V_A = \frac{1}{\lambda} = 10$ V

$$r_o = \frac{V_A}{I_D} = \frac{10}{0.1} = 100 \text{ k}\Omega$$

$A_v = -g_m(R_D \parallel r_o)$

$= -1(10 \parallel 100) = -9.1$ V/V

7.26 $A_v = -10 = -g_m R_D = -g_m \times 20$

$g_m = 0.5$ mA/V

To allow for a −0.2-V signal swing at the drain while maintaining saturation-region operation, the minimum voltage at the drain must be at least equal to V_{OV}. Thus

$V_{DS} = 0.2 + V_{OV}$

Since

$$A_v = -\frac{V_{DD} - V_{DS}}{\frac{1}{2}V_{OV}}$$

$$-10 = -\frac{1.8 - 0.2 - V_{OV}}{0.5V_{OV}}$$

$\Rightarrow V_{OV} = 0.27$ V

The value of I_D can be found from

$$g_m = \frac{2I_D}{V_{OV}}$$

$$0.5 = \frac{2 \times I_D}{0.27}$$

$\Rightarrow I_D = 0.067$ mA

The required value of k_n can be found from

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

$$0.067 = \frac{1}{2}k_n \times 0.27^2$$

$\Rightarrow k_n = 1.83$ mA/V^2

Since $k_n' = 0.2$ mA/V^2, the W/L ratio must be

$$\frac{W}{L} = \frac{k_n}{k_n'} = \frac{1.83}{0.2} = 9.14$$

Finally,

$V_{GS} = V_t + V_{OV} = 0.4 + 0.27 = 0.67$ V

7.27 $A_v = -g_m R_D$

Upon substituting for g_m from Eq. (7.42), we can write

$$A_v = -\frac{2I_D R_D}{V_{OV}}$$

$$= -\frac{2(V_{DD} - V_{DS})}{V_{OV}} \qquad \text{Q.E.D} \qquad (1)$$

$v_{GS}\big|_{\max} = V_{GS} + \hat{v}_i = V_t + V_{OV} + \hat{v}_i$

$v_{DS}\big|_{\min} = V_{DS} - |A_v|\hat{v}_i$

To just maintain saturation-mode operation,

$v_{GS}\big|_{\max} = v_{DS}\big|_{\min} + V_t$

which results in

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

Substituting for $|A_v|$ from Eq. (1) yields

$$V_{OV} + \hat{v}_i = V_{DS} - \frac{2(V_{DD} - V_{DS})}{V_{OV}}\hat{v}_i$$

$V_{DS}[1 + 2(\hat{v}_i/V_{OV})]$

$= V_{OV} + \hat{v}_i + 2V_{DD}(\hat{v}_i/V_{OV})$

$$\Rightarrow V_{DS} = \frac{V_{OV} + \hat{v}_i + 2V_{DD}(\hat{v}_i/V_{OV})}{1 + 2(\hat{v}_i/V_{OV})} \qquad \text{Q.E.D}$$

For

$V_{DD} = 2.5$ V, $\hat{v}_i = 20$ mV and $m = 15$

$V_{OV} = m\hat{v}_i = 15 \times 20 = 0.3$ V

$$V_{DS} = \frac{0.3 + 0.02 + 2 \times 2.5 \times (0.02/0.3)}{1 + 2(0.02/0.3)}$$

$= 0.576$ V

$$A_v = -\frac{2(V_{DD} - V_{DS})}{V_{OV}} = -\frac{2(2.5 - 0.576)}{0.3}$$

$= -12.82$ V/V

$\hat{v}_o = |A_v|\hat{v}_i = 12.82 \times 20 \text{ mV} = 0.256$ V

To operate at $I_D = 200\ \mu\text{A} = 0.2$ mA,

$$R_D = \frac{2.5 - 0.576}{0.2} = 9.62\ \text{k}\Omega$$

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

$$0.2 = \frac{1}{2}k_n \times 0.3^2$$

$\Rightarrow k_n = 4.44$ mA/V^2

The required *W*/*L* ratio can now be found as

$$\frac{W}{L} = \frac{k_n}{k_n'} = \frac{4.44}{0.1} = 44.4$$

7.28 Given $\mu_n = 500$ cm^2/V·s,

$\mu_p = 250$ cm^2/V·s, and $C_{ox} = 0.4$ fF/μm^2,

$k_n' = \mu_n C_{ox} = 20\ \mu\text{A/V}^2$

$k_p' = 10\ \mu\text{A/V}^2$

See table below.

Case type	I_D (mA)	$\lvert V_{GS}\rvert$ (V)	$\lvert V_t\rvert$ (V)	$\lvert V_{OV}\rvert$ (V)	W (μm)	L (μm)	$\frac{W}{L}$	$k'\frac{W}{L}$ (mA/V^2)	g_m (mA/V)
a (N)	1	3	2	1	100	1	100	2	2
b (N)	1	1.2	0.7	0.5	50	0.125	400	8	4
c (N)	10	—	—	2	250	1	250	5	10
d (N)	0.5	—	—	0.5	—	—	200	4	2
e (N)	0.1	—	—	1.41	10	2	5	0.1	0.141
f (N)	0.1	1.8	0.8	1	40	4	10	0.2	0.2
g (P)	0.5	—	—	2	—	—	25	0.25	0.5
h (P)	1	3	1	2	—	—	50	0.5	1
i (P)	10	—	—	1	4000	2	2000	20	20
j (P)	10	—	—	4	—	—	125	1.25	5
k (P)	0.05	—	—	1	30	3	10	0.1	0.1
l (P)	1	—	—	5	—	—	8	0.08	0.4

Note: The circled entries are the givens.

7.29 Given $\mu_n C_{ox} = 250\ \mu\text{A/V}^2$,

$V_t = 0.5$ V,

$L = 0.5\ \mu$m

For $g_m = 2$ mA/V^2 and $I_D = 0.25$ mA,

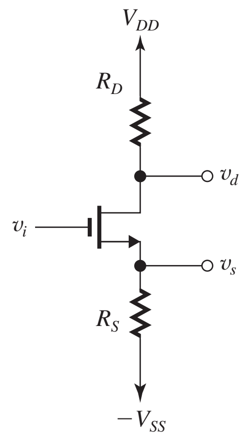
$$g_m = \sqrt{2\mu_n C_{ox} \frac{W}{L} I_D} \Rightarrow \frac{W}{L} = 32$$

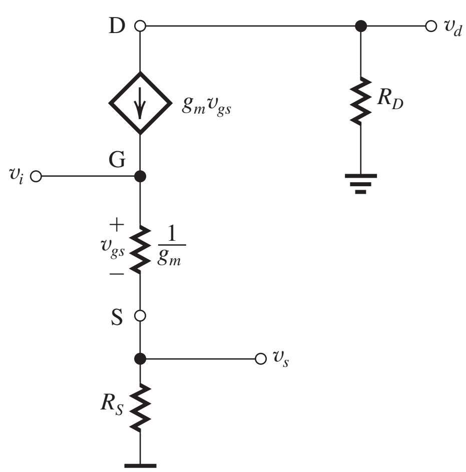
$\therefore W = 16\ \mu$m

$$V_{OV} = \frac{2I_D}{g_m} = 0.25 \text{ V}$$

$\therefore V_{GS} = V_{OV} + V_t = 0.75$ V

7.30





$$v_i = (g_m v_{gs})\left(\frac{1}{g_m} + R_S\right)$$

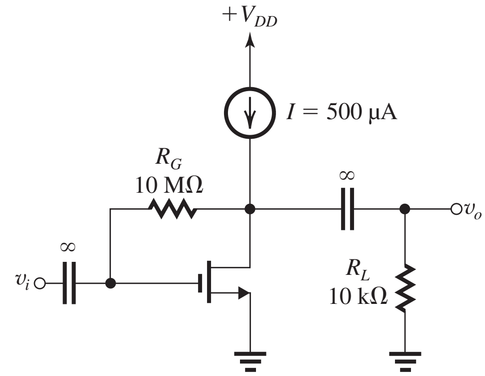
$$v_d = -g_m v_{gs} R_D$$

$$v_s = +g_m v_{gs} R_S$$

$$\therefore \frac{v_s}{v_i} = \frac{R_S}{\frac{1}{g_m} + R_S} = \frac{+g_m R_S}{1 + g_m R_S}$$

$$\frac{v_d}{v_i} = \frac{-R_D}{\frac{1}{g_m} + R_S} = \frac{-g_m R_D}{1 + g_m R_S}$$

7.31



$V_t = 0.5$ V

$V_A = 50$ V

Given $V_{DS} = V_{GS} = 1$ V. Also, $I_D = 0.5$ mA.

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

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

$$\frac{v_o}{v_i} = -g_m\,(R_G \parallel R_L \parallel r_o) = -18.2 \text{ V/V}$$

For $I_D = 1$ mA:

V_{OV} increases by $\sqrt{\frac{1}{0.5}} = \sqrt{2}$ to

$\sqrt{2} \times 0.5 = 0.707$ V.

$V_{GS} = V_{DS} = 1.207$ V

$g_m = 2.83$ mA/V, $r_o = 50$ kΩ and

$$\frac{v_o}{v_i} = -23.6 \text{ V/V}$$

7.32 For the NMOS device:

$$I_D = 100 = \frac{1}{2}\mu_n C_{ox} \frac{W}{L} V_{OV}^2$$

$$= \frac{1}{2} \times 400 \times \frac{10}{0.5} \times V_{OV}^2$$

$$\Rightarrow V_{OV} = 0.16 \text{ V}$$

$$g_m = \frac{2I_D}{V_{OV}} = \frac{2 \times 0.1 \text{ mA}}{0.16} = 1.25 \text{ mA/V}$$

$$V_A = 5L = 5 \times 0.5 = 2.5 \text{ V}$$

$$r_o = \frac{V_A}{I_D} = \frac{2.5}{0.1} = 25 \text{ k}\Omega$$

For the PMOS device:

$$I_D = 100 = \frac{1}{2}\mu_p C_{ox}\frac{W}{L}V_{OV}^2$$

$$= \frac{1}{2} \times 100 \times \frac{10}{0.5} \times V_{OV}^2$$

$$\Rightarrow V_{OV} = 0.316 \text{ V}$$

$$g_m = \frac{2I_D}{V_{OV}} = \frac{2 \times 0.1}{0.316} = 0.63 \text{ mA/V}$$

$$V_A = 6L = 6 \times 0.5 = 3 \text{ V}$$

$$r_o = \frac{V_A}{I_D} = \frac{3}{0.1} = 30 \text{ k}\Omega$$

7.33 (a) Open-circuit the capacitors to obtain the bias circuit shown in Fig. 1, which indicates the given values.

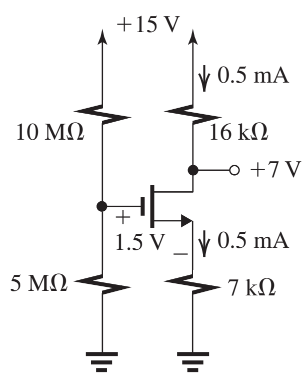


Figure 1

From the voltage divider, we have

$$V_G = 15\frac{5}{10+5} = 5 \text{ V}$$

From the circuit, we obtain

$$V_G = V_{GS} + 0.5 \times 7$$

$$= 1.5 + 3.5 = 5 \text{ V}$$

which is consistent with the value provided by the voltage divider.

Since the drain voltage (+7 V) is higher than the gate voltage (+5 V), the transistor is operating in saturation.

From the circuit

$V_D = V_{DD} - I_D R_D = 15 - 0.5 \times 16 = +7$ V, as assumed

Finally,

$V_{GS} = 1.5$ V, thus $V_{OV} = 1.5 - V_t = 1.5 - 1$ $= 0.5$ V

$$I_D = \frac{1}{2}k_n V_{OV}^2 = \frac{1}{2} \times 4 \times 0.5^2 = 0.5 \text{ mA}$$

which is equal to the given value. Thus the bias calculations are all consistent.

(b) $g_m = \dfrac{2I_D}{V_{OV}} = \dfrac{2 \times 0.5}{0.5} = 2$ mA/V

$$r_o = \frac{V_A}{I_D} = \frac{100}{0.5} = 200 \text{ k}\Omega$$

(c) See Fig. 2 below.

(d) $R_{\text{in}} = 10 \text{ M}\Omega \parallel 5 \text{ M}\Omega = 3.33 \text{ M}\Omega$

$$\frac{v_{gs}}{v_{\text{sig}}} = \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} = \frac{3.33}{3.33 + 0.2}$$

$$= 0.94 \text{ V/V}$$

$$\frac{v_o}{v_{gs}} = -g_m(200 \parallel 16 \parallel 16)$$

$$= -2 \times 7.69 = -15.38 \text{ V/V}$$

$$\frac{v_o}{v_{\text{sig}}} = \frac{v_{gs}}{v_{\text{sig}}} \times \frac{v_o}{v_{gs}} = -0.94 \times 15.38$$

$$= -14.5 \text{ V/V}$$

7.34 (a) Using the exponential characteristic:

$$i_c = I_C e^{v_{be}/V_T} - I_C$$

giving $\dfrac{i_c}{I_C} = e^{v_{be}/V_T} - 1$

(b) Using small-signal approximation:

$$i_c = g_m v_{be} = \frac{I_C}{V_T} \cdot v_{be}$$

This figure belongs to Problem 7.33, part (c).

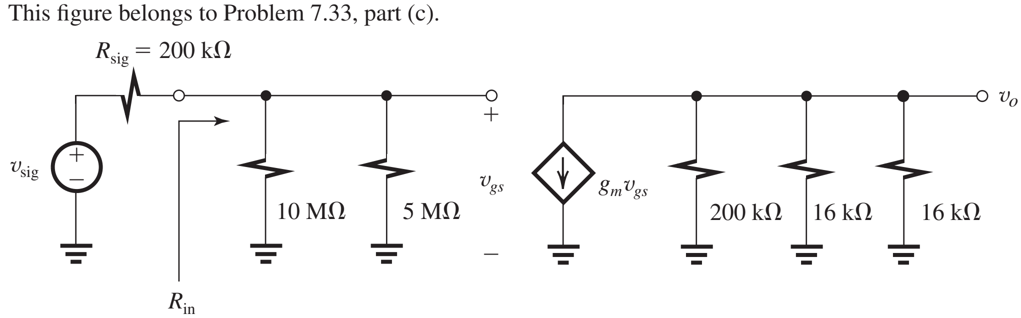


Figure 2

Thus, $\frac{i_c}{I_C} = \frac{v_{be}}{V_T}$

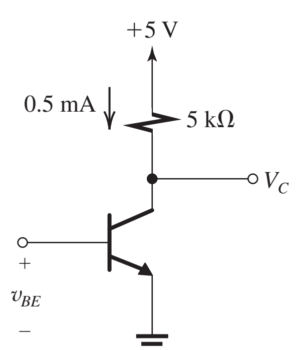
See table below.

For signals at ±5 mV, the error introduced by the small-signal approximation is 10%.

The error increases to above 20% for signals at ±10 mV.

v_{be} (mV)	i_c/I_C Exponential	i_c/I_C Small signal	Error (%)
+1	+0.041	+0.040	–2.4
–1	–0.039	–0.040	+2.4
+2	+0.083	+0.080	–3.6
–2	–0.077	–0.080	+3.9
+5	+0.221	+0.200	–9.7
–5	–0.181	–0.200	+10.3
+8	+0.377	+0.320	–15.2
–8	–0.274	–0.320	+16.8
+10	+0.492	+0.400	–18.7
–10	–0.330	–0.400	+21.3
+12	+0.616	+0.480	–22.1
–12	–0.381	–0.480	+25.9

7.35



With $v_{BE} = 0.700$ V

$V_C = V_{CC} - R_C I_C$

$= 5 - 5 \times 0.5 = 2.5$ V

For $v_{BE} = 705$ mV $\Rightarrow v_{be} = 5$ mV

$i_C = I_C e^{v_{be}/V_T}$

$= 0.5 \times e^{5/25} = 0.611$ mA

$v_C = V_{CC} - R_C i_C = 5 - 5 \times 0.611 = 1.95$ V

$v_{ce} = v_C - V_C = 1.95 - 2.5 = -0.55$ V

Voltage gain, $A_v = \frac{v_{ce}}{v_{be}} = -\frac{0.55 \text{ V}}{5 \text{ mV}}$

$= -110$ V/V

Using small-signal approximation, we write

$A_v = -g_m R_C$

where

$g_m = \frac{I_C}{V_T} = \frac{0.5 \text{ mA}}{0.025 \text{ V}} = 20$ mA/V

$A_v = -20 \times 5 = -100$ V/V

Thus, the small-signal approximation at this signal level ($v_{be} = 5$ mV) introduces an error of -9.1% in the gain magnitude.

7.36 At $I_C = 0.5$ mA,

$g_m = \frac{I_C}{V_T} = \frac{0.5 \text{ mA}}{0.025 \text{ V}} = 20$ mA/V

$r_\pi = \frac{\beta}{g_m} = \frac{100}{20 \text{ mA/V}} = 5$ kΩ

$r_e = \frac{V_T}{I_E} = \frac{\alpha V_T}{I_C}$

where

$\alpha = \frac{\beta}{\beta + 1} = \frac{100}{100 + 1} = 0.99$

$r_e = \frac{0.99 \times 25 \text{ mV}}{0.5 \text{ mA}} \simeq 50\ \Omega$

At $I_C = 50\ \mu$A $= 0.05$ mA,

$g_m = \frac{I_C}{V_T} = \frac{0.05}{0.025} = 2$ mA/V

$r_\pi = \frac{\beta}{g_m} = \frac{100}{2 \text{ mA/V}} = 50$ kΩ

$r_e = \frac{\alpha V_T}{I_C} = \frac{0.99 \times 25 \text{ mV}}{0.5 \text{ mA}} \simeq 500\ \Omega$

7.37 $g_m = \frac{I_C}{V_T} = \frac{1 \text{ mA}}{0.025 \text{ V}} = 40$ mA/V

$r_e = \frac{\alpha}{g_m} = \frac{0.99}{40 \text{ mA/V}} \simeq 25\ \Omega$

$r_\pi = \frac{\beta}{g_m} = \frac{100}{40 \text{ mA/V}} = 2.5$ kΩ

$A_v = -g_m R_C = -40 \times 5 = -200$ V/V

$\hat{v}_o = |A_v| \hat{v}_{be} = 200 \times 5 \text{ mV} = 1$ V

7.38 For $g_m = 30$ mA/V,

$g_m = \frac{I_C}{V_T} \Rightarrow I_C = g_m V_T = 30 \times 0.025 = 0.75$ mA

$r_\pi = \frac{\beta}{g_m} = \frac{\beta}{30 \text{ mA/V}}$

For $r_\pi \geq 3\ \text{k}\Omega$, we require

$\beta \geq 90$

That is, $\beta_{\min} = 90$.

7.39 $r_\pi = \dfrac{\beta}{g_m}$

where

$$g_m = \frac{I_C}{V_T}$$

Nominally, $g_m = 40$ mA/V. However, I_C varies by $\pm 20\%$, so g_m ranges from 32 mA/V to 48 mA/V. Thus

$$r_\pi = \frac{50 \text{ to } 150}{32 \text{ to } 48 \text{ mA/V}}$$

Thus, the extreme values of r_π are $\dfrac{50}{48} = 1.04\ \text{k}\Omega$ and $\dfrac{150}{32} = 4.7\ \text{k}\Omega$.

7.40 $V_{CC} = 3$ V, $\quad V_C = 1$ V, $\quad R_C = 2\ \text{k}\Omega$

$$I_C = \frac{3-1}{2} = 1 \text{ mA}$$

$$g_m = \frac{I_C}{V_T} = \frac{1 \text{ mA}}{0.025 \text{ V}} = 40 \text{ mA/V}$$

$$v_{be} = 0.005 \sin \omega t$$

$$i_c = g_m v_{be} = 0.2 \sin \omega t, \text{ mA}$$

$$i_C(t) = I_C + i_c = 1 + 0.2 \sin \omega t, \text{ mA}$$

$$v_C(t) = V_{CC} - R_C i_C$$

$$= 3 - 2(1 + 0.2 \sin \omega t)$$

$$= 1 - 0.4 \sin \omega t, \text{ V}$$

$$i_B(t) = i_C(t)/\beta$$

$$= 0.01 + 0.002 \sin \omega t, \text{ mA}$$

$$A_v = \frac{v_c}{v_{be}} = -\frac{0.4}{0.005} = -80 \text{ V/V}$$

7.41 Since $\hat{V}_{be}$ is the maximum value for acceptable linearity, the largest signal at the collector will be obtained by designing for maximum gain magnitude. This in turn is achieved by biasing the transistor at the lowest V_{CE} consistent with the transistor remaining in the active mode at the negative peak of v_o. Thus

$$V_{CE} - |A_v|\hat{V}_{be} = 0.3$$

where we have assumed $V_{CE\text{sat}} = 0.3$ V. Since

$$V_{CE} = V_{CC} - I_C R_C$$

and

$$|A_v| = g_m R_C = \frac{I_C}{V_T} R_C$$

then

$$V_{CC} - I_C R_C - \frac{\hat{V}_{be}}{V_T} I_C R_C = 0.3$$

which can be manipulated to yield

$$I_C R_C = \frac{V_{CC} - 0.3}{1 + \dfrac{\hat{V}_{be}}{V_T}} \qquad (1)$$

Since the voltage gain is given by

$$A_v = -\frac{I_C R_C}{V_T}$$

then

$$A_v = \frac{V_{CC} - 0.3}{V_T + \hat{V}_{be}}$$

For $V_{CC} = 3$ V and $\hat{V}_{be} = 5$ mV,

$$I_C R_C = \frac{3 - 0.3}{1 + \dfrac{5}{25}} = 2.25 \text{ V}$$

Thus,

$$V_{CE} = V_{CC} - I_C R_C$$

$$= 3 - 2.25 = 0.75 \text{ V}$$

$$\hat{V}_o = V_{CE} - 0.3 = 0.75 - 0.3 = 0.45 \text{ V}$$

$$A_v = -\frac{3 - 0.3}{0.025 + 0.005} = -90 \text{ V/V}$$

Check:

$$A_v = -g_m R_C = -\frac{I_C R_C}{V_T} = -\frac{2.25}{0.025} = -90 \text{ V/V}$$

$$\hat{V}_o = |A_v| \times \hat{V}_{be} = 90 \times 5 = 450 \text{ mV} = 0.45 \text{ V}$$

7.42

Transistor	**a**	**b**	**c**	**d**	**e**	**f**	**g**
α	1.000	0.990	0.980	1	0.990	0.900	0.940
β	∞	100	50	∞	100	9	15.9
I_C (mA)	1.00	0.99	1.00	1.00	0.248	4.5	17.5
I_E (mA)	1.00	1.00	1.02	1.00	0.25	5	18.6
I_B (mA)	0	0.010	0.020	0	0.002	0.5	1.10
g_m (mA/V)	40	39.6	40	40	9.92	180	700
r_e (Ω)	25	25	24.5	25	100	5	1.34
r_π (Ω)	∞	2.525 k	1.25 k	∞	10.1 k	50	22.7

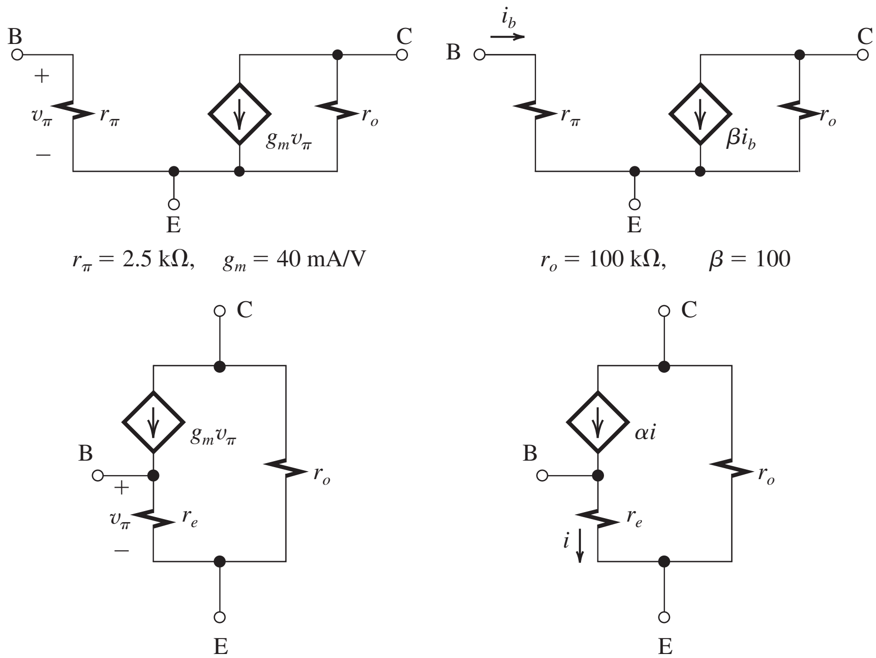
7.43 $I_C = 1$ mA, $\quad \beta = 100$, $\quad V_A = 100$ V

$$g_m = \frac{I_C}{V_T} = \frac{1 \text{ mA}}{0.025 \text{ V}} = 40 \text{ mA/V}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{40 \text{ mA/V}} = 2.5\ \text{k}\Omega$$

$$r_o = \frac{V_A}{I_C} = \frac{100 \text{ V}}{1 \text{ mA}} = 100\ \text{k}\Omega$$

This figure belongs to Problem 7.43.



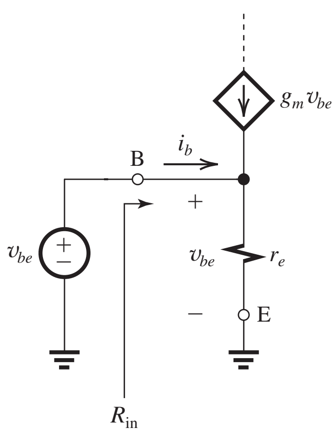
$r_\pi = 2.5$ kΩ, $g_m = 40$ mA/V $r_o = 100$ kΩ, $\beta = 100$

$r_e = 24.75\ \Omega$, $g_m = 40$ mA/V $r_o = 100$ kΩ, $\alpha = 0.99$

$$\alpha = \frac{\beta}{\beta+1} = \frac{100}{100+1} = 0.99$$

$$r_e = \frac{V_T}{I_E} = \frac{\alpha V_T}{I_C} = \frac{0.99 \times 25\text{ mV}}{1\text{ mA}} = 24.75\ \Omega$$

7.44



$$i_b = \frac{v_{be}}{r_e} - g_m v_{be}$$

$$= v_{be}\left(\frac{1}{r_e} - g_m\right)$$

Since

$$r_e = \frac{\alpha}{g_m}$$

$$i_b = v_{be}\left(\frac{g_m}{\alpha} - g_m\right)$$

$$= g_m v_{be}\frac{1-\alpha}{\alpha}$$

$$= \frac{g_m v_{be}}{\beta}$$

$$R_{\text{in}} \equiv \frac{v_{be}}{i_b} = \frac{\beta}{g_m} = r_\pi \qquad \text{Q.E.D}$$

7.45 Refer to Fig. 7.26.

$$i_c = \alpha i_e = \alpha \frac{v_{be}}{r_e} = \frac{\alpha}{r_e} v_{be}$$

$$= g_m v_{be} \qquad \text{Q.E.D}$$

7.46 The large-signal model of Fig. 6.5(d) is shown in Fig. 1.

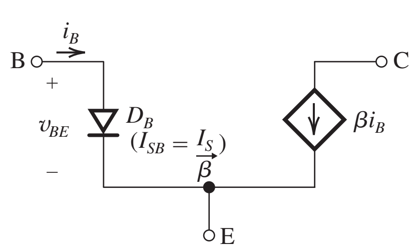


Figure 1

For v_{BE} undergoing an incremental change v_{be} from its equilibrium value of V_{BE}, the current i_B

changes from I_B by an increment i_b, which is related to v_{be} by the incremental resistance of D_B at the bias current I_B. This resistance is given by V_T/I_B, which is r_π.

The collector current βi_B changes from βI_B to $\beta(I_B + i_b)$. The incremental changes around the equilibrium or bias point are related to each other by the circuit shown in Fig. 2,

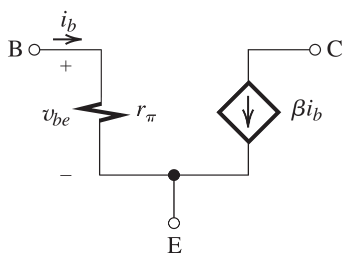


Figure 2

which is the hybrid-π model of Fig. 7.24(b). Q.E.D.

7.47 The large-signal T model of Fig. 6.5(b) is shown below in Fig. 1.

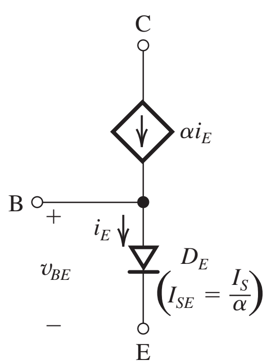


Figure 1

If i_E undergoes an incremental change i_e from its equilibrium or bias value I_E, the voltage v_{BE} will correspondingly change by an incremental amount v_{be} (from its equilibrium or bias value V_{BE}), which is related to i_e by the incremental resistance of diode D_E. The latter is equal to V_T/I_E, which is r_e.

The incremental change i_e in i_E gives rise to an incremental change αi_e in the current of the controlled source.

The incremental quantities can be related by the equivalent circuit model shown in Fig. 2,

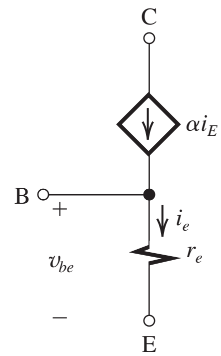


Figure 2

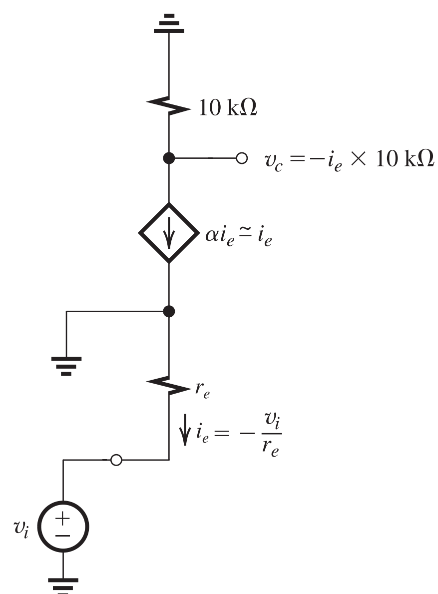
which is the small-signal T model of Fig. 7.26(b). Q.E.D.

7.48 Refer to Fig. P7.48:

$V_C = 3 - 0.2 \times 10 = 1$ V

$$r_e = \frac{V_T}{I_E} = \frac{25 \text{ mV}}{0.2 \text{ mA}} = 125\ \Omega$$

Replacing the BJT with the T model of Fig. 7.26(b), we obtain the equivalent circuit shown below.



$v_c = -i_e \times 10\text{ k}\Omega$

where

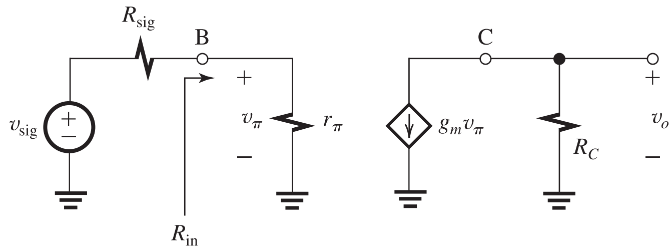
$$i_e = -\frac{v_i}{r_e} = -\frac{v_i}{0.125\text{ k}\Omega}$$

Thus,

$$\frac{v_c}{v_i} = \frac{10\text{ k}\Omega}{0.125\text{ k}\Omega}$$

$= 80$ V/V

This figure belongs to Problem 7.50.



7.49 $v_{ce} = |A_v| v_{be}$

$|A_v| = g_m R_C = 50 \times 2 = 100$ V/V

For v_{ce} being 1 V peak to peak,

$$v_{be} = \frac{1 \text{ V}}{100} = 0.01 \text{ V peak to peak}$$

$$i_b = \frac{v_{be}}{r_\pi}$$

where

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{50} = 2 \text{ k}\Omega$$

Thus,

$$i_b = \frac{0.01 \text{ V}}{2 \text{ k}\Omega} = 0.005 \text{ mA peak to peak}$$

7.50

$$R_{\text{in}} \equiv \frac{v_\pi}{i_b} = r_\pi$$

$$\frac{v_\pi}{v_{\text{sig}}} = \frac{r_\pi}{r_\pi + R_{\text{sig}}}$$

$$v_o = -g_m v_\pi R_C$$

$$\frac{v_o}{v_\pi} = -g_m R_C$$

The overall voltage gain can be obtained as follows:

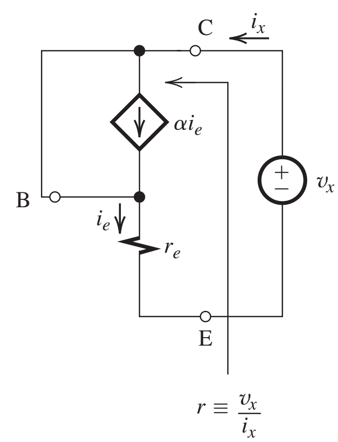
$$\frac{v_o}{v_{\text{sig}}} = \frac{v_o}{v_\pi}\frac{v_\pi}{v_{\text{sig}}}$$

$$= -g_m R_C \frac{r_\pi}{r_\pi + R_{\text{sig}}}$$

$$= -g_m r_\pi \frac{R_C}{r_\pi + R_{\text{sig}}}$$

$$= -\frac{\beta R_C}{r_\pi + R_{\text{sig}}} \qquad \text{Q.E.D.}$$

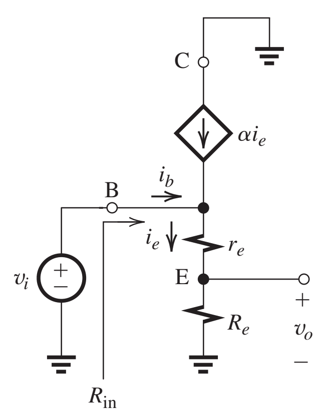
7.51 Replacing the BJT with the T model of Fig. 7.26(b), we obtain the circuit shown below.



Since v_x appears across r_e and $i_x = i_e = \dfrac{v_x}{r_e}$, the small-signal resistance r is given by

$$r \equiv \frac{v_x}{i_x} = \frac{v_x}{i_e} = r_e$$

7.52 Refer to Fig. P7.52. Replacing the BJT with the T model of Fig. 7.26(b) results in the following amplifier equivalent circuit:



$$R_{in} \equiv \frac{v_i}{i_b} = \frac{v_i}{(1-\alpha)i_e}$$

From the circuit we see that

$$i_e = \frac{v_i}{r_e + R_e}$$

Thus,

$$R_{in} = \frac{r_e + R_e}{1-\alpha}$$

But

$$1 - \alpha = \frac{1}{\beta + 1}$$

Thus,

$$R_{in} = (\beta + 1)(r_e + R_e) \qquad \text{Q.E.D.}$$

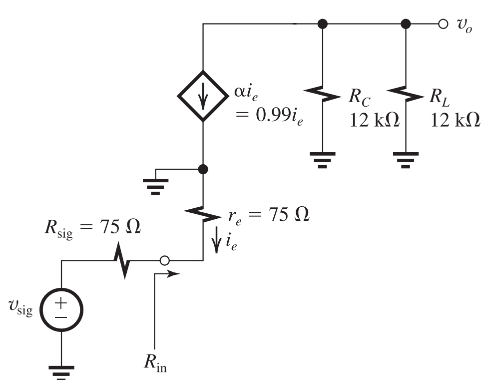
From the equivalent circuit, we see that v_o and v_i are related by the ratio of the voltage divider formed by r_e and R_e:

$$\frac{v_o}{v_i} = \frac{R_e}{R_e + r_e} \qquad \text{Q.E.D.}$$

7.53 Refer to Fig. P7.53. The transistor is biased at $I_E = 0.33$ mA. Thus

$$r_e = \frac{V_T}{I_E} = \frac{25 \text{ mV}}{0.33 \text{ mA}} = 75\ \Omega$$

Replacing the BJT with its T model results in the following amplifier equivalent circuit.



The input resistance R_{in} can be found by inspection to be

$$R_{in} = r_e = 75\ \Omega$$

To determine the voltage gain (v_o/v_i) we first find i_e:

$$i_e = -\frac{v_i}{R_{sig} + r_e} = -\frac{v_i}{150\ \Omega} = -\frac{v_i}{0.15\ \text{k}\Omega}$$

The output voltage v_o is given by

$$v_o = -\alpha\, i_e (R_C \parallel R_L)$$

$$= -0.99\, i_e \times (12 \parallel 12) = -0.99 \times 6 i_e$$

$$= -0.99 \times 6 \times \frac{-v_i}{0.15}$$

Thus,

$$\frac{v_o}{v_i} = 39.6 \text{ V/V}$$

7.54 Refer to Fig. P7.54.

$$\alpha = \frac{\beta}{\beta + 1} = \frac{200}{201} = 0.995$$

$$I_C = \alpha \times I_E = 0.995 \times 10 = 9.95 \text{ mA}$$

$$V_C = I_C R_C = 9.95 \times 0.1\ \text{k}\Omega = 0.995 \text{ V} \simeq 1 \text{ V}$$

Replacing the BJT with its hybrid-π model results in the circuit shown below.

$$g_m = \frac{I_C}{V_T} \simeq \frac{10 \text{ mA}}{0.025 \text{ V}} = 400 \text{ mA/V}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{200}{400} = 0.5\ \text{k}\Omega$$

$$R_{ib} = r_\pi = 0.5\ \text{k}\Omega$$

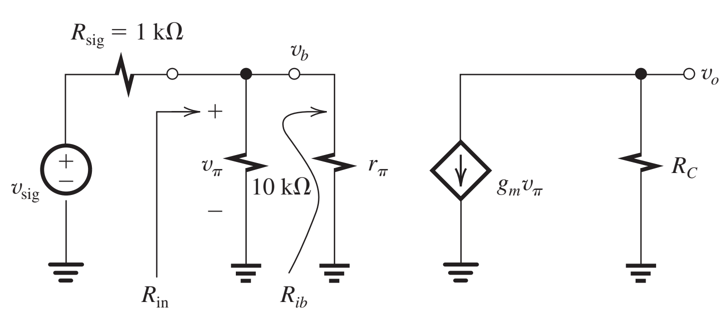
$$R_{in} = 10\ \text{k}\Omega \parallel 0.5\ \text{k}\Omega = 0.476\ \text{k}\Omega$$

$$\frac{v_\pi}{v_{sig}} = \frac{R_{in}}{R_{in} + R_{sig}} = \frac{0.476}{0.476 + 1} = 0.322 \text{ V/V}$$

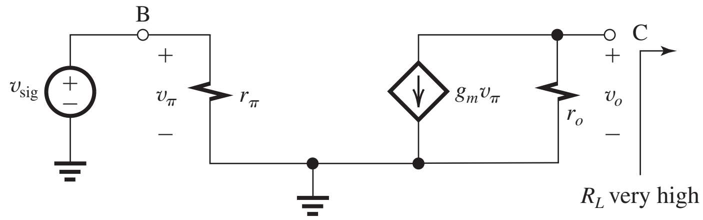
$$\frac{v_o}{v_\pi} = -g_m R_C = -400 \times 0.1 = -40 \text{ V/V}$$

$$\frac{v_o}{v_{sig}} = -40 \times 0.322 = -12.9 \text{ V/V}$$

This figure belongs to Problem 7.54.



This figure belongs to Problem 7.55.



For

$v_o = \pm 0.4$ V/V

$$v_b = v_\pi = \frac{\pm 0.4}{-40} = \mp 0.01 \text{ V} = \mp 10 \text{ mV}$$

$$v_{sig} = \frac{\pm 0.4}{-12.9} = \mp 31 \text{ mV}$$

7.55 The largest possible voltage gain is obtained when $R_L \to \infty$, in which case

$$\frac{v_o}{v_{sig}} = -g_m r_o = -\frac{I_C}{V_T}\frac{V_A}{I_C}$$

$$= -\frac{V_A}{V_T}$$

For $V_A = 25$ V, $\dfrac{v_o}{v_{sig}} = -\dfrac{25}{0.025}$

$= -1000$ V/V

For $V_A = 125$ V, $\dfrac{v_o}{v_{sig}} = -\dfrac{125}{0.025}$

$= -5000$ V/V

7.56 Refer to Fig. 7.30:

$R_{in} \simeq r_e$

To obtain an input resistance of 75 Ω,

$$r_e = 75\ \Omega = \frac{V_T}{I_E}$$

Thus,

$$I_E = \frac{25 \text{ mV}}{75\ \Omega} = 0.33 \text{ mA}$$

This current is obtained by raising R_E to the value found from

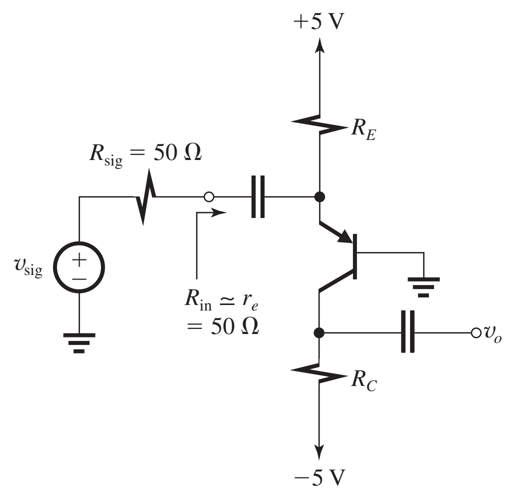
$$I_E = \frac{10 - 0.7}{R_E} = 0.33 \text{ mA}$$

$\Rightarrow R_E = 28.2$ kΩ

Note that the dc voltage at the collector remains unchanged. The voltage gain now becomes

$$\frac{v_o}{v_i} = \frac{\alpha R_C}{r_e} = \frac{0.99 \times 14.1}{0.075} = 186 \text{ V/V}$$

7.57



$$r_e = 50\ \Omega = \frac{V_T}{I_E}$$

$\Rightarrow I_E = 0.5$ mA

Thus,

$$\frac{5 - V_E}{R_E} = 0.5 \text{ mA}$$

where

$V_E \simeq 0.7$ V

$\Rightarrow R_E = 8.6$ kΩ

To obtain maximum gain and the largest possible signal swing at the output for v_{eb} of 10 mV, we select a value for R_C that results in

$$V_C + |A_v| \times 0.01 \text{ V} = +0.4 \text{ V}$$

which is the highest allowable voltage at the collector while the transistor remains in the active region. Since

$$V_C = -5 + I_C R_C \simeq -5 + 0.5 R_C$$

then

$$-5 + 0.5 R_C + g_m R_C \times 0.01 = 0.4$$

Substituting $g_m = 20$ mA/V results in

$R_C = 7.7\ \text{k}\Omega$

The overall voltage gain achieved is

$$\frac{v_o}{v_{sig}} = \frac{R_{in}}{R_{in} + R_{sig}} \times g_m R_C$$

$$= \frac{50}{50+50} \times 20 \times 7.7$$

$$= 77\ \text{V/V}$$

7.58 Refer to Fig. P7.58. Since β is very large, the dc base current can be neglected. Thus the dc voltage at the base is determined by the voltage divider,

$$V_B = 5\frac{100}{100+100} = 2.5\ \text{V}$$

and the dc voltage at the emitter will be

$$V_E = V_B - 0.7 = 1.8\ \text{V}$$

The dc emitter current can now be found as

$$I_E = \frac{V_E}{R_E} = \frac{1.8}{3.6} = 0.5\ \text{mA}$$

and

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

Replacing the BJT with the T model of Fig. 7.26(b) results in the following equivalent circuit model for the amplifier.

$$i_e = \frac{v_i}{R_E + r_e}$$

$$v_{o1} = i_e R_E = v_i \frac{R_E}{R_E + r_e}$$

$$\frac{v_{o1}}{v_i} = \frac{R_E}{R_E + r_e} \qquad \text{Q.E.D.}$$

$$v_{o2} = -\alpha i_e R_C = -\alpha \frac{v_i}{R_E + r_e} R_C$$

$$\frac{v_{o2}}{v_i} = -\frac{\alpha R_C}{R_E + r_e} \qquad \text{Q.E.D.}$$

For $\alpha \simeq 1$,

$$r_e = \frac{V_T}{I_E} = \frac{25\ \text{mV}}{0.5\ \text{mA}} = 50\ \Omega$$

$$\frac{v_{o1}}{v_i} = \frac{3.6}{3.6+0.05} = 0.986\ \text{V/V}$$

$$\frac{v_{o2}}{v_i} = -\frac{3.3}{3.6+0.05} = 0.904\ \text{V/V}$$

If v_{o1} is connected to ground, R_E will in effect be short-circuited at signal frequencies, and v_{o2}/v_i will become

$$\frac{v_{o2}}{v_i} = -\frac{\alpha R_C}{r_e} = -\frac{3.3}{0.05} = -66\ \text{V/V}$$

7.59 See figure on next page.

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

$$= \frac{100}{100+20} \times 100 \times \frac{2}{2+0.1}$$

$$= 79.4\ \text{V/V}$$

$$i_o = \frac{v_o}{R_L}$$

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

$$\frac{i_o}{i_i} = \frac{v_o}{v_{sig}} \frac{R_{sig} + R_{in}}{R_L}$$

$$= G_v \frac{R_{sig} + R_{in}}{R_L}$$

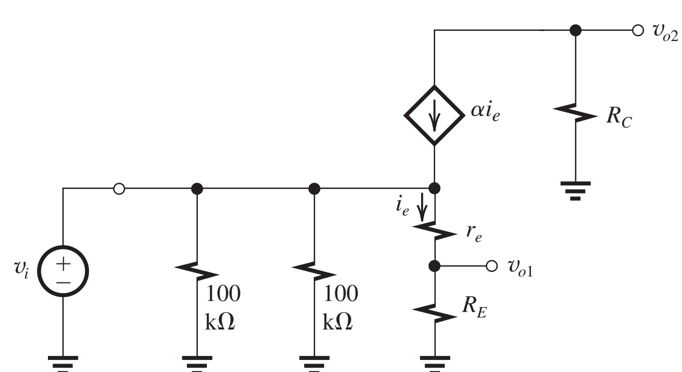
$$= 79.4 \times \frac{20+100}{2} = 4762\ \text{A/A}$$

7.60 (a) $\dfrac{R_{in}}{R_{in} + R_{sig}} = 0.95$

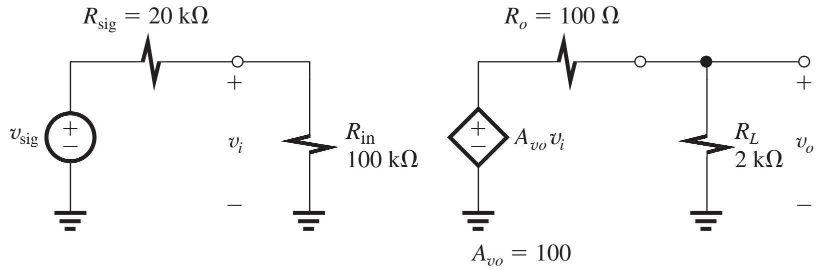
$$\frac{R_{in}}{R_{in} + 100} = 0.95$$

$$\Rightarrow R_{in} = 1.9\ \text{M}\Omega$$

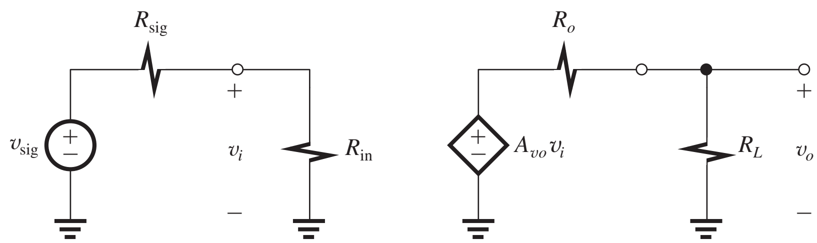
This figure belongs to Problem 7.58.



This figure belongs to Problem 7.59.



This figure belongs to Problem 7.60.



(b) With $R_L = 2\ k\Omega$,

$$v_o = A_{vo} v_i \frac{2}{2 + R_o}$$

With $R_L = 1\ k\Omega$,

$$v_o = A_{vo} v_i\ \frac{1}{1 + R_o}$$

Thus the change in v_o is

$$\Delta v_o = A_{vo} v_i \left[\frac{2}{2 + R_o} - \frac{1}{1 + R_o} \right]$$

To limit this change to 5% of the value with $R_L = 2\ k\Omega$, we require

$$\left[\frac{2}{2 + R_o} - \frac{1}{1 + R_o} \right] \Big/ \left(\frac{2}{2 + R_o} \right) = 0.05$$

$$\Rightarrow R_o = \frac{1}{9}\ k\Omega = 111\ \Omega$$

(c) $G_v = 10 = \dfrac{R_{in}}{R_{in} + R_{sig}} A_{vo} \dfrac{R_L}{R_L + R_o}$

$$= \frac{1.9}{1.9 + 0.1} \times A_{vo} \times \frac{2}{2 + 0.111}$$

$$\Rightarrow A_{vo} = 11.1\ V/V$$

The values found about are limit values; that is, we require

$R_{in} \geq 1.9\ M\Omega$

$R_o \leq 111\ \Omega$

$A_{vo} \geq 11.1\ V/V$

7.61 The circuit in Fig. 1(b) (see figure on next page) is that in Fig. P7.61, with the output current source expressed as $G_m v_i$. Thus, for equivalence, we write

$$G_m = \frac{A_{vo}}{R_o}$$

To determine G_m (at least conceptually), we short-circuit the output of the equivalent circuit in Fig. 1(b). The short-circuit current will be

$$i_o = G_m v_i$$

Thus G_m is defined as

$$G_m = \left. \frac{i_o}{v_i} \right|_{R_L = 0}$$

and is known as the short-circuit transconductance. From Fig. 2 on next page,

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

$$v_o = G_m v_i (R_o \parallel R_L)$$

Thus,

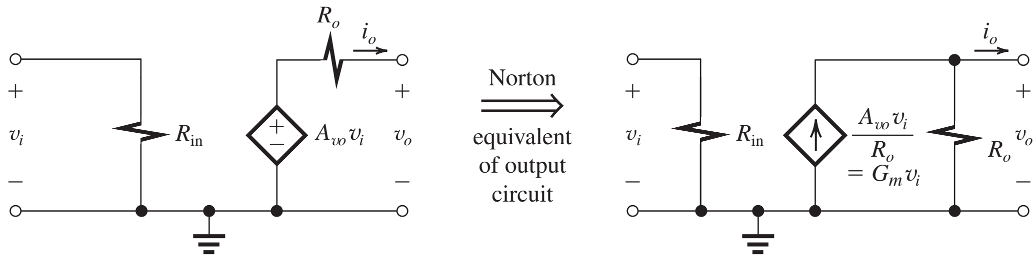
$$\frac{v_o}{v_{sig}} = \frac{R_{in}}{R_{in} + R_{sig}} G_m (R_o \parallel R_L)$$

7.62

$$G_{vo} = \left. \frac{v_o}{v_{sig}} \right|_{R_L = \infty}$$

Now, setting $R_L = \infty$ in the equivalent circuit in Fig. 1(b), we can determine G_{vo} from

This figure belongs to Problem 7.61.



(a) (b)

Figure 1

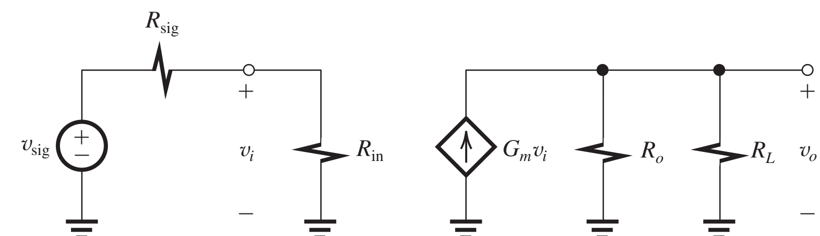
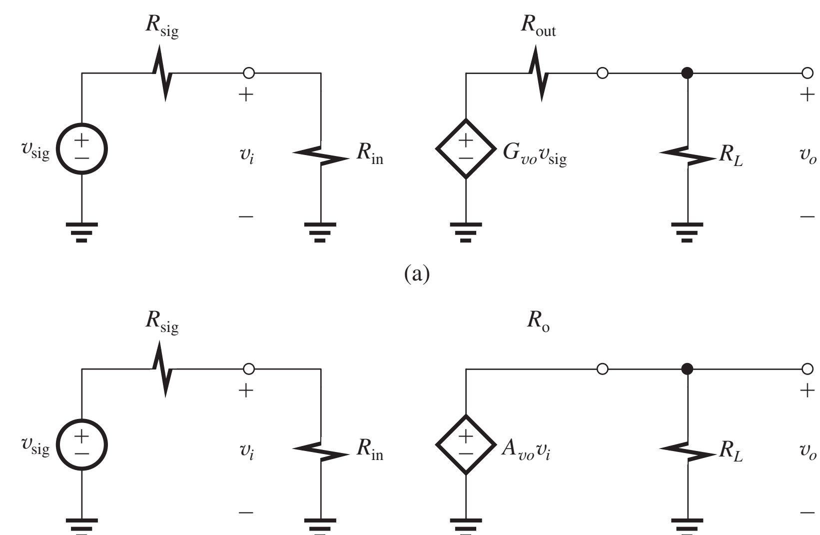


Figure 2

This figure belongs to Problem 7.62.



(a)

(b)

Figure 1

$$G_{vo} = \frac{R_{in}}{R_{in} + R_{sig}}\bigg|_{R_L=\infty} A_{vo}$$

Denoting R_{in} with $R_L = \infty$ as R_i, we can express G_{vo} as

$$G_{vo} = \frac{R_i}{R_i + R_{sig}} A_{vo} \qquad \text{Q.E.D.}$$

From the equivalent circuit in Fig. 1(a), the overall voltage G_v can be obtained as

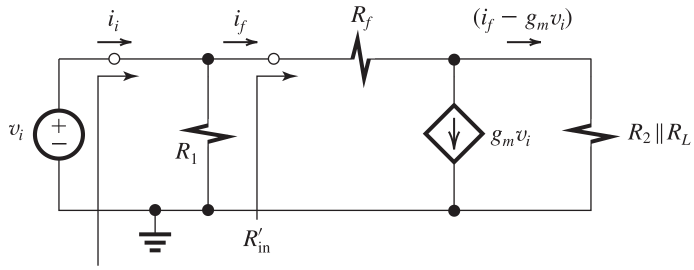
$$G_v = G_{vo}\frac{R_L}{R_L + R_{out}} \qquad \text{Q.E.D.}$$

7.63 Refer to Fig. P7.63. To determine R_{in}, we simplify the circuit as shown in Fig. 1, where

$$R_{in} \equiv \frac{v_i}{i_i} = R_1 \parallel R'_{in}, \quad \text{where } R'_{in} \equiv \frac{v_i}{i_f}$$

$$v_i = i_f R_f + (i_f - g_m v_i)(R_2 \parallel R_L)$$

This figure belongs to Problem 7.63.



$R_{in} \equiv \frac{v_i}{i_i} = R_1 \| R'_{in}$, where $R'_{in} = \frac{v_i}{i_f}$

Figure 1

Thus,

$$v_i[1 + g_m(R_2 \| R_L)] = i_f[R_f + (R_2 \| R_L)]$$

$$R'_{in} \equiv \frac{v_i}{i_f} = \frac{R_f + (R_2 \| R_L)}{1 + g_m(R_2 \| R_L)}$$

and

$$R_{in} = R_1 \| R'_{in}$$

$$= R_1 \| \left[\frac{R_f + (R_2 \| R_L)}{1 + g_m(R_2 \| R_L)}\right] \qquad \text{Q.E.D.}$$

To determine A_{vo}, we open-circuit R_L and use the circuit in Fig. 2, where

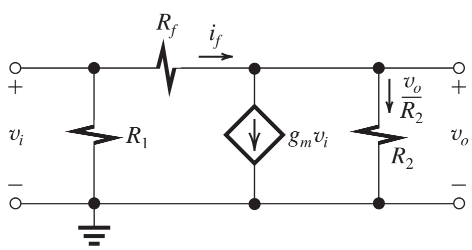


Figure 2

$$i_f = g_m v_i + \frac{v_o}{R_2}$$

$$v_i = i_f R_f + v_o = \left(g_m v_i + \frac{v_o}{R_2}\right)R_f + v_o$$

$$v_i(1 - g_m R_f) = v_o\left(1 + \frac{R_f}{R_2}\right)$$

Thus,

$$A_{vo} \equiv \frac{v_o}{v_i} = \frac{1 - g_m R_f}{1 + \dfrac{R_f}{R_2}}$$

which can be manipulated to the form

$$A_{vo} = -g_m R_2 \frac{1 - 1/g_m R_f}{1 + (R_2/R_f)} \qquad \text{Q.E.D.}$$

Finally, to obtain R_o we short-circuit v_i in the circuit of Fig. P7.63. This will disable the controlled source $g_m v_i$. Thus, looking between the output terminals (behind R_L), we see R_2 in parallel with R_f,

$$R_o = R_2 \| R_f \qquad \text{Q.E.D.}$$

For $R_1 = 100\ \text{k}\Omega,\ R_f = 1\ \text{M}\Omega,\ g_m = 100\ \text{mA/V}$

$R_2 = 100\ \Omega$ and $R_L = 1\ \text{k}\Omega$

$$R_{in} = 100 \| \frac{1000 + (0.1 \| 1)}{1 + 100(0.1 \| 1)} = 100 \| 99.1$$

$$= 49.8\ \text{k}\Omega$$

Without R_f present (i.e., $R_f = \infty$), $R_{in} = 100\ \text{k}\Omega$ and

$$A_{vo} = -100 \times 0.1 \frac{1 - (1/100 \times 1000)}{1 + \dfrac{0.1}{1000}}$$

$$\simeq -10\ \text{V/V}$$

Without R_f, $-A_{vo} = 10\ \text{V/V}$ and

$$R_o = 0.1 \| 1000 \simeq 0.1\ \text{k}\Omega = 100\ \Omega$$

Without R_f, $R_o = 100\ \Omega$.

Thus the only parameter that is significantly affected by the presence of R_f is R_{in}, which is reduced by a factor of 2!

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

With R_f,

$$G_v = \frac{49.8}{49.8 + 100} \times -10 \times \frac{1}{1 + 0.1}$$

$$= -3\ \text{V/V}$$

Without R_f,

$$G_v = \frac{100}{100 + 100} \times -10 \times \frac{1}{1 + 0.1} = -4.5\ \text{V/V}$$

7.64 $R_{sig} = 1\ \text{M}\Omega,\ R_L = 10\ \text{k}\Omega$

$g_m = 2\ \text{mA/V},\ R_D = 10\ \text{k}\Omega$

$G_v = -g_m(R_D \parallel R_L)$

$= -2(10 \parallel 10) = -10$ V/V

7.65 $R_{\text{in}} = \infty$

$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}V_{OV}^2$

$320 = \frac{1}{2} \times 400 \times 10 \times V_{OV}^2$

$\Rightarrow V_{OV} = 0.4$ V

$g_m = \frac{2I_D}{V_{OV}} = \frac{2 \times 0.32}{0.4} = 1.6$ mA/V

$A_{vo} = -g_m R_D = -1.6 \times 10 = -16$ V/V

$R_o = R_D = 10$ kΩ

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

$= -16 \times \frac{10}{10+10} = -8$ V/V

Peak value of $v_{\text{sig}} = \frac{0.2 \text{ V}}{8} = 25$ mV.

7.66 $R_D = 2R_L = 30$ kΩ

$V_{OV} = 0.25$ V

$G_v = -g_m(R_D \parallel R_L)$

$-10 = -g_m(30 \parallel 15)$

$\Rightarrow g_m = 1$ mA/V

$g_m = \frac{2I_D}{V_{OV}}$

$1 = \frac{2 \times I_D}{0.25}$

$\Rightarrow I_D = 0.125$ mA $= 125$ μA

If R_D is reduced to 15 kΩ,

$G_v = -g_m(R_D \parallel R_L)$

$= -1 \times (15 \parallel 15) = -7.5$ V/V

7.67 (a) See figure below.

(b) $g_{m1} = g_{m2} = \frac{2I_D}{V_{OV}} = \frac{2 \times 0.3}{0.2} = 3$ mA/V

$R_{D1} = R_{D2} = 10$ kΩ

$R_L = 10$ kΩ

$G_v = \frac{v_{gs2}}{v_{gs1}} \times \frac{v_o}{v_{gs2}}$

$= -g_{m1}R_{D1} \times -g_{m2}(R_{D2} \parallel R_L)$

$= 3 \times 10 \times 3 \times (10 \parallel 10)$

$= 450$ V/V

7.68 $g_m = \frac{I_C}{V_T} = \frac{0.5 \text{ mA}}{0.025 \text{ V}} = 20$ mA/V

$r_\pi = \frac{\beta}{g_m} = \frac{100}{20 \text{ mA/V}} = 5$ kΩ

$R_{\text{in}} = r_\pi = 5$ kΩ

$R_o = R_C = 10$ kΩ

$A_{vo} = -g_m R_C = -20 \times 10 = -200$ V/V

$A_v = A_{vo}\frac{R_L}{R_L + R_o} = -200 \times \frac{10}{10+10}$

$= -100$ V/V

$G_v = \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}}A_v$

$= \frac{5}{5+10} \times -100$

$= -33.3$ V/V

For $\hat{v}_\pi = 5$ mV, $\hat{v}_{\text{sig}}$ can be found from

$\hat{v}_\pi = \hat{v}_{\text{sig}} \times \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} = \hat{v}_{\text{sig}} \times \frac{5}{5+10}$

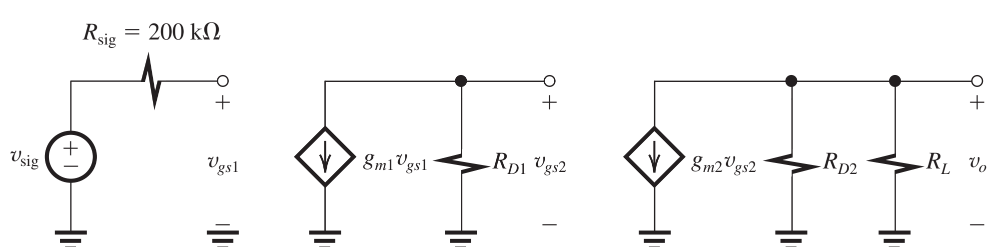
$\Rightarrow \hat{v}_{\text{sig}} = 15$ mV

Correspondingly, $\hat{v}_o$ will be

$\hat{v}_o = G_v \hat{v}_{\text{sig}}$

$= 15 \times 33.3 = 500$ mV $= 0.5$ V

This figure belongs to Problem 7.67.



7.69 $|G_v| = \dfrac{R'_L}{(R_{sig}/\beta) + (1/g_m)}$

$R'_L = 10\text{ k}\Omega,\ R_{sig} = 10\text{ k}\Omega,\ g_m = \dfrac{I_C}{V_T}$

$= \dfrac{1}{0.025} = 40\text{ mA/V}$

Nominal $\beta = 100$

(a) Nominal $|G_v| = \dfrac{10}{(10/100) + 0.025}$

$= 80\text{ V/V}$

(b) $\beta = 50,\ |G_v| = \dfrac{10}{(10/50) + 0.025}$

$= 44.4\text{ V/V}$

$\beta = 150,\ |G_v| = \dfrac{10}{(10/150) + 0.025}$

$= 109.1\text{ V/V}$

Thus, $|G_v|$ ranges from 44.4 V/V to 109.1 V/V.

(c) For $|G_v|$ to be within ±20% of nominal (i.e., ranging between 64 V/V and 96 V/V), the corresponding allowable range of β can be found as follows:

$64 = \dfrac{10}{(10/\beta_{min}) + 0.025}$

$\Rightarrow \beta_{min} = 76.2$

$96 = \dfrac{10}{(10/\beta_{max}) + 0.025}$

$\Rightarrow \beta_{max} = 126.3$

(d) By varying I_C, we vary the term $1/g_m$ in the denominator of the $|G_v|$ expression. If β varies in the range 50 to 150 and we wish to keep $|G_v|$ within ±20% of a new nominal value of $|G_v|$ given by

$|G_v|_{nominal} = \dfrac{10}{(10/100) + (1/g_m)}$

then

$0.8\,|G_v|_{nominal} = \dfrac{10}{(10/50) + (1/g_m)}$

That is,

$\dfrac{8}{0.1 + (1/g_m)} = \dfrac{10}{0.2 + (1/g_m)}$

$\Rightarrow \dfrac{1}{g_m} = 0.3$ or $g_m = 3.33\text{ mA/V}$

$|G_v|_{nominal} = \dfrac{10}{0.1 + 0.3} = 25\text{ V/V}$

$|G_v|_{min} = \dfrac{10}{0.2 + 0.3}$

$= 20\text{ V/V}$ (-20% of nominal)

We need to check the value obtained for $\beta = 150$,

$|G_v|_{max} = \dfrac{10}{10/150 + 0.3} = 27.3\text{ V/V}$

which is less than the allowable value of $1.2\,|G_v|_{nominal} = 30\text{ V/V}$. Thus, the new bias current is

$I_C = g_m \times V_T = 3.33 \times 0.025 = 0.083\text{ mA}$

$|G_v|_{nominal} = 25\text{ V/V}$

7.70 (a) See figure below.

(b) $R_{C1} = R_{C2} = 10\text{ k}\Omega \quad R_{sig} = 10\text{ k}\Omega$

$R_L = 10\text{ k}\Omega$

$g_{m1} = g_{m2} = \dfrac{I_C}{V_T} = \dfrac{0.25\text{ mA}}{0.025\text{ V}} = 10\text{ mA/V}$

$r_{\pi1} = r_{\pi2} = \dfrac{\beta}{g_m} = \dfrac{100}{10} = 10\text{ k}\Omega$

$\dfrac{v_{\pi1}}{v_{sig}} = \dfrac{r_{\pi1}}{r_{\pi1} + R_{sig}} = \dfrac{10}{10 + 10} = 0.5\text{ V/V}$

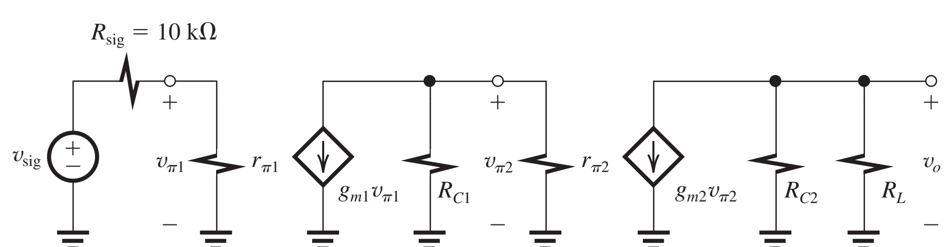
$\dfrac{v_{\pi2}}{v_{\pi1}} = -g_{m1}(R_{C1} \parallel r_{\pi2}) = -10(10 \parallel 10)$

$= -50\text{ V/V}$

$\dfrac{v_o}{v_{\pi2}} = -g_{m2}(R_{C2} \parallel R_L)$

$= -10(10 \parallel 10) = -50\text{ V/V}$

This figure belongs to Problem 7.70.



$$\frac{v_o}{v_{sig}} = \frac{v_o}{v_{\pi 2}} \times \frac{v_{\pi 2}}{v_{\pi 1}} \times \frac{v_{\pi 1}}{v_{sig}}$$

$= -50 \times -50 \times 0.5$

$= 1250$ V/V

7.71 $g_m\big|_{\text{effective}} = \dfrac{g_m}{1 + g_m R_s}$

$$2 = \frac{5}{1 + 5R_s}$$

$\Rightarrow R_s = 0.3\ \text{k}\Omega = 300\ \Omega$

7.72 The gain magnitude is reduced by a factor of $(1 + g_m R_s)$. Thus, to reduce the gain from -10 V/V to -5 V/V, we write

$2 = 1 + g_m R_s$

$$\Rightarrow R_s = \frac{1}{g_m} = \frac{1}{2} = 0.5\ \text{k}\Omega$$

7.73 Including R_s reduced the gain by a factor of 2, thus

$1 + g_m R_s = 2$

$$\Rightarrow g_m = \frac{1}{R_s} = \frac{1}{0.5} = 2\ \text{mA/V}$$

The gain without R_s is -20 V/V. To obtain a gain of -16 V/V, we write

$$16 = \frac{20}{1 + g_m R_s} = \frac{20}{1 + 2R_s}$$

$\Rightarrow R_s = 125\ \Omega$

7.74 $g_m = \dfrac{I_C}{V_T} = \dfrac{0.5}{0.025} = 20$ mA/V

$$r_e \simeq \frac{1}{g_m} = 50\ \Omega$$

$R_{in} = (\beta + 1)(r_e + R_e)$

$= 101(50 + 250) = 30.3\ \text{k}\Omega$

$$A_{vo} = -\frac{\alpha R_C}{r_e + R_e} = -\frac{0.99 \times 12}{0.3} \simeq -40\ \text{V/V}$$

$R_o = R_C = 12\ \text{k}\Omega$

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

$$= -40 \times \frac{12}{12 + 12} = -20\ \text{V/V}$$

$$G_v = \frac{R_{in}}{R_{in} + R_{sig}} \times A_v$$

$$= \frac{30.3}{30.3 + 10} \times -20 = -15\ \text{V/V}$$

$$\hat{v}_\pi = 5\ \text{mV} \Rightarrow \hat{v}_{sig} = \hat{v}_\pi\left(\frac{R_{in} + R_{sig}}{R_{in}}\right)$$

$$\hat{v}_{sig} = 5 \times \frac{30.3 + 10}{30.3} = 6.65\ \text{mV}$$

$\hat{v}_o = \hat{v}_{sig} \times |G_v|$

$= 6.65 \times 15 \simeq 100$ mV

7.75 $R_{in} = (\beta + 1)(r_e + R_e)$

$15 = 75(r_e + R_e)$

$$r_e + R_e = \frac{15\ \text{k}\Omega}{75} = 200\ \Omega$$

$$\hat{v}_\pi = \hat{v}_{sig}\frac{R_{in}}{R_{in} + R_{sig}}\,\frac{r_e}{r_e + R_e}$$

$$5 = 150 \times \frac{15}{15 + 30}\left(\frac{r_e}{r_e + R_e}\right)$$

$$\Rightarrow \frac{r_e}{r_e + R_e} = 0.1$$

But $r_e + R_e = 200\ \Omega$, thus

$r_e = 20\ \Omega$

which requires a bias current I_E of

$$I_E = \frac{V_T}{r_e} = \frac{25\ \text{mV}}{20\ \Omega} = 1.25\ \text{mA}$$

$I_C \simeq I_E = 1.25$ mA

$R_e = 180\ \Omega$

$$G_v = \frac{R_{in}}{R_{in} + R_{sig}} \times \frac{-\alpha \times \text{Total resistance in collector}}{\text{Total resistance in emitter}}$$

$$= \frac{15}{15 + 30} \times \frac{-0.99 \times 6}{0.2}$$

$\simeq -10$ V/V

$\hat{v}_0 = 0.15 \times |G_v| = 1.5$ V

7.76 Using Eq. (7.113), we have

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

$$\simeq -\frac{R_C \parallel R_L}{(R_{sig}/\beta) + (r_e + R_e)}$$

$$|G_v| = \frac{10}{(10/\beta) + 0.025 + R_e}$$

Without R_e,

$$|G_v| = \frac{10}{(10/\beta) + 0.025}$$

For the nominal case, $\beta = 100$,

$$\big|G_v\big|_{\text{nominal}} = \frac{10}{0.1 + 0.025} = 80\ \text{V/V}$$

For $\beta = 50$,

$$\left|G_v\right|_{\text{low}} = \frac{10}{0.2 + 0.025} = 44.4 \text{ V/V}$$

For $\beta = 150$,

$$\left|G_v\right|_{\text{high}} = \frac{10}{(1/15) + 0.025} = 109.1 \text{ V/V}$$

Thus, $|G_v|$ ranges from 44.4 V/V to 109.1 V/V with a nominal value of 80 V/V. This is a range of -44.5% to $+36.4\%$ of nominal.

To limit the range of $|G_v|$ to $\pm 20\%$ of a new nominal value, we connect a resistance R_e and find its value as follows. With R_e,

$$\left|G_v\right|_{\text{nominal}} = \frac{10}{(10/100) + 0.025 + R_e}$$

$$= \frac{10}{0.125 + R_e}$$

Now, $\beta = 50$,

$$\left|G_v\right|_{\text{low}} = \frac{10}{0.225 + R_e}$$

To limit this value to -20% of $\left|G_v\right|_{\text{nominal}}$, we use

$$\frac{10}{0.225 + R_e} = 0.8 \times \frac{10}{0.125 + R_e}$$

$$\Rightarrow R_e = 0.275 \text{ k}\Omega = 275\ \Omega$$

With this value of R_e,

$$\left|G_v\right|_{\text{nominal}} = \frac{10}{0.125 + 0.275} = 25 \text{ V/V}$$

$$\left|G_v\right|_{\text{low}} = \frac{10}{0.225 + 0.275}$$

$$= 20 \text{ V/V } (-20\% \text{ of nominal})$$

$$\left|G_v\right|_{\text{high}} = \frac{10}{(1/15) + 0.025 + 0.275}$$

$$= 27.3 \text{ V/V } (+9.1\% \text{ of nominal})$$

7.77 $R_{\text{in}} = \dfrac{1}{g_m} = \dfrac{1}{2 \text{ mA/V}} = 0.5 \text{ k}\Omega$

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

$$= \frac{0.5}{0.5 + 0.75} \times 2(5 \parallel 5)$$

$$= 2 \text{ V/V}$$

For $R_{\text{in}} = R_{\text{sig}} = 0.75 \text{ k}\Omega$

$$\frac{1}{g_m} = 0.75 \Rightarrow g_m = 1.33 \text{ mA/V}$$

Since $g_m = \sqrt{2k_n I_D}$, then to change g_m by a factor $\dfrac{1.33}{2} = 0.67$, I_D must be changed by a factor of $(0.67)^2 = 0.45$.

7.78 Adding a resistance of 100 Ω in series with the 100-Ω R_{sig} changes the input voltage divider ratio from

$$\frac{1/g_m}{(1/g_m) + 100} \text{ to } \frac{1/g_m}{1/g_m + 200}$$

Since this has changed the overall voltage gain from 12 to 10, then

$$\frac{12}{10} = \frac{(1/g_m) + 200}{(1/g_m) + 100}, \text{ where } g_m \text{ is in A/V}$$

$$\Rightarrow g_m = \frac{0.2}{80} \text{ A/V} = 2.5 \text{ mA/V}$$

For $I_D = 0.25$ mA

$$2.5 = \frac{2I_D}{V_{OV}} = \frac{2 \times 0.25}{V_{OV}}$$

$$\Rightarrow V_{OV} = 0.2 \text{ V}$$

7.79 For $R_{\text{in}} = R_{\text{sig}} = 50\ \Omega$,

$$r_e = 50\ \Omega$$

and, with $\alpha \simeq 1$,

$$I_C \simeq \frac{V_T}{r_e} = \frac{25 \text{ mV}}{50\ \Omega} = 0.5 \text{ mA}$$

$$g_m = I_C/V_T = 20 \text{ mA/V}$$

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

$$G_v = \frac{50}{50 + 50} \times 20 \times (10 \parallel 10)$$

$$= 50 \text{ V/V}$$

7.80 Refer to the circuit in Fig. P7.80. Since $R_{\text{sig}} \gg r_e$, most of i_{sig} flows into the emitter of the BJT. Thus

$$i_e \simeq i_{\text{sig}}$$

and

$$i_c = \alpha i_e \simeq i_{\text{sig}}$$

Thus,

$$v_o = i_c R_C = i_{\text{sig}} R_C$$

7.81 $R_{\text{in}} = r_e = \dfrac{V_T}{I_E} = \dfrac{25 \text{ mV}}{0.2 \text{ mA}} = 125\ \Omega$

$$g_m = \frac{I_C}{V_T} \simeq \frac{0.2 \text{ mA}}{0.025 \text{ V}} = 8 \text{ mA/V}$$

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

$$= \frac{0.125}{0.125 + 0.5} \times 8(10 \parallel 10) = 8 \text{ V/V}$$

$$\hat{v}_\pi = \hat{v}_{sig} \frac{R_{in}}{R_{in} + R_{sig}}$$

$$10 = \hat{v}_{sig} \frac{0.125}{0.125 + 0.5}$$

$$\Rightarrow \hat{v}_{sig} = 50 \text{ mV}$$

$$\hat{v}_o = G_v \hat{v}_{sig} = 8 \times 50 = 400 \text{ mV} = 0.4 \text{ V}$$

7.82 $A_v = \dfrac{R_L}{R_L + R_o}$

$$A_v\big|_{nominal} = \frac{2}{2 + R_o}$$

$$A_v\big|_{low} = \frac{1.5}{1.5 + R_o}$$

$$A_v\big|_{high} = \frac{5}{5 + R_o}$$

For $A_v\big|_{high} = 1.1\, A_v\big|_{nominal}$

$$\frac{5}{5 + R_o} = \frac{1.1 \times 2}{2 + R_o}$$

$$\Rightarrow R_o = 0.357 \text{ k}\Omega$$

$$A_v\big|_{nominal} = \frac{2}{2.357} = 0.85 \text{ V/V}$$

$$A_v\big|_{high} = \frac{5}{5.357}$$

$$= 0.93$$

(+10% above nominal)

$$A_v\big|_{low} = \frac{1.5}{1.5 + 0.357}$$

$$= 0.81 \ (-5\% \text{ from nominal})$$

$$\frac{1}{g_m} = R_o = 0.357 \text{ k}\Omega$$

$$\Rightarrow g_m = 2.8 \text{ mA/V}$$

To find I_D, we use

$$g_m = \sqrt{2k_n I_D}$$

$$\Rightarrow I_D = g_m^2 / 2k_n$$

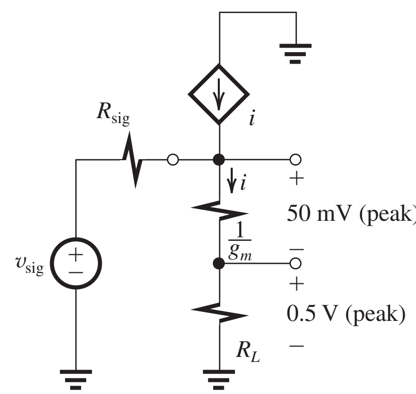
$$= \frac{2.8^2}{2 \times 2.5} = 1.6 \text{ mA}$$

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

$$1.6 = \frac{1}{2} \times 2.5 \times V_{OV}^2$$

$$\Rightarrow V_{OV} = 1.13 \text{ V}$$

7.83



From the figure above, we have

$$\frac{1}{g_m} = 0.1 \times R_L$$

$$= 0.1 \times 2 = 0.2 \text{ k}\Omega$$

$$g_m = 5 \text{ mA/V}$$

$$g_m = \sqrt{2k_n I_D}$$

$$5 = \sqrt{2 \times 5 \times I_D}$$

$$I_D = 2.5 \text{ mA}$$

At the peak of the sine wave,

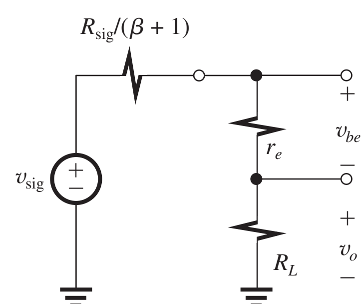
$$i_d = \frac{0.5 \text{ V}}{2 \text{ k}\Omega} = 0.25 \text{ mA, thus}$$

$$i_{Dmax} = I_D + 0.25 = 2.75 \text{ mA}$$

$$i_{Dmin} = I_D - 0.25 = 2.25 \text{ mA}$$

$$\hat{v}_{sig} = \hat{v}_{gs} + \hat{v}_o = 0.05 + 0.5 = 0.55 \text{ V}$$

7.84



$$\hat{v}_o = 0.5 \text{ V}$$

$$R_L = 2 \text{ k}\Omega$$

$$\hat{v}_{be} = 5 \text{ mV}$$

From the figure above we see that

$$\frac{r_e}{R_L} = \frac{5\text{ mV}}{500\text{ mV}}$$

$$\Rightarrow r_e = \frac{R_L}{100} = 20\ \Omega$$

$$I_E = \frac{V_T}{r_e} = \frac{25\text{ mV}}{20\ \Omega} = 1.25\text{ mA}$$

At the peak of the output sine wave, we have

$$\hat{i}_e = \frac{\hat{v}_o}{R_L} = \frac{0.5}{2} = 0.25\text{ mA}$$

Thus,

$$i_{E\max} = 1.25 + 0.25 = 1.5\text{ mA}$$

and

$$i_{E\min} = 1.25 - 0.25 = 1.0\text{ mA}$$

From the figure, we have

$$G_v = \frac{v_o}{v_{\text{sig}}} = \frac{R_L}{R_L + r_e + \dfrac{R_{\text{sig}}}{\beta + 1}}$$

$$= \frac{2}{2 + 0.02 + \dfrac{200}{101}} = 0.5\text{ V/V}$$

Thus,

$$\hat{v}_{\text{sig}} = \frac{\hat{v}_o}{G_v} = \frac{0.5\text{ V}}{0.5\text{ V/V}} = 1\text{ V}$$

7.85 $I_C = 2$ mA

$$r_e = \frac{V_T}{I_E} \simeq \frac{V_T}{I_C} = \frac{25}{2} = 12.5\ \Omega$$

(a) $R_{\text{in}} = (\beta + 1)\ (r_e + R_L)$

$$= 101 \times (12.5 + 500) = 51.76\text{ k}\Omega$$

$$\frac{v_b}{v_{\text{sig}}} = \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} = \frac{51.76}{51.76 + 10}$$

$$= 0.84\text{ V/V}$$

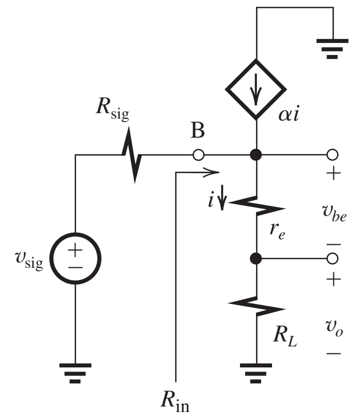
$$\frac{v_o}{v_{\text{sig}}} = \frac{v_b}{v_{\text{sig}}} \times \frac{v_o}{v_b}$$

$$= 0.84 \times \frac{R_L}{R_L + r_e}$$

$$= 0.84 \times \frac{0.5}{0.5 + 0.0125}$$

$$= 0.82\text{ V/V}$$

(b)



$$\hat{v}_{be} = 10\text{ mV}$$

$$\hat{v}_o = \frac{R_L}{r_e} \times \hat{v}_{be}$$

$$= \frac{500}{12.5} \times 10$$

$$= 400\text{ mV} = 0.4\text{ V}$$

$$\hat{v}_{\text{sig}} = \frac{\hat{v}_o}{G_v} = \frac{0.4}{0.82} = 0.488\text{ V}$$

(c) $G_{vo} = 1$

$$R_{\text{out}} = r_e + \frac{R_{\text{sig}}}{\beta + 1} = 12.5 + \frac{10{,}000}{101}$$

$$= 111.5\ \Omega$$

Thus,

$$G_v = G_{vo}\frac{R_L}{R_L + R_{\text{out}}}$$

$$= 1 \times \frac{500}{500 + 111.5} = 0.82\text{ V/V}$$

which is the same value obtained in (a) above.

For $R_L = 250\ \Omega$,

$$G_v = G_{vo}\frac{R_L}{R_L + R_{\text{out}}}$$

$$= 1 \times \frac{250}{250 + 111.5} = 0.69\text{ V/V}$$

7.86 $R_{\text{out}} = r_e + \dfrac{R_{\text{sig}}}{\beta + 1}$

$$r_e = \frac{V_T}{I_E} \simeq \frac{V_T}{I_C} = \frac{25\text{ mV}}{0.5\text{ mA}} = 50\ \Omega$$

$$R_{\text{out}} = 50 + \frac{10{,}000}{101} = 50 + 99 = 149\ \Omega$$

$$G_v = \frac{R_L}{R_L + r_e + \dfrac{R_{\text{sig}}}{\beta + 1}} = \frac{R_L}{R_L + R_{\text{out}}}$$

$$= \frac{1000}{1000 + 149} = 0.87 \text{ V}$$

If β varies between 50 and 150, then we have

$$R_{\text{outmax}} = 50 + \frac{10{,}000}{51} = 50 + 196$$

$$= 246\ \Omega$$

$$R_{\text{outmin}} = 50 + \frac{10{,}000}{151} = 50 + 66.2$$

$$= 116\ \Omega$$

$$G_{v_{\min}} = \frac{R_L}{R_L + R_{\text{outmax}}} = \frac{1000}{1000 + 246}$$

$$= 0.80 \text{ V/V}$$

$$G_{v_{\max}} = \frac{R_L}{R_L + R_{\text{outmin}}} = \frac{1000}{1000 + 116}$$

$$= 0.90 \text{ V/V}$$

7.87 $R_{\text{out}} = r_e + \dfrac{R_{\text{sig}}}{\beta + 1}$

$$150 = r_e + \frac{5000}{\beta + 1} \quad (1)$$

$$250 = r_e + \frac{10{,}000}{\beta + 1} \quad (2)$$

Subtracting Eq. (1) from Eq. (2), we have

$$100 = \frac{5000}{\beta + 1}$$

$$\beta + 1 = 50$$

Substituting in Eq. (1) yields

$$150 = r_e + \frac{5000}{50}$$

$$\Rightarrow r_e = 50\ \Omega$$

$$G_v = \frac{R_L}{R_L + r_e + \dfrac{R_{\text{sig}}}{\beta + 1}}$$

$$= \frac{1000}{1000 + 50 + \dfrac{10{,}000}{50}} = 0.8 \text{ V/V}$$

7.88 (a) Refer to Fig. P7.88.

$$\frac{v_c}{v_{\text{sig}}} = \frac{-i_c R_C}{i_b R_B + i_e (r_e + R_E)}$$

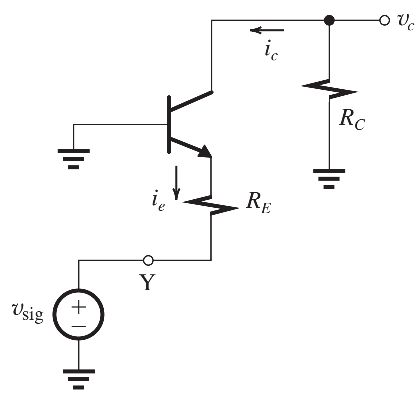
$$= -\frac{i_c}{i_b} \frac{R_C}{R_B + \left(\dfrac{i_e}{i_b}\right)(r_e + R_E)}$$

$$= -\beta \frac{R_C}{R_B + (\beta + 1)(r_e + R_E)}$$

$$\frac{v_e}{v_{\text{sig}}} = \frac{-i_e R_E}{i_b R_B + i_e (r_e + R_E)}$$

$$= \frac{R_E}{\dfrac{R_B}{\beta + 1} + r_e + R_E}$$

(b)



$$i_e = -\frac{v_{\text{sig}}}{r_e + R_E}$$

$$i_c = -i_c R_C = -\alpha i_e R_C$$

$$\frac{v_c}{v_{\text{sig}}} = \frac{-i_c R_C}{i_e (r_e + R_E)} = \alpha \frac{R_C}{r_e + R_E}$$

7.89 With the Early effect neglected, we can write

$$G_v = -100 \text{ V/V}$$

With the Early effect taken into account, the effective resistance in the collector is reduced from $R_C = 10\text{ k}\Omega$ to $(R_C \parallel r_o)$, where

$$r_o = \frac{V_A}{I_C} = \frac{100 \text{ V}}{1 \text{ mA}} = 100 \text{ k}\Omega$$

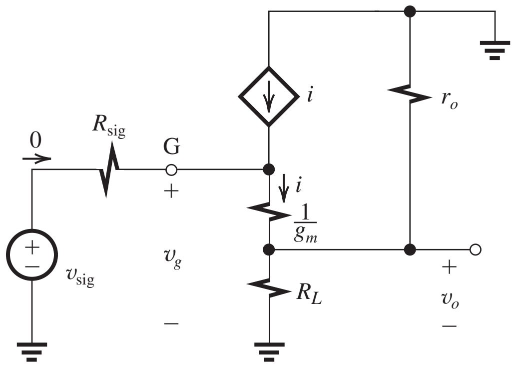
$$(R_C \parallel r_o) = 10 \parallel 100 = 9.1 \text{ k}\Omega$$

Thus, G_v becomes

$$G_v = -100 \times \frac{9.1 \text{ k}\Omega}{10 \text{ k}\Omega}$$

$$= -91 \text{ V/V}$$

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

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

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

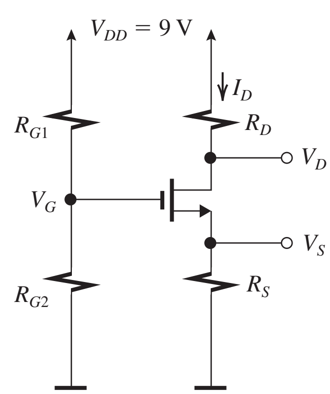
I_C (mA)	$1/g_m$ (kΩ)	r_o (kΩ)	$\lvert G_v \rvert$ (V/V)
0.1	0.250	250	27.5
0.2	0.125	125	41.2
0.5	0.050	50	55.6
1.0	0.025	25	57.1
1.25	0.020	20	55.6

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

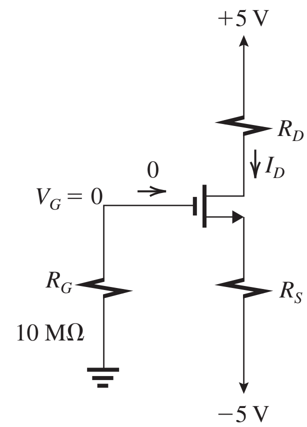
Note that this will cause V_G to deviate slightly from the required value of 5 V. Specifically,

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

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

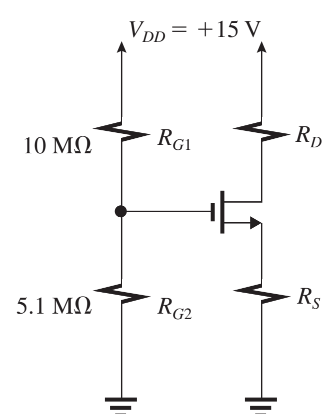
V_D is required to be halfway between cutoff (+5 V) and saturation ($0 - V_t = -1$ V). Thus

$V_D = +2$ V

and

$R_D = \frac{5 - 2}{0.5} = 6$ kΩ

7.94



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

$$= 15 \times \frac{5.1}{10 + 5.1} = 5.07 \text{ V}$$

$$k_n = 0.2 \text{ to } 0.3 \text{ mA/V}^2$$

$$V_t = 1.0 \text{ V to } 1.5 \text{ V}$$

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

With $R_S = 0$,

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

$I_{D\max}$ is obtained with $V_{t\min}$ and $k_{n\max}$:

$$I_{D\max} = \frac{1}{2} \times 0.3(5.07 - 1)^2 = 2.48 \text{ mA}$$

$I_{D\min}$ is obtained with $V_{t\max}$ and $k_{n\min}$:

$$I_{D\min} = \frac{1}{2} \times 0.2(5.07 - 1.5)^2 = 1.27 \text{ mA}$$

With R_S installed and $V_t = 1$ V,
$k_n = 0.3$ mA/V^2, we required $I_D = 1.5$ mA:

$$1.5 = \frac{1}{2} \times 0.3(V_{GS} - 1)^2$$

$$\Rightarrow V_{GS} = 4.16 \text{ V}$$

Since $V_G = 5.07$ V,

$$V_S = V_G - V_{GS} = 5.07 - 4.16 = 0.91 \text{ V}$$

Thus,

$$R_S = \frac{V_S}{I_D} = \frac{0.91}{1.5} = 607 \ \Omega$$

From Appendix J, the closest 5% resistor is 620 Ω. With $R_S = 620 \ \Omega$,

$$V_S = I_D R_S = 0.62 I_D$$

$$V_{GS} = V_G - V_S = 5.07 - 0.62 I_D$$

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

$$= \frac{1}{2} k_n (5.07 - 0.62 I_D - V_t)^2$$

For $k_n = 0.3$ mA/V^2 and $V_t = 1$,

$$I_D = \frac{1}{2} \times 0.3(4.07 - 0.62 I_D)^2$$

$$= 0.15(4.07^2 - 2 \times 4.07 \times 0.62 I_D + 0.62^2 I_D^2)$$

$$0.058 I_D^2 - 1.757 I_D + 2.488 = 0$$

which results in

$$I_D = 28.8 \text{ mA, or } 1.49 \text{ mA}$$

The first value does not make physical sense. Thus,

$$I_D = 1.49 \text{ mA} \simeq 1.5 \text{ mA}$$

which is the maximum value. The minimum value can be obtained by using $k_n = 0.2$ mA/V^2 and $V_t = 1.5$ V in Eq. (1),

$$I_D = \frac{1}{2} \times 0.2(3.57 - 0.62 I_D)^2$$

$$= 0.1(3.57^2 - 2 \times 3.57 \times 0.62 I_D + 0.62^2 I_D^2)$$

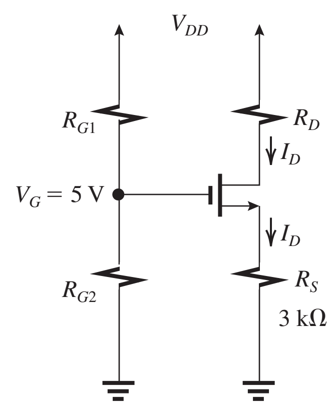
$$0.038 \, I_D^2 - 1.442 I_D + 1.274 = 0$$

which results in

$$I_D = 37 \text{ mA or } 0.91 \text{ mA}$$

Here again, the physically meaningful answer is $I_D = 0.91$ mA, which is the minimum value of I_D. Thus with a 0.62-kΩ resistance connected in the source lead, the value of I_D is limited to the range of 0.91 mA to 1.5 mA.

7.95



$$V_S = I_D R_S = 3 I_D$$

$$V_{GS} = 5 - V_S = 5 - 3 I_D$$

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

$$= \frac{1}{2} \times 2(5 - 3 I_D - 1)^2$$

$$= 16 - 24 I_D + 9 I_D^2$$

$$9 I_D^2 - 25 I + 16 = 0$$

$$I_D = 1.78 \text{ mA or } 1 \text{ mA}$$

The first answer is physically meaningless, as it would result in $V_S = 5.33$ V, which is greater than V_G, implying that the transistor is cut off. Thus, $I_D = 1$ mA.

If a transistor for which $k_n = 3$ mA/V^2 is used, then

$$I_D = \frac{1}{2} \times 3(5 - 3 I_D - 1)^2$$

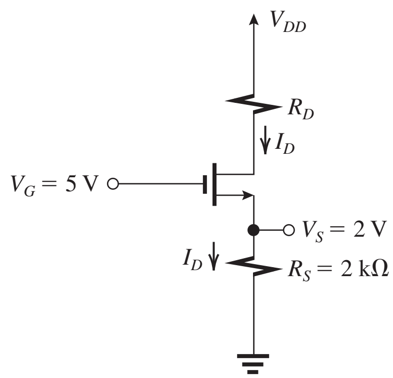
$$= 1.5(16 - 24 I + 9 I_D^2)$$

$9I_D^2 - 24.67I_D + 16 = 0$

whose physically meaningful solution is

$I_D = 1.05$ mA

7.96



$$I_D = \frac{2 \text{ V}}{2 \text{ k}\Omega} = 1 \text{ mA}$$

But

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

$$1 = \frac{1}{2} \times 2(V_G - V_S - V_t)^2$$

$$1 = (5 - 2 - V_t)^2$$

$$V_t = 2 \text{ V}$$

If $V_t = 1.5$ V, then we have

$$V_S = I_D R_S = 2I_D$$

$$V_{GS} = V_G - V_S = 5 - 2I_D$$

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

$$4I_D^2 - 15I_D + 12.25 = 0$$

$$I_D = 1.2 \text{ mA}$$

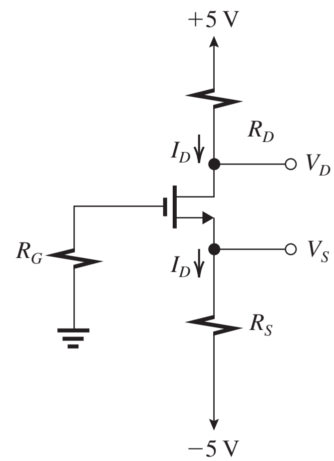
$$V_S = 2.4 \text{ V}$$

7.97 $I_D = 0.5 \text{ mA} = \frac{1}{2} \times 4(V_{GS} - 1)^2$

$\Rightarrow V_{GS} = 1.5$ V

Since $V_G = 0$ V, $V_S = -1.5$ V, and

$$R_S = \frac{-1.5 - (-5)}{0.5} = 7 \text{ k}\Omega$$



Maximum gain is obtained by using the largest possible value of R_D, that is, the lowest possible value of V_D that is consistent with allowing negative voltage signal swing at the drain of 1 V. Thus

$$V_D - 1 = v_{D\min} = V_G - V_t = 0 - 1$$

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

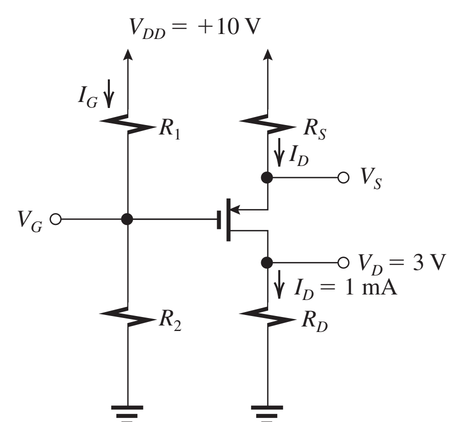
where we have assumed that the signal voltage at the gate is small. Now,

$$V_D = 0 = V_{DD} - I_D R_D$$

$$0 = 5 - 0.5 \times R_D$$

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

7.98



$I_D = 1$ mA and $V_D = 3$ V

Thus,

$$R_D = \frac{V_D}{I_D} = \frac{3 \text{ V}}{1 \text{ mA}} = 3 \text{ k}\Omega$$

For the transistor to operate 1 V from the edge of saturation

$V_D = V_G + |V_t| - 1$

Thus,

$3 = V_G + |V_t| - 1$

$V_G + |V_t| = 4$ V

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

$V_G = 3$ V

$$R_2 = \frac{V_G}{I_G} = \frac{3 \text{ V}}{10 \ \mu\text{A}} = 0.3 \text{ M}\Omega$$

$$R_1 = \frac{V_{DD} - V_G}{I_G} = \frac{7 \text{ V}}{10 \ \mu\text{A}} = 0.7 \text{ M}\Omega$$

$V_D = 3$ V

$R_D = 3$ kΩ

$$I_D = \frac{1}{2} k_p (V_{SG} - |V_t|)^2$$

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

$\Rightarrow V_{SG} = 3$ V

$V_S = V_G + 3 = 3 + 3 = 6$ V

$$R_S = \frac{V_{DD} - V_S}{I_D}$$

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

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

$V_G = 4 - |V_t| = 2$ V

$$R_2 = \frac{V_G}{I_G} = \frac{2 \text{ V}}{10 \ \mu\text{A}} = 0.2 \text{ M}\Omega$$

$$R_1 = \frac{V_{DD} - V_G}{I_G} = \frac{8 \text{ V}}{10 \ \mu\text{A}} = 0.8 \text{ M}\Omega$$

$V_D = 3$ V

$R_D = 3$ kΩ

$$I_D = \frac{1}{2} k_p (V_{SG} - |V_t|)^2$$

$$1 = \frac{1}{2} \times 1.25(V_{SG} - 2)^2$$

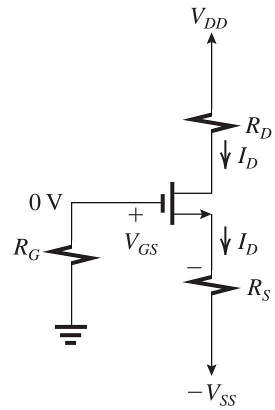
$V_{SG} = 3.265$ V

$V_S = V_G + 3.265 = 2 + 3.265$

$= 5.265$ V

$$R_S = \frac{10 - 5.265}{1} = 4.7 \text{ k}\Omega$$

7.99



(a) $V_{GS} + I_D R_S = V_{SS}$

But

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

$$= K(V_{GS} - V_t)^2$$

$$\Rightarrow V_{GS} = V_t + \sqrt{\frac{I_D}{K}}$$

Thus,

$$V_t + \sqrt{\frac{I_D}{K}} + I_D R_S = V_{SS}$$

Differentiating relative to K, we have

$$0 + \frac{1}{2\sqrt{I_D/K}} \left[\frac{1}{K} \frac{\partial I_D}{\partial K} - \frac{I_D}{K^2} \right] + R_S \frac{\partial I_D}{\partial K} = 0$$

$$\frac{\partial I_D}{\partial K} \frac{K}{I_D} = \frac{1}{1 + 2\sqrt{K I_D}\, R_S}$$

$S_K^{I_D} = 1/[1 + 2\sqrt{K I_D}\, R_S]$ Q.E.D

(b) $K = 100\ \mu$A/V^2, $\dfrac{\Delta K}{K} = \pm 0.1$, and $V_t = 1$ V. We require $I_D = 100\ \mu$A and $\dfrac{\Delta I_D}{I_D} = \pm 0.01$. Thus,

$$S_K^{I_D} = \frac{\Delta I_D / I_D}{\Delta K / K} = \frac{0.01}{0.10} = 0.1$$

Substituting in the expression derived in (a),

$$0.1 = \frac{1}{1 + 2\sqrt{0.1 \times 0.1} R_S}$$

$\Rightarrow R_S = 45$ kΩ

To find V_{GS},

$I_D = K(V_{GS} - V_t)^2$

$100 = 100(V_{GS} - 1)^2$

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

$V_{GS} + I_D R_S = V_{SS}$

$2 + 0.1 \times 45 = 6.5\text{ V}$

(c) For $V_{SS} = 5\text{ V}$ and $V_{GS} = 2\text{ V}$,

$I_D R_S = 3\text{ V}$

$$R_S = \frac{3}{0.1} = 30\text{ k}\Omega$$

$$S_K^{I_D} = \frac{1}{1 + 2\sqrt{0.1 \times 0.1} \times 30} = \frac{1}{7}$$

$$\frac{\Delta I_D}{I_D} = \frac{1}{7} \times \frac{\Delta K}{K} = \frac{1}{7} \times \pm 10\% = \pm 1.4\%$$

7.100 (a) With a fixed V_{GS},

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

$$\frac{\partial I_D}{\partial V_t} = -k_n(V_{GS} - V_t)$$

$$S_{V_t}^{I_D} \equiv \frac{\partial I_D}{\partial V_t}\frac{V_t}{I_D} = -\frac{k_n(V_{GS} - V_t)V_t}{I_D}$$

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

$$= -\frac{2V_t}{V_{GS} - V_t} = -\frac{2V_t}{V_{OV}} \qquad \text{Q.E.D}$$

For $V_t = 0.5\text{ V}$, $\dfrac{\Delta V_t}{V_t} = \pm 5\%$, and $V_{OV} = 0.25\text{ V}$, we have

$$\frac{\Delta I_D}{I_D} = S_{V_t}^{I_D}\left(\frac{\Delta V_t}{V_t}\right)$$

$$= -\frac{2 \times 0.5}{0.25} \times \pm 5\%$$

$$= \mp 20\%$$

(b) For fixed bias at the gate V_G and a resistance R_S in the source lead, we have

$$V_G = V_{GS} + I_D R_S$$

where V_{GS} is obtained from

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

$$\Rightarrow V_{GS} = V_t + \sqrt{\frac{2I_D}{k_n}}$$

Thus

$$V_t + \sqrt{\frac{2I_D}{k_n}} + I_D R_S = V_G$$

Differentiating relative to V_t, we have

$$1 + \frac{1}{2\sqrt{2I_D/k_n}}\frac{2}{k_n}\frac{\partial I_D}{\partial V_t} + R_S\frac{\partial I_D}{\partial V_t} = 0$$

$$\frac{\partial I_D}{\partial V_t}\left[\frac{1}{\sqrt{2k_n I_D}} + R_S\right] = -1$$

$$\frac{\partial I_D}{\partial V_t} = -\frac{1}{\dfrac{1}{\sqrt{2k_n I_D}} + R_S}$$

$$S_{V_t}^{I_D} = \frac{\partial I_D}{\partial V_t}\frac{V_t}{I_D} = -\frac{V_t}{\sqrt{\dfrac{I_D}{2k_n}} + I_D R_S}$$

But

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

Thus

$$S_{V_t}^{I_D} = -\frac{2V_t}{V_{OV} + 2I_D R_S} \qquad \text{Q.E.D}$$

For $V_t = 0.5\text{ V}$, $\dfrac{\Delta V_t}{V_t} = \pm 5\%$, and $V_{OV} = 0.25\text{ V}$, to limit $\dfrac{\Delta I_D}{I_D}$ to $+5\%$ we require

$$S_{V_t}^{I_D} = 1$$

Thus

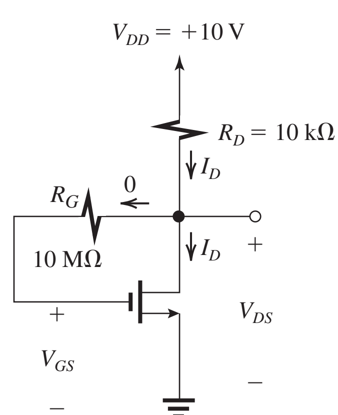
$$-1 = -\frac{2 \times 0.5}{0.25 + 2I_D R_S}$$

$$\Rightarrow I_D R_S = 0.375\text{ V}$$

For $I_D = 0.1\text{ mA}$,

$$R_S = \frac{0.375}{0.1} = 3.75\text{ k}\Omega$$

7.101



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

$= 10 - 10 I_D$

(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

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

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

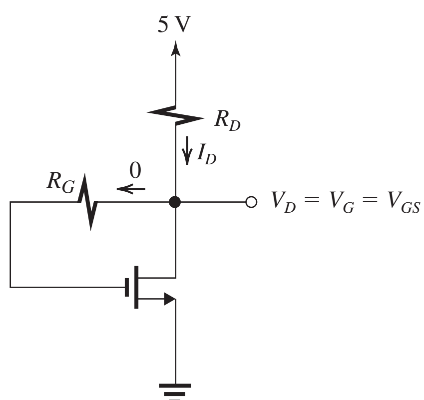
$I_D = 0.92$ mA or 0.695 mA

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

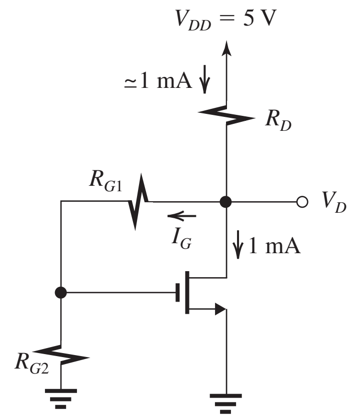


$$I_D = 0.2 = \frac{1}{2} \times 10(V_{GS} - V_t)^2$$

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

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

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

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

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

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

$I_{C\max} = 1 \times e^{(0.710-0.699)/0.025}$

$= 1.55$ mA

and

$I_{C\min} = 1 \times e^{(0.710-0.721)/0.025}$

$I_{C\min} = 0.64$ mA

V_{CE} will range from

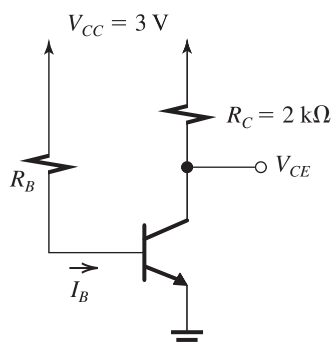
$V_{CE\min} = 3 - 1.55 \times 2 = -0.1$ V

which is impossible, implying that the transistor will saturate at this value of dc bias!

$V_{CE\max} = 3 - 0.64 \times 2 = 1.72$ V

It should be clear that this biasing arrangement is useless, since even the small and inevitable tolerances in R_{B1} and R_{B2} caused such huge variations in I_C that in one extreme the transistor left the active mode of operation altogether!

7.105



To obtain $I_C = 1$ mA, we write

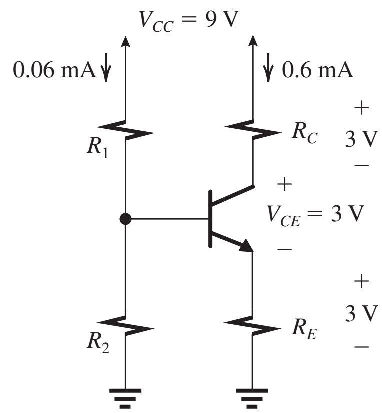
$$I_B = \frac{I_C}{\beta} = \frac{1\text{ mA}}{100} = 0.01\text{ mA}$$

Thus,

$$R_B = \frac{V_{CC} - V_{BE}}{I_B} \simeq \frac{3-0.7}{0.01} = 230\text{ k}\Omega$$

Since β ranges from 50 to 150 and I_B is fixed at 0.01 mA, the collector current I_C will range from $0.01 \times 50 = 0.5$ mA to $0.01 \times 150 = 1.5$ mA. Correspondingly, V_{CE} will range from $(3 - 0.5 \times 2) = 1$ V to $(3 - 1.5 \times 2) = 0$ V. The latter value implies that the high-β transistor will leave the active region of operation and saturate. Obviously, this bias method is very intolerant of the inevitable variations in β. Thus it is not a good method for biasing the BJT.

7.106



Initial design: $\beta = \infty$

$$R_C = R_E = \frac{3\text{ V}}{0.6} = 5\text{ k}\Omega$$

$$R_1 + R_2 = \frac{9}{0.06} = 150\text{ k}\Omega$$

$$V_B = V_E + V_{BE} = 3 + 0.7 = 3.7\text{ V}$$

$$R_2 = \frac{3.7}{0.06} = 61.7\text{ k}\Omega$$

$$R_1 = 150 - 61.7 = 88.3\text{ k}\Omega$$

Using 5% resistors from Appendix J, and selecting R_1 and R_2 so as to obtain a V_{BB} that is slightly higher than 3.7 V, we write

$R_1 = 82$ kΩ and $R_2 = 62$ kΩ

$R_E = 5.1$ kΩ and $R_C = 5.1$ kΩ

$$V_{BB} = V_{CC}\frac{R_2}{R_1 + R_2} = 9 \times \frac{62}{62+82} = 3.875$$

$$I_E = \frac{V_{BB} - V_{BE}}{R_E + \dfrac{R_B}{\beta+1}}$$

where

$$R_B = R_1 \parallel R_2 = 62 \parallel 82 = 35.3\text{ k}\Omega$$

$$I_E = \frac{3.875 - 0.7}{5.1 + \dfrac{35.3}{91}} = 0.58\text{ mA}$$

$$V_E = 0.58 \times 5.1 = 3.18$$

$$V_B = 3.88\text{ V}$$

$$I_C = \alpha I_E = \frac{90}{91} \times 0.58 = 0.57\text{ mA}$$

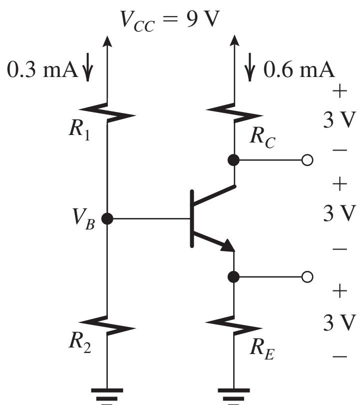
$$V_C = 6.1\text{ V}$$

$$I_{R2} = \frac{V_B}{R_2} = \frac{3.88}{62} = 0.063\text{ mA}$$

$$I_B = \frac{I_E}{\beta+1} = \frac{0.58}{91} = 0.006 \text{ mA and}$$

$$I_{R1} = 0.069 \text{ mA}$$

7.107



Initial design: $\beta = \infty$

$$R_C = R_E = \frac{3 \text{ V}}{0.6 \text{ mA}} = 5 \text{ k}\Omega$$

$$R_1 + R_2 = \frac{9}{0.3} = 30 \text{ k}\Omega$$

$$V_B = V_E + V_{BE} = 3.7 \text{ V}$$

$$R_2 = \frac{3.7}{0.3} = 12.3 \text{ k}\Omega$$

$$R_1 = 30 - 12.3 = 17.7 \text{ k}\Omega$$

If we select 5% resistors, we will have

$$R_E = R_C = 5.1 \text{ k}\Omega$$

$$R_1 = 18 \text{ k}\Omega, \quad R_2 = 13 \text{ k}\Omega$$

$$V_{BB} = 9 \times \frac{13}{13+18} = 3.774 \text{ V}$$

$$I_E = \frac{V_{BB} - V_{BE}}{R_E + \dfrac{R_1 \parallel R_2}{\beta+1}} = \frac{3.774 - 0.7}{5.1 + \dfrac{18 \parallel 13}{91}} =$$
0.593 mA

$$V_E = I_E R_E = 3.02 \text{ V}$$

$$V_B = 3.72 \text{ V}$$

$$I_C = \alpha I_E = \frac{90}{91} \times 0.593 = 0.586 \text{ mA}$$

$$V_C = V_{CC} - I_C R_C = 9 - 0.586 \times 5.1 = 6 \text{ V}$$

I_C falls to the value obtained in Problem 7.106, namely, 0.57 mA at the value of β obtained from

$$I_C = \alpha \frac{V_{BB} - V_{BE}}{R_E + \dfrac{R_1 \parallel R_2}{\beta+1}}$$

$$0.57 = \frac{\beta}{\beta+1} \frac{3.774 - 0.7}{5.1 + \dfrac{18 \parallel 13}{\beta+1}}$$

$$= \frac{\beta \times 3.074}{5.1(\beta+1) + 7.548}$$

$$\Rightarrow \beta = 75.7$$

7.108 Refer to Fig. 7.52.

(a) $I_E = \dfrac{V_{BB} - V_{BE}}{R_E + \dfrac{R_B}{\beta+1}}$

$$I_E\big|_{\text{nominal}} = \frac{V_{BB} - V_{BE}}{R_E + \dfrac{R_B}{101}}$$

$$I_E\big|_{\text{high}} = \frac{V_{BB} - V_{BE}}{R_E + \dfrac{R_B}{151}}$$

$$I_E\big|_{\text{low}} = \frac{V_{BE} - V_{BE}}{R_E + \dfrac{R_B}{51}}$$

Let's constrain $I_E\big|_{\text{low}}$ to be equal to $I_E\big|_{\text{nominal}} \times$ 0.95 and then check $I_E\big|_{\text{high}}$:

$$0.95 \frac{V_{BB} - V_{BE}}{R_E + \dfrac{R_B}{101}} = \frac{V_{BB} - V_{BE}}{R_E + \dfrac{R_B}{51}}$$

$$0.95 = \frac{1 + \dfrac{R_B/R_E}{101}}{1 + \dfrac{R_B/R_E}{51}}$$

$$\Rightarrow \frac{R_B}{R_E} = 5.73$$

For this value,

$$I_E\big|_{\text{nominal}} = 0.946\left(\frac{V_{BB} - V_{BE}}{R_E}\right)$$

$$I_E\big|_{\text{low}} = 0.90\left(\frac{V_{BB} - V_{BE}}{R_E}\right) = 0.95\, I_E\big|_{\text{nominal}}$$

$$I_E\big|_{\text{high}} = 0.963\left(\frac{V_{BE} - V_{BE}}{R_E}\right) = 1.02\, I_E\big|_{\text{nominal}}$$

Thus, the maximum allowable ratio is

$$\frac{R_B}{R_E} = 5.73$$

(b) $I_E = \dfrac{V_{BB} - V_{BE}}{R_E\left(1 + \dfrac{R_B/R_E}{\beta+1}\right)}$

$$I_E R_E = \frac{V_{BB} - V_{BE}}{1 + \frac{5.73}{\beta + 1}}$$

$$\frac{V_{CC}}{3} = \frac{V_{BB} - V_{BE}}{1 + \frac{5.73}{101}}$$

$\Rightarrow V_{BB} = V_{BE} + 0.352 V_{CC}$

(c) $V_{CC} = 5$ V

$V_{BB} = 0.7 + 0.352 \times 5 = 2.46$ V

$$R_E = \frac{V_{CC}/3}{I_E} = \frac{5/3}{0.5} = 3.33\text{ k}\Omega$$

$R_B = 5.73 \times R_E = 19.08\text{ k}\Omega$

$$V_{BB} = V_{CC}\frac{R_2}{R_1 + R_2}$$

$$2.46 = 5\frac{R_2}{R_1 + R_2}$$

$$2.46 R_1 = 5\frac{R_1 R_2}{R_1 + R_2} = 5R_B$$

$= 5 \times 19.08$

$\Rightarrow R_1 = 38.8\text{ k}\Omega$

$$R_2 = 1 \Bigg/ \left(\frac{1}{R_B} - \frac{1}{R_1}\right) = 37.5\text{ k}\Omega$$

(d) $V_{CE} = V_{CC} - R_C I_G$

$1 = 5 - R_C \times 0.99 \times 0.5$

$\Rightarrow R_C = 8.1\text{ k}\Omega$

Check design:

$$V_{BB} = V_{CC}\frac{R_2}{R_1 + R_2} = 5 \times \frac{37.5}{37.5 + 38.8}$$

$= 2.46$ V

$R_B = R_1 \parallel R_2 = 37.5 \parallel 38.8 = 19.07\text{ k}\Omega$

$$I_E\big|_{\text{nominal}} = \frac{2.46 - 0.7}{3.33 + \frac{19.07}{101}} = 0.5\text{ mA}$$

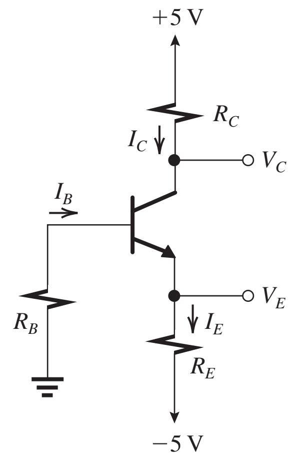
$$I_E\big|_{\text{low}} = \frac{2.46 - 0.7}{3.33 + \frac{19.07}{51}} = 0.475\text{ mA}$$

which is 5% lower than $I_E\big|_{\text{nominal}}$, and

$$I_E\big|_{\text{high}} = \frac{2.46 - 0.7}{3.33 + \frac{19.07}{151}} = 0.509\text{ mA}$$

which is 1.8% higher than $I_E\big|_{\text{nominal}}$.

7.109



Required: $I_C = 0.5$ mA and $V_C = V_E + 2$.

(a) $\beta = \infty$

$V_B = 0$

$V_E = -0.7$ V

$$I_E = 0.5 = \frac{V_E - (-5)}{R_E} = \frac{4.3}{R_E}$$

$\Rightarrow R_E = 8.6\text{ k}\Omega$

$V_C = V_E + 2 = -0.7 + 2 = +1.3$ V

$$R_C = \frac{V_{CC} - V_C}{I_C} = \frac{5 - 1.3}{0.5} = 7.4\text{ k}\Omega$$

(b) $\beta_{\min} = 50$

$$I_{B\max} = \frac{I_E}{51} = \frac{0.5}{51} \simeq 0.01\text{ mA}$$

$I_E R_E = 0.5 \times 8.6 = 4.3$ V

$I_{B\max} R_{B\max} = 0.1 I_E R_E = 0.43$ V

$$R_{B\max} = \frac{0.43}{0.01} = 43\text{ k}\Omega$$

(c) Standard 5% resistors:

$R_B = 43\text{ k}\Omega$

$R_E = 8.2\text{ k}\Omega$

$R_C = 7.5\text{ k}\Omega$

(d) $\beta = \infty$:

$V_B = 0, \quad V_E = -0.7$ V

$$I_E = \frac{-0.7 - (-5)}{8.2} = 0.52\text{ mA}$$

$I_C = 0.52$ mA

$V_C = 5 - 0.52 \times 7.5 = 1.1$ V

$\beta = 50$:

$$I_E = \frac{5 - 0.7}{8.2 + \frac{43}{51}} = 0.48 \text{ mA}$$

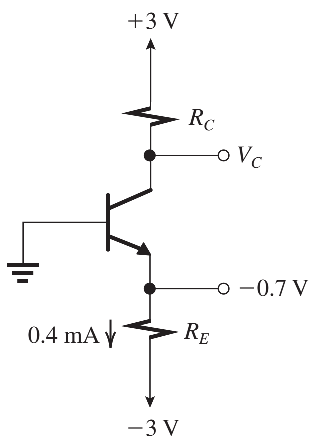
$V_E = -5 + 0.48 \times 8.2 = -1.064$ V

$V_B = -0.364$ V

$$I_C = \alpha I_E = \frac{50}{51} \times 0.48 = 0.47 \text{ mA}$$

$V_C = 5 - 0.47 \times 7.5 = 1.475$ V

7.110



$$R_E = \frac{-0.7 - (-3)}{0.4}$$

$= 5.75$ kΩ

To maximize gain while allowing for ±1 V signal swing at the collector, design for the lowest possible V_C consistent with

$V_C - 1 = -0.7 + V_{CE\text{sat}}$

$= -0.7 + 0.3 = -0.4$ V

$V_C = 0.6$ V

$$R_C = \frac{V_{CC} - V_C}{I_C} = \frac{3 - 0.6}{0.39} = 6.2 \text{ k}\Omega$$

As temperature increases from 25°C to 125°C, (i.e., by 100°C), V_{BE} decreases by 2 mV × 100 = − 200 mV. Thus I_E increases by $\frac{0.2 \text{ V}}{R_E} =$ $\frac{0.2 \text{ V}}{5.75 \text{ k}\Omega} = 0.035$ mA to become 0.435 mA. The collector current becomes

$$I_C = \frac{\beta}{\beta + 1} \times 0.435$$

where β is the increased value of 150,

$$I_C = \frac{150}{151} \times 0.435 \text{ mA}$$

$= 0.432$ mA

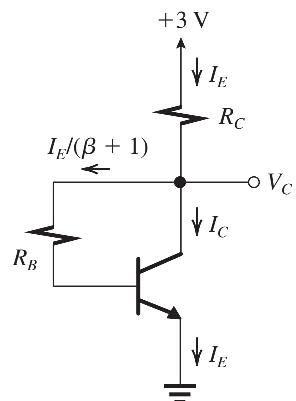
Thus,

$\Delta I_C = 0.432 - 0.39 = 0.042$ mA

for a percentage increase of

$$\frac{\Delta I_C}{I_C} \times 100 = \frac{0.042}{0.39} \times 100 = 10.8\%$$

7.111



$V_C = V_{CE\text{sat}} + 1$ V

$= 1.3$ V

$$I_E = \frac{3 - 1.3}{R_C} = 0.5 \text{ mA}$$

$\Rightarrow R_C = 3.4$ kΩ

$$I_B = \frac{I_E}{\beta + 1} = \frac{0.5}{101} \simeq 0.005 \text{ mA}$$

$V_C = V_{BE} + I_B R_B$

$1.3 = 0.7 + 0.005 \times R_B$

$\Rightarrow R_B = 120$ kΩ

Standard 5% resistors:

$R_C = 3.3$ kΩ

$R_B = 120$ kΩ

If the actual BJT has $\beta = 50$, then

$$I_E = \frac{V_{CC} - V_{BE}}{R_C + \frac{R_B}{\beta + 1}} = \frac{3 - 0.7}{3.3 + \frac{120}{51}} = 0.41 \text{ mA}$$

$V_C = 3 - I_E R_C = 3 - 0.41 \times 3.3 = 1.65$ V

Allowable negative signal swing at the collector is as follows:

$V_C - V_{CE\text{sat}} = 1.65 - 0.3 = 1.35$ V

An equal positive swing is *just* possible. For $\beta = 150$:

$$I_E = \frac{3 - 0.7}{3.3 + \frac{120}{151}} = 0.56 \text{ mA}$$

$$V_C = 3 - I_E R_C = 3 - 0.56 \times 3.3 = 1.15 \text{ V}$$

Allowable negative signal swing at the collector $= 1.15 - 0.3 = 0.85$ V. An equal positive swing is possible.

7.112

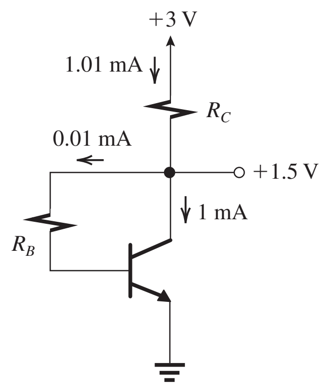


Figure 1

(a) From the circuit diagram of Fig. 1, we can write

$$R_C = \frac{3 - 1.5}{1.01 \text{ mA}} \simeq 1.5 \text{ k}\Omega$$

$$1.5 = 0.01 R_B + V_{BE}$$

$$= 0.01 R_B + 0.7$$

$$\Rightarrow R_B = 80 \text{ k}\Omega$$

(b) Selecting 5% resistors, we have

$$R_C = 1.5 \text{ k}\Omega$$

$$R_B = 82 \text{ k}\Omega$$

$$I_E = \frac{V_{CC} - V_{BE}}{R_C + \frac{R_B}{\beta + 1}}$$

$$= \frac{3 - 0.7}{1.5 + \frac{82}{101}} = 0.99 \text{ mA}$$

$$I_C = \alpha I_E = 0.99 \times 0.99 = 0.98 \text{ mA}$$

$$V_C = 3 - 1.5 \times 0.99 = 1.52 \text{ V}$$

(c) $\beta = \infty$:

$$I_C = I_E = \frac{V_{CC} - V_{BE}}{R_C} = \frac{3 - 0.7}{1.5} = 1.53 \text{ mA}$$

$$V_C = 0.7 \text{ V}$$

(d) From the circuit diagram of Fig. 2, we can write

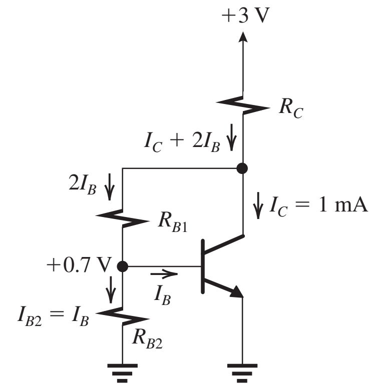


Figure 2

$$I_B = \frac{I_C}{\beta} = \frac{1}{100} = 0.01 \text{ mA}$$

$$R_{B2} = \frac{0.7}{I_{B2}} = \frac{0.7}{0.01}$$

$$= 70 \text{ k}\Omega$$

$$1.5 = 2 I_B R_{B1} + 0.7$$

$$0.8 = 2 \times 0.01 \times R_{B1}$$

$$R_{B1} = 40 \text{ k}\Omega$$

$$R_C = \frac{3 - 1.5}{I_C + 2I_B} = \frac{1.5}{1.02} = 1.47 \text{ k}\Omega$$

For $\beta = \infty$:

$$I_B = 0, \quad I_{B2} = \frac{0.7}{R_{B2}} = \frac{0.7}{70} = 0.01 \text{ mA}$$

$$I_{B1} = I_{B2} = 0.01 \text{ mA}$$

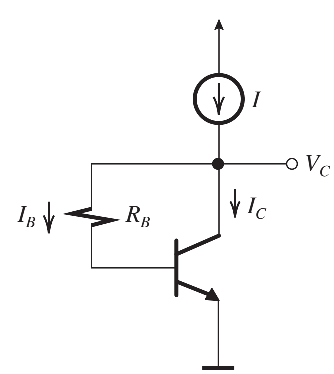
$$V_C = 0.01 R_{B1} + 0.7 = 0.01 \times 40 + 0.7$$

$$= 1.1 \text{ V}$$

$$I_C + 0.01 = \frac{3 - 1.1}{R_C} = \frac{3 - 1.1}{1.47} = 1.29$$

$$I_C = 1.28 \text{ mA}$$

7.113



$I_C = 1$ mA

$I = I_C + I_B$

$= I_C + \dfrac{I_C}{\beta}$

$= 1\left(1 + \dfrac{1}{\beta}\right)$

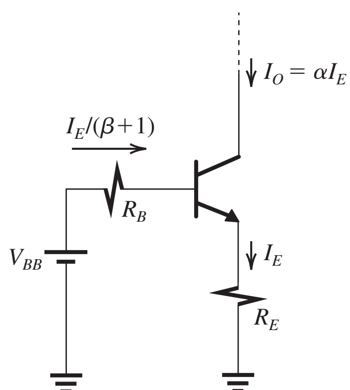
$I = 1.01$ mA

$V_C = 1.5\text{ V} = I_B R_B + V_{BE}$

$1.5 = 0.01 \times R_B + 0.7$

$R_B = 80\text{ k}\Omega$

7.114 Refer to the circuit in Fig. P7.114. Replacing V_{CC} together with the voltage divider (R_1, R_2) by its Thévenin equivalent results in the circuit shown below.



where

$$V_{BB} = V_{CC}\frac{R_2}{R_1 + R_2}$$

and

$$R_B = (R_1 \parallel R_2)$$

Now,

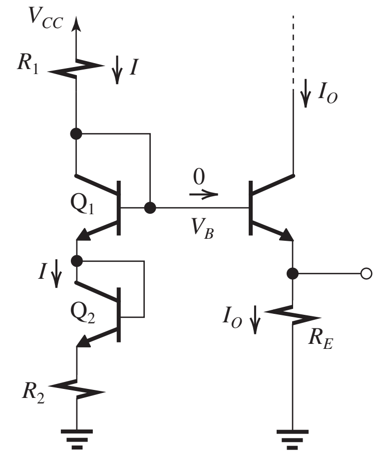
$$V_{BB} = \frac{I_E}{\beta + 1}R_B + V_{BE} + I_E R_E$$

$$I_E = \frac{V_{BB} - V_{BE}}{R_E + (R_1 \parallel R_2)/(\beta + 1)}$$

$$I_C = \alpha I_E$$

$$= \alpha\frac{V_{CC}[R_2/(R_1 + R_2)] - V_{BE}}{R_E + (R_1 \parallel R_2)/(\beta + 1)}$$

7.115



$$I = \frac{V_{CC} - V_{BE1} - V_{BE2}}{R_1 + R_2}$$

$$V_B = IR_2 + V_{BE2} + V_{BE1}$$

$$V_{E3} = V_B - V_{BE3}$$

$$V_{E3} = IR_2 + V_{BE2} + V_{BE1} - V_{BE3}$$

$$= (V_{CC} - V_{BE1} - V_{BE2})\frac{R_2}{R_1 + R_2} + V_{BE1}$$

$$+V_{BE2} - V_{BE3}$$

$$I_O = \frac{V_E}{R_E} = \frac{\alpha}{R_E}\left[(V_{CC} - V_{BE1} - V_{BE2})\frac{R_2}{R_1 + R_2}\right.$$

$$\left. + V_{BE1} + V_{BE2} - V_{BE3}\right]$$

Now, for $R_1 = R_2$ and the currents in all junctions equal,

$$V_{BE1} = V_{BE2} = V_{BE3} = V_{BE}$$

$$I_O = \frac{1}{R_E}\left[(V_{CC} - 2V_{BE}) \times \frac{1}{2} + V_{BE}\right]$$

$$I_O = \frac{V_{CC}}{2R_E} \qquad \text{Q.E.D}$$

Thus,

$$I_O R_E = \frac{V_{CC}}{2}$$

$$V_B = \frac{V_{CC}}{2} + V_{BE}$$

$$I = (V_B - 2V_{BE})/R_2 = \left(\frac{V_{CC}}{2} - V_{BE}\right)\Big/ R_2$$

But since I must be equal to I_O, we have

$$\frac{V_{CC}}{2R_E} = \frac{V_{CC}/2 - V_{BE}}{R_2}$$

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,

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

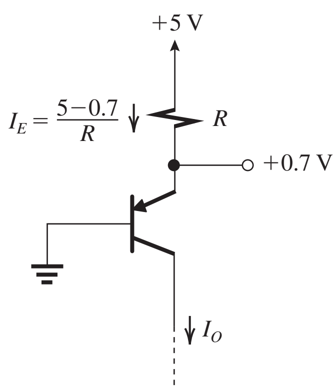
To obtain $I_O = 0.5$ mA,

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

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

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

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.

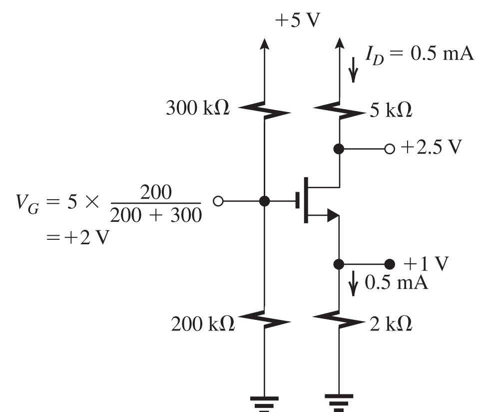


Figure 1

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.

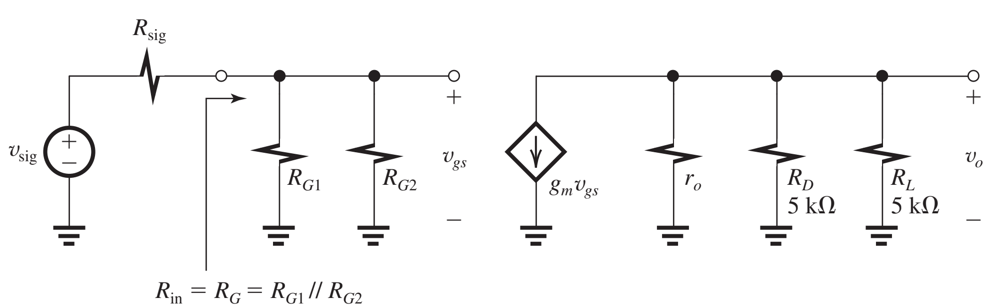


Figure 2

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) $+ v_{\text{sig}}$

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

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

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:

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

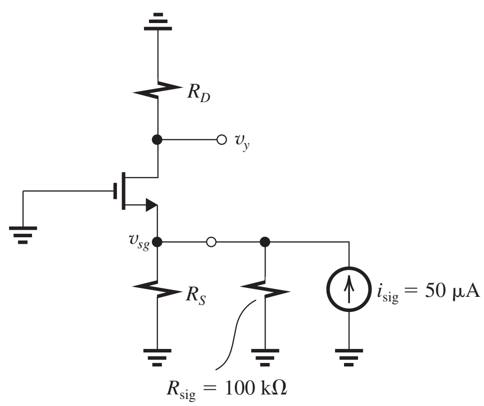
$$= \frac{(9.5 \parallel 100)}{(9.5 \parallel 100) + \dfrac{1}{2}} = 0.946\ \text{V/V}$$

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):

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

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

(b) Refer to Fig. P7.122(b):

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

$$\frac{v_o}{v_{i2}} = \frac{5 \parallel 2}{1/g_m} = 10(5 \parallel 2) = 14.3\text{ V/V}$$

(c) $v_{i2} = (A_{vo} v_i)\dfrac{R_{\text{in}}}{R_{\text{in}} + R_o}$

$$= 0.99 \times v_i \times \frac{99}{99 + 99}$$

$$\simeq 0.5 v_i$$

$$v_o = 14.3 \times v_{i2} = 14.3 \times 0.5 v_i$$

$$\frac{v_o}{v_i} = 7.15\text{ V/V}$$

7.123 (a) DC bias:

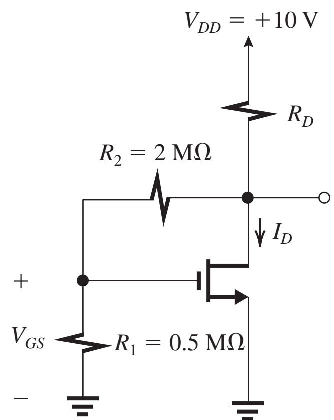


Figure 1

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

$$= 0.6 + 0.2 = 0.8\text{ V}$$

From the voltage divider (R_1, R_2: see Fig. 1), we can write

$$V_{GS} = V_D \frac{R_1}{R_1 + R_2} = V_D \frac{0.5}{0.5 + 2}$$

$$V_D = 5V_{GS} = 5 \times 0.8 = 4\text{ V}$$

$$I_D = \frac{1}{2} k_n V_{OV}^2 \left(1 + \frac{V_{DS}}{V_A}\right)$$

$$I_D = \frac{1}{2} \times 5 \times 0.2^2 \left(1 + \frac{4}{60}\right)$$

$$= 0.107\text{ mA}$$

The current in the voltage divider is

$$I = \frac{V_D}{R_1 + R_2} = \frac{4}{2.5} = 1.6\ \mu\text{A} = 0.0016\text{ mA}$$

Thus the current through R_D will be $(0.107 + 0.0016) \simeq 0.109$ mA and

$$R_D = \frac{V_{DD} - V_D}{0.109} = \frac{10 - 4}{0.109} = 55\text{ k}\Omega$$

(b) $g_m = \dfrac{2I_D}{V_{OV}} = \dfrac{2 \times 0.107}{0.2} = 1.07\text{ mA/V}$

$$r_o = \frac{V_A}{I_D} = \frac{60}{0.107} = 561\text{ k}\Omega$$

(c) Upon replacing the MOSFET with its hybrid-π model, we obtain the small-signal equivalent circuit of the amplifier, shown in Fig. 2.

Node equation at the output:

$$\frac{v_o}{R_D} + \frac{v_o}{r_o} + \frac{v_o - v_{gs}}{R_2} + g_m v_{gs} = 0$$

$$v_o\left(\frac{1}{R_D} + \frac{1}{r_o} + \frac{1}{R_2}\right) = -g_m\left(1 - \frac{1}{g_m R_2}\right) v_{gs}$$

Thus,

$$v_o = -\overbrace{g_m (R_D \parallel r_o \parallel R_2)\left(1 - \frac{1}{g_m R_2}\right)}^{A} v_{gs} \qquad (1)$$

Next, we express v_{gs} in terms of v_{sig} and v_o using superposition:

$$v_{gs} = v_{\text{sig}} \frac{R_2}{R_1 + R_2} + v_o \frac{R_1}{R_1 + R_2} \qquad (2)$$

This figure belongs to Problem 7.123(c).

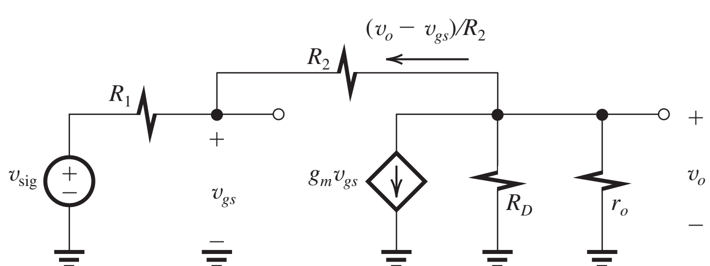


Figure 2

Substituting for v_{gs} from Eq. (2) into Eq. (1) yields

$$v_o = -Av_{\text{sig}}\frac{R_2}{R_1+R_2} - Av_o\frac{R_1}{R_1+R_2}$$

where

$$A = g_m(R_D \parallel r_o \parallel R_2)\left(1-\frac{1}{g_mR_2}\right)$$

Thus,

$$v_o\left(1+A\frac{R_1}{R_1+R_2}\right) = -A\frac{R_2}{R_1+R_2}v_{\text{sig}}$$

$$\frac{v_o}{v_{\text{sig}}} = \frac{-A\dfrac{R_2}{R_1+R_2}}{1+A\dfrac{R_1}{R_1+R_2}}$$

$$= \frac{-R_2/R_1}{1+\dfrac{1+R_2/R_1}{A}}$$

Thus,

$$\frac{v_o}{v_{\text{sig}}} = -\frac{R_2/R_1}{1+\dfrac{1+R_2/R_1}{g_m(R_D \parallel r_o \parallel R_2)(1-1/g_mR_2)}}$$

Q.E.D

Substituting numerical values yields

$$\frac{v_o}{v_{\text{sig}}} =$$

$$-\frac{2/0.5}{1+\dfrac{1+(2/0.5)}{1.07(55 \parallel 561 \parallel 2000)(1-1/1.07\times 2000)}}$$

$$= -\frac{4}{\left(1+\dfrac{5}{52.6}\right)}$$

$$= -3.65\text{ V/V}$$

Note that the gain is nearly equal to $-R_2/R_1 = -4$, which is the gain of an op amp connected in the inverting configuration.

7.124 (a) DC bias:

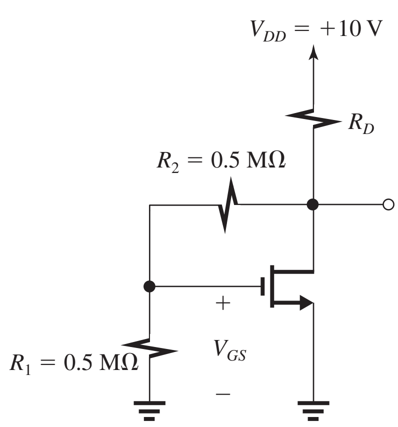


Figure 1

$$V_{OV} = 0.2\text{ V}$$

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

$$= 0.6 + 0.2 = 0.8\text{ V}$$

From the voltage divider (R_1, R_2: see Fig. 1), we can write

$$V_{GS} = \frac{R_1}{R_1+R_2}V_D = \frac{0.5}{0.5+0.5}V_D = 0.5V_D$$

Thus

$$V_D = 2V_{GS} = 1.6\text{ V}$$

$$I_D = \frac{1}{2}k_nV_{OV}^2$$

$$= \frac{1}{2}\times 5\times 0.2^2 = 0.1\text{ mA}$$

$$I_{\text{divider}} = \frac{V_D}{1\text{ M}\Omega} = \frac{1.6\text{ V}}{1\text{ M}\Omega} = 1.6\ \mu\text{A}$$

$$I_{R_D} = 0.1 + 0.0016 \simeq 0.102\text{ mA}$$

$$R_D = \frac{V_{DD}-V_D}{I_{R_D}} = \frac{10-1.6}{0.102} = 82.4\text{ k}\Omega$$

(b) $g_m = \dfrac{2I_D}{V_{OV}} = \dfrac{2\times 0.1}{0.2} = 1\text{ mA/V}$

(c) Replacing the MOSFET with its T model results in the amplifier equivalent circuit shown in Fig. 2. At the output node,

$$v_o = i[R_D \parallel (R_1+R_2)]$$

$$v_o = iR'_D \tag{1}$$

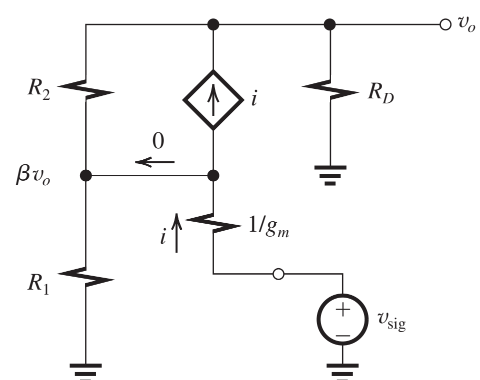


Figure 2

where $R'_D = R_D \parallel (R_1+R_2)$. The voltage at the gate is a fraction β of v_o with

$$\beta = \frac{R_1}{R_1+R_2}$$

Now, the current i can be found from

$$i = \frac{v_{\text{sig}}-\beta v_o}{1/g_m} = g_mv_{\text{sig}} - \beta g_mv_o \tag{2}$$

Substituting for i from Eq. (2) into Eq. (1) yields

$$v_o = (g_m v_{sig} - \beta g_m v_o)R'_D$$

Thus

$$\frac{v_o}{v_{sig}} = \frac{g_m R'_D}{1 + \beta g_m R'_D}$$

$$= \frac{1/\beta}{1 + \dfrac{1/\beta}{g_m R'_D}}$$

$$= \frac{1 + (R_2/R_1)}{1 + \dfrac{1 + R_2/R_1}{g_m R'_D}} \qquad \text{Q.E.D} \qquad (3)$$

The input resistance R_{in} can be obtained as follows:

$$R_{in} = \frac{v_{sig}}{i}$$

Substituting for i from Eq. (1) yields

$$R_{in} = \frac{v_{sig}}{v_o} R'_D$$

and replacing $\frac{v_{sig}}{v_o}$ by the inverse of the gain expression in Eq. (3) gives

$$R_{in} = R'_D\left[\frac{1}{g_m R'_D} + \frac{1}{1 + (R_2/R_1)}\right]$$

$$R_{in} = \frac{1}{g_m}\left[1 + g_m R'_D \frac{R_1}{R_1 + R_2}\right] \qquad \text{Q.E.D}$$

(d) Substituting numerical values:

$$\frac{v_o}{v_{sig}} = \frac{1 + (0.5/0.5)}{1 + \dfrac{1 + (0.5/0.5)}{1 \times (82.4 \parallel 1000)}}$$

$$= \frac{2}{1 + \dfrac{2}{76.13}} = 1.95 \text{ V/V}$$

Note that the gain $\simeq 1 + \frac{R_2}{R_1} = 2$, similar to that of an op amp connected in the noninverting configuration!

$$R_{in} = \frac{1}{1}\left[1 + 1 \times (82.4 \parallel 1000)\frac{0.5}{0.5 + 0.5}\right]$$

$$= 39.1 \text{ k}\Omega$$

7.125 Refer to the circuit of Fig. P7.125.

$$I_C = \frac{\alpha(V_{BB} - V_{BE})}{R_E + \dfrac{R_B}{\beta + 1}}$$

where

$$V_{BB} = V_{CC}\frac{R_2}{R_2 + R_1} = 15 \times \frac{15}{15 + 27} = 5.357 \text{ V}$$

$$R_B = R_1 \parallel R_2 = 15 \parallel 27 = 9.643 \text{ k}\Omega$$

$$I_C = \frac{0.99(5.357 - 0.7)}{2.4 + \dfrac{9.643}{101}} = 1.85 \text{ mA}$$

$$g_m = \frac{I_C}{V_T} = \frac{1.85 \text{ mA}}{0.025 \text{ V}} = 74 \text{ mA/V}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{74} = 1.35 \text{ k}\Omega$$

Replacing the BJT with its hybrid-π model results in the equivalent circuit shown at the bottom of the page:

$$R_{in} = R_1 \parallel R_2 \parallel r_\pi = R_B \parallel r_\pi = 9.643 \parallel 1.35$$

$$= 1.18 \text{ k}\Omega$$

$$\frac{v_\pi}{v_{sig}} = \frac{R_{in}}{R_{in} + R_{sig}} = \frac{1.18}{1.18 + 2} = 0.371 \text{ V/V}$$

$$\frac{v_o}{v_\pi} = -g_m(R_C \parallel R_L)$$

$$= -74(3.9 \parallel 2) = -97.83$$

$$\frac{v_o}{v_{sig}} = -0.371 \times 97.83 = -36.3 \text{ V/V}$$

7.126 Refer to the circuit of Fig. P7.125.

DC design:

$$V_B = 5 \text{ V}, \quad V_{BE} = 0.7 \text{ V}$$

$$V_E = 4.3 \text{ V}$$

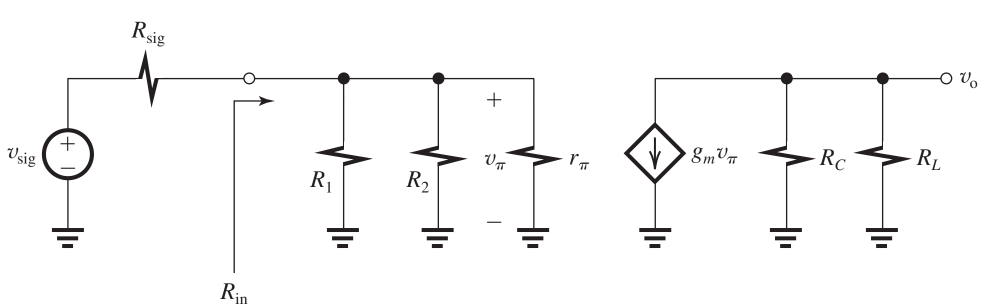
For

$$I_E = 2 \text{ mA}, \quad R_E = \frac{V_E}{I_E} = \frac{4.3}{2} = 2.15 \text{ k}\Omega$$

$$I_{R_2} = 0.2 \text{ mA}, \quad R_2 = \frac{5}{0.2} = 25 \text{ k}\Omega$$

$$I_B = \frac{I_E}{\beta + 1} = \frac{2}{101} \simeq 0.02 \text{ mA}$$

This figure belongs to Problem 7.125.



$$I_{R_1} = I_{R_2} + I_B = 0.2 + 0.02 = 0.22 \text{ mA}$$

$$R_1 = \frac{V_{CC} - V_B}{I_{R_1}} = \frac{15 - 5}{0.22} = 45.5 \text{ k}\Omega$$

Choosing 5% resistors:

$$R_E = 2.2 \text{ k}\Omega, \quad R_1 = 47 \text{ k}\Omega, \quad R_2 = 24 \text{ k}\Omega$$

For these values,

$$I_E = \frac{V_{BB} - V_{BE}}{R_E + \dfrac{R_B}{\beta + 1}}$$

where

$$V_{BB} = V_{CC}\frac{R_2}{R_1 + R_2} = 15 \times \frac{24}{24 + 47} = 5.07 \text{ V}$$

$$R_B = R_1 \parallel R_2 = 47 \parallel 24 = 15.89 \text{ k}\Omega$$

$$I_E = \frac{5.07 - 0.7}{2.2 + \dfrac{15.89}{101}} = 1.85 \text{ mA}$$

$$V_B = I_E R_E + V_{BE} = 1.85 \times 2.2 + 0.7 = 4.8 \text{ V}$$

$$I_C = \alpha I_E = 0.99 \times 1.85 = 1.84 \text{ mA}$$

$$g_m = \frac{I_C}{V_T} = \frac{1.84}{0.025} = 73.4 \text{ mA/V}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{73.4} = 1.36 \text{ k}\Omega$$

$$R_{\text{in}} = R_1 \parallel R_2 \parallel r_\pi = 47 \parallel 24 \parallel 1.36 = 1.25 \text{ k}\Omega$$

$$\frac{v_\pi}{v_{\text{sig}}} = \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} = \frac{1.25}{1.25 + 2} = 0.385 \text{ V/V}$$

For an overall gain of -40 V/V,

$$\frac{v_o}{v_\pi} = -\frac{40}{0.385} = -104 \text{ V/V}$$

But

$$\frac{v_o}{v_\pi} = -g_m(R_C \parallel R_L)$$

$$-104 = -73.4\ (R_C \parallel 2)$$

$$(R_C \parallel 2) = 1.416$$

$$R_C = 4.86 \text{ k}\Omega$$

We can select either 4.7 kΩ or 5.1 kΩ. With 4.7 kΩ, the gain will be

$$\frac{v_o}{v_{\text{sig}}} = -0.385 \times 73.4 \times (4.7 \parallel 2) = -39.6 \text{ V/V}$$

which is slightly lower than the required -40 V/V, and we will obtain

$$V_C = 15 - 4.7 \times 1.84 = 6.4 \text{ V}$$

allowing for about 2 V of negative signal swing at the collector. If we choose 5.1 kΩ, the gain will be

$$\frac{v_o}{v_{\text{sig}}} = -0.385 \times 73.4 \times (5.1 \parallel 2) = -40.6 \text{ V/V}$$

which is slightly higher than the required gain, and we will obtain

$$V_C = 15 - 5.1 \times 1.84 = 5.6 \text{ V}$$

which allows for only 1.2-V negative signal swing.

7.127 Refer to the circuit of Fig. P7.125:

$$I_C = \frac{\alpha(V_{BB} - V_{BE})}{R_E + \dfrac{R_B}{\beta + 1}}$$

where

$$V_{BB} = V_{CC}\frac{R_2}{R_2 + R_1} = 15 \times \frac{47}{47 + 82} = 5.465 \text{ V}$$

$$R_B = R_1 \parallel R_2 = 47 \parallel 82 = 29.88 \text{ k}\Omega$$

$$I_C = \frac{0.99(5.465 - 0.7)}{7.2 + \dfrac{29.88}{101}} = 0.63 \text{ mA}$$

$$g_m = \frac{I_C}{V_T} = \frac{0.63}{0.025} = 25.2 \text{ mA/V}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{25.2} = 4 \text{ k}\Omega$$

$$R_{\text{in}} = R_1 \parallel R_2 \parallel r_\pi = R_B \parallel r_\pi$$

$$= 29.88 \parallel 4 = 3.5 \text{ k}\Omega$$

$$\frac{v_\pi}{v_{\text{sig}}} = \frac{3.5}{3.5 + 2} = 0.636 \text{ V/V}$$

$$\frac{v_o}{v_\pi} = -g_m(R_C \parallel R_L)$$

$$= -25.2(12 \parallel 2) = -43.2 \text{ V/V}$$

$$\frac{v_o}{v_{\text{sig}}} = -0.636 \times 43.2 = -27.5 \text{ V/V}$$

Comparing the results above to those of Problem 7.125, we see that raising the resistance values has indeed resulted in increasing the transmission from source to transistor base, from 0.371 V/V to 0.636 V/V. However, because I_C has decreased and g_m has correspondingly decreased, the gain from base to collector has decreased by a larger factor (from 97.83 V/V to 43.2 V/V), with the result that the overall gain has in fact decreased (from 36.3 V/V to 27.5 V/V). Thus, this is not a successful strategy!

7.128 Refer to the circuit of Fig. P7.128.

DC voltage drop across $R_B = 0.2$ V, and

$$I_B R_B = 0.2 \text{ V}$$

$$\frac{I}{\beta + 1} R_B = 0.2 \text{ V}$$

$$I R_B = 0.2 \times 101 \qquad (1)$$

$R_{\text{in}} = R_B \parallel r_\pi = 10 \text{ k}\Omega$

$R_B \parallel \dfrac{V_T}{I_B} = 10$

$R_B \parallel \dfrac{0.025}{I/(\beta + 1)} = 10$

$R_B \parallel \left(\dfrac{0.025 \times 101}{I}\right) = 10$

$$\frac{R_B \times \dfrac{0.025 \times 101}{I}}{R_B + \dfrac{0.025 \times 101}{I}} = 10$$

$$\frac{0.025 \times 101 R_B}{IR_B + 0.025 \times 101} = 10 \qquad (2)$$

Substituting for IR_B from Eq. (1) yields

$$\frac{0.025 \times 101 R_B}{0.2 \times 101 + 0.025 \times 101} = 10$$

$$\frac{0.025 R_B}{0.225} = 10$$

$\Rightarrow R_B = 90 \text{ k}\Omega$

$I = \dfrac{0.2 \times 101}{90} = 0.22 \text{ mA}$

To maximize the open-circuit voltage gain between base and collector while ensuring that the instantaneous collector voltage does not fall below $(v_B - 0.4)$ when v_{be} is as high as 5 mV, we impose the constraint

$V_C - |A_{vo}| \times 0.005 = V_B + 0.005 - 0.4$

where

$V_C = V_{CC} - I_C R_C$

$= 5 - 0.99 \times 0.22 R_C$

$= 5 - 0.22 R_C$

$|A_{vo}| = g_m R_C = \dfrac{0.99 \times 0.22}{0.025} R_C = 8.7 R_C$

and

$V_B = -\dfrac{0.22}{101} \times 90 = -0.2 \text{ V}$

Thus,

$5 - 0.22 R_C - 8.7 R_C \times 0.005 = -0.2 - 0.395$

$\Rightarrow R_C = 21.2 \text{ k}\Omega$

Selecting 5% resistors, we find

$R_B = 91 \text{ k}\Omega$

$R_C = 22 \text{ k}\Omega$

and specifying I to one significant digit gives

$I = 0.2 \text{ mA}$

$g_m = \dfrac{\alpha I_C}{V_T} \simeq \dfrac{0.2}{0.025} = 8 \text{ mA/V}$

$A_{vo} = -g_m R_C = -8 \times 22 = -176 \text{ V/V}$

$r_\pi = \dfrac{\beta}{g_m} = \dfrac{100}{8} = 12.5 \text{ k}\Omega$

$R_{\text{in}} = R_B \parallel r_\pi = 91 \parallel 12.5 = 11 \text{ k}\Omega$

$G_v = -\dfrac{11}{20 + 11} \times 8(22 \parallel 20)$

$= -29.7 \text{ V/V}$

7.129 Refer to the circuit of Fig. P7.129.

(a) $I_E = 0.5$ mA. Writing a loop equation for the base–emitter circuit results in

$I_B R_{\text{sig}} + V_{BE} + I_E R_E = 3$

$\dfrac{I_E}{\beta + 1} R_{\text{sig}} + V_{BE} + I_E R_E = 3$

$\dfrac{0.5}{101} \times 2.5 + 0.7 + 0.5 R_E = 3$

$\Rightarrow R_E = 4.6 \text{ k}\Omega$

(b) $I_C = \alpha I_E \simeq 0.5 \text{ mA}$

$V_C = 0.5 = 3 - 0.5 R_C$

$\Rightarrow R_C = 5 \text{ k}\Omega$

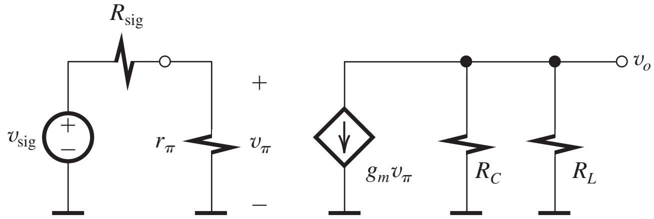
(c) $g_m = \dfrac{I_C}{V_T} = \dfrac{0.5 \text{ mA}}{0.025 \text{ V}} = 20 \text{ mA/V}$

$r_\pi = \dfrac{\beta}{g_m} = \dfrac{100}{20} = 5 \text{ k}\Omega$

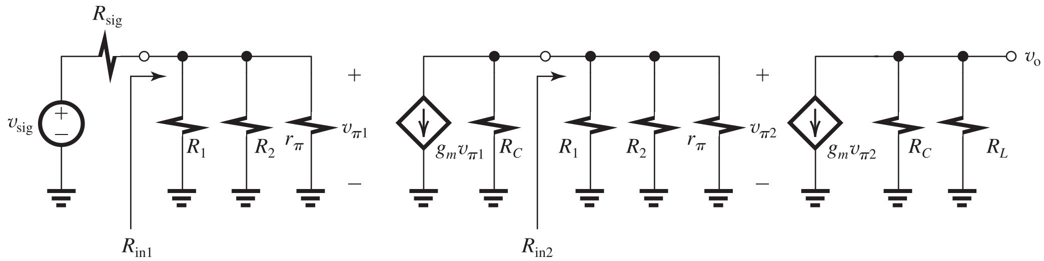
$G_v = \dfrac{v_o}{v_{\text{sig}}} = -\dfrac{5}{5 + 2.5} \times 20 \times (5 \parallel 10)$

$= -44.4 \text{ V/V}$

This figure belongs to Problem 7.129.



This figure belongs to Problem 7.130.



7.130 Refer to the circuit of Fig. P7.130.

(a) DC analysis of each of the two stages:

$$V_{BB} = V_{CC}\frac{R_2}{R_1+R_2} = 15\frac{47}{100+47} = 4.8 \text{ V}$$

$$R_B = R_1 \parallel R_2 = 100 \parallel 47 = 32 \text{ k}\Omega$$

$$I_E = \frac{V_{BB} - V_{BE}}{R_E + \dfrac{R_B}{\beta+1}}$$

$$= \frac{4.8-0.7}{3.9+\dfrac{32}{101}} = 0.97 \text{ mA} \simeq 1 \text{ mA}$$

$$I_C = \alpha I_E \simeq 1 \text{ mA}$$

$$V_C = V_{CC} - I_C R_C = 15 - 1\times 6.8 = 8.2 \text{ V}$$

(b) See figure above.

$$g_m = \frac{I_C}{V_T} = 40 \text{ mA/V}$$

$$r_\pi = \frac{\beta}{g_m} = 2.5 \text{ k}\Omega$$

(c) $R_{in1} = R_1 \parallel R_2 \parallel r_\pi = R_B \parallel r_\pi = 32 \parallel 2.5$

$= 2.32 \text{ k}\Omega$

$$\frac{v_{b1}}{v_{sig}} = \frac{R_{in}}{R_{in}+R_{sig}} = \frac{2.32}{2.32+5} = 0.32 \text{ V/V}$$

(d) $R_{in2} = R_1 \parallel R_2 \parallel r_\pi = R_{in1} = 2.32 \text{ k}\Omega$

$$\frac{v_{b2}}{v_{b1}} = \frac{v_{b2}}{v_{\pi1}} = -g_m(R_C \parallel R_{in2})$$

$= -40(6.8 \parallel 2.32) = -69.2$ V/V

(e) $\dfrac{v_o}{v_{b2}} = \dfrac{v_o}{v_{\pi2}} = -g_m(R_C \parallel R_L)$

$= -40(6.8 \parallel 2) = -61.8$ V/V

(f) $\dfrac{v_o}{v_{sig}} = \dfrac{v_o}{v_{b2}} \times \dfrac{v_{b2}}{v_{b1}} \times \dfrac{v_{b1}}{v_{sig}} = -61.8$

$\times -69.2 \times 0.32 = 1368.5$ V/V

7.131 Refer to the circuit in Fig. P7.131:

$I_E = 0.1$ mA

$$r_e = \frac{V_T}{I_E} = \frac{25 \text{ mV}}{0.1 \text{ mA}} = 250\ \Omega$$

$$g_m = \frac{I_C}{V_T} \simeq \frac{0.1 \text{ mA}}{0.025 \text{ V}} = 4 \text{ mA/V}$$

Note that the emitter has a resistance $R_e = 250\ \Omega$.

$R_{in} = 200 \text{ k}\Omega \parallel (\beta+1)(r_e+R_e)$

$= 200 \parallel [101 \times (0.25+0.25)]$

$= 200 \parallel 50.5 = 40.3 \text{ k}\Omega$

$$\frac{v_b}{v_{sig}} = \frac{R_{in}}{R_{in}+R_{sig}} = \frac{40.3}{40.3+20} = 0.668 \text{ V/V}$$

$$\frac{v_o}{v_b} = -\alpha\frac{\text{Total resistance in collector}}{\text{Total resistance in emitter}}$$

$$\simeq -\frac{20 \parallel 20}{0.25+0.25} = -20 \text{ V/V}$$

$$G_v = \frac{v_o}{v_{sig}} = -0.668 \times 20 = -13.4 \text{ V/V}$$

For v_{be} to be limited to 5 mV, the signal between base and ground will be 10 mV (because of the 5 mV across R_e). The limit on v_{sig} can be obtained by dividing the 10 mV by v_b/v_{sig},

$$\hat{v}_{sig} = \frac{10 \text{ mV}}{0.668} = 15 \text{ mV}$$

Correspondingly, at the output we have

$$\hat{v}_o = |G_v|\hat{v}_{sig} = 13.4 \times 15 = 200 \text{ mV} = 0.2 \text{ V}$$

7.132 (a)

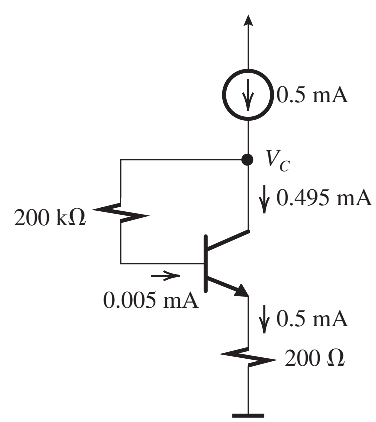


Figure 1

From Fig. 1 we see that

$I_C = 0.495$ mA

$V_C = I_B \times 200\ \text{k}\Omega + I_E \times 0.2\ \text{k}\Omega + V_{BE}$

$= 0.005 \times 200 + 0.5 \times 0.2 + 0.7$

$= 1.18$ V

(b)

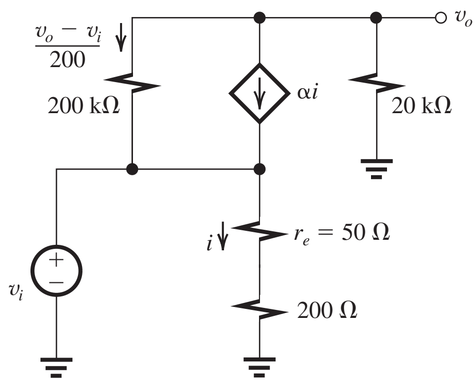


Figure 2

From Fig. 2, we have

$$g_m = \frac{I_C}{V_T} = \frac{0.495}{0.025} \simeq 20\ \text{mA/V}$$

$$r_e = \frac{V_T}{I_E} = 50\ \Omega$$

$$i = \frac{v_i}{r_e + R_e} = \frac{v_i}{50 + 200}$$

$$= \frac{v_i}{250\ \Omega} = \frac{v_i}{0.25\ \text{k}\Omega} = 4\ v_i,\ \text{mA}$$

Node equation at the output:

$$\frac{v_o}{20} + \alpha i + \frac{v_o - v_i}{200} = 0$$

$$\frac{v_o}{20} + 0.99 \times 4 v_i + \frac{v_o}{200} - \frac{v_i}{200} = 0$$

$$v_o\left(\frac{1}{20} + \frac{1}{200}\right) = -v_i\left(4 \times 0.99 - \frac{1}{200}\right)$$

$$\frac{v_o}{v_i} = -71.9\ \text{V/V}$$

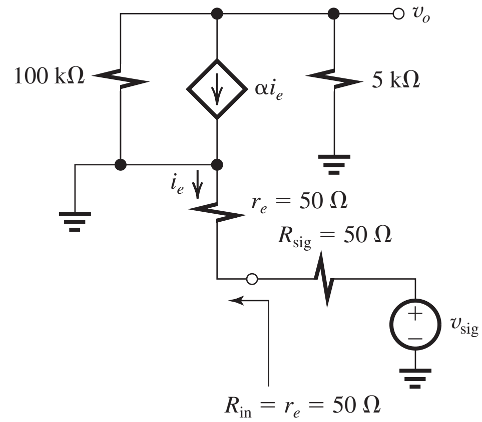
7.133 Refer to the circuit in Fig. P7.133.

The dc emitter current is equal to 0.5 mA, and $I_C = \alpha I_E \simeq 0.5$ mA; also,

$$r_e = \frac{V_T}{I_E} = \frac{25\ \text{mV}}{0.5\ \text{mA}} = 50\ \Omega$$

$$R_{\text{in}} = r_e = 50\ \Omega$$

$$i_e = \frac{-v_{\text{sig}}}{r_e + R_{\text{sig}}} = \frac{-v_{\text{sig}}}{50 + 50}$$



$$= \frac{-v_{\text{sig}}}{100\ \Omega} = \frac{-v_{\text{sig}}}{0.1\ \text{k}\Omega}$$

At the output node,

$$v_o = -\alpha i_e (5 \parallel 100)$$

$$= \alpha \frac{v_{\text{sig}}}{0.1}(5 \parallel 100)$$

$$\frac{v_o}{v_{\text{sig}}} = \alpha \frac{5 \parallel 100}{0.1} \simeq 47.6\ \text{V/V}$$

7.134 (a) $I_E = \dfrac{3 - 0.7}{1 + \dfrac{100}{\beta + 1}}$

$\beta = 50$:

$$I_E = \frac{2.3}{1 + \dfrac{100}{51}} = 0.78\ \text{mA}$$

$$V_E = I_E R_E = 0.78\ \text{V}$$

$$V_B = V_E + 0.7 = 1.48\ \text{V}$$

$\beta = 200$:

$$I_E = \frac{2.3}{1 + \dfrac{100}{201}} = 1.54\ \text{mA}$$

$$V_E = I_E R_E = 1.54\ \text{V}$$

$$V_B = V_E + 0.7 = 2.24\ \text{V}$$

(b) $R_{\text{in}} = 100 \parallel (\beta + 1)[r_e + (1 \parallel 1)]$

$= 100 \parallel (\beta + 1)(r_e + 0.5)$

$\beta = 50$:

$$r_e = \frac{V_T}{I_E} = \frac{25\ \text{mV}}{0.78\ \text{mA}} = 32.1\ \Omega$$

$$R_{\text{in}} = 100 \parallel [51 \times (0.0321 + 0.5)]$$

$= 21.3\ \text{k}\Omega$

$\beta = 200$:

$$r_e = \frac{V_T}{I_E} = \frac{25\ \text{mV}}{1.54\ \text{mA}} = 16.2\ \Omega$$

$R_{\text{in}} = 100 \parallel [201 \times (0.0162 + 0.5)]$

$= 50.9\ \text{k}\Omega$

(c) $\dfrac{v_b}{v_{\text{sig}}} = \dfrac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}}$

$$\frac{v_o}{v_b} = \frac{(1 \parallel 1)}{(1 \parallel 1) + r_e} = \frac{500}{500 + r_e}(r_e \text{ in } \Omega)$$

$\beta = 50$:

$$\frac{v_b}{v_{\text{sig}}} = \frac{21.3}{21.3 + 10} = 0.68 \text{ V/V}$$

$$\frac{v_o}{v_b} = \frac{500}{500 + 32.1} = 0.94 \text{ V/V}$$

$$\frac{v_o}{v_{\text{sig}}} = 0.68 \times 0.94 = 0.64 \text{ V/V}$$

$\beta = 200$:

$$\frac{v_b}{v_{\text{sig}}} = \frac{50.9}{50.9 + 10} = 0.836 \text{ V/V}$$

$$\frac{v_o}{v_b} = \frac{500}{500 + 16.2} = 0.969 \text{ V/V}$$

$$\frac{v_o}{v_{\text{sig}}} = 0.836 \times 0.969 = 0.81 \text{ V/V}$$

7.135 Refer to the circuit in Fig. P7.135.

$$I_E = \frac{3 - 0.7}{3.3 + \dfrac{100}{\beta + 1}}$$

$$= \frac{2.3}{3.3 + \dfrac{100}{101}} = 0.54 \text{ mA}$$

$$r_e = \frac{V_T}{I_E} = \frac{25 \text{ mV}}{0.54 \text{ mA}} = 46.3\ \Omega$$

$R_{\text{in}} = (\beta + 1)[r_e + (3.3 \parallel 2)]$

$= 101 \times (0.0463 + 1.245)$

$= 130.4\ \text{k}\Omega$

$$\frac{v_b}{v_{\text{sig}}} = \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} = \frac{130.4}{130.4 + 100}$$

$= 0.566$ V/V

$$\frac{v_o}{v_b} = \frac{3.3 \parallel 2}{(3.3 \parallel 2) + r_e} = \frac{1.245}{1.245 + 0.0463}$$

$= 0.964$ V/V

$$\frac{v_o}{v_{\text{sig}}} = 0.566 \times 0.964 = 0.55 \text{ V/V}$$

$$i_o = \frac{v_o}{2\ \text{k}\Omega}$$

$$i_i = \frac{v_i}{R_{\text{in}}} = \frac{v_b}{130.4\ \text{k}\Omega}$$

$$\frac{i_o}{i_i} = \frac{v_o}{v_b} \times \frac{130.4}{2} = 0.964 \times 65.2$$

$= 62.9$ A/A

$$R_{\text{out}} = 3.3 \parallel \left(r_e + \frac{100}{\beta + 1}\right)$$

$$= 3.3 \parallel \left(0.0463 + \frac{100}{101}\right)$$

$= 0.789\ \text{k}\Omega = 789\ \Omega$

7.136 Refer to the circuit in Fig. P7.136.

For dc analysis, open-circuit the two coupling capacitors. Then replace the 9-V source and the two 20-kΩ resistors by their Thévenin equivalent, namely, a 4.5-V source and a 10-kΩ series resistance. The latter can be added to the 10-kΩ resistor that is connected to the base. The result is the circuit shown in Fig. 1, which can be used to calculate I_E.

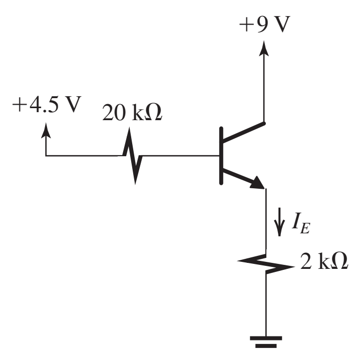


Figure 1

(a) $I_E = \dfrac{4.5 - 0.7}{2 + \dfrac{20}{\beta + 1}}$

$$= \frac{3.8}{2 + \dfrac{20}{101}} = 1.73 \text{ mA}$$

$I_C = \alpha I_E = 0.99 \times 1.73$ mA

$= 1.71$ mA

$$g_m = \frac{I_C}{V_T} = 68.4 \text{ mA/V}$$

$$r_e = \frac{V_T}{I_E} = \frac{25 \text{ mV}}{1.73 \text{ mA}} = 14.5\ \Omega$$

$= 0.0145\ \text{k}\Omega$

$r_\pi = (\beta + 1)r_e = 101 \times 0.0145$

$= 1.4645\ \text{k}\Omega$

(b) Replacing the BJT with its T model (without r_o) and replacing the capacitors with short circuits results in the equivalent-circuit model shown in Fig. 2.

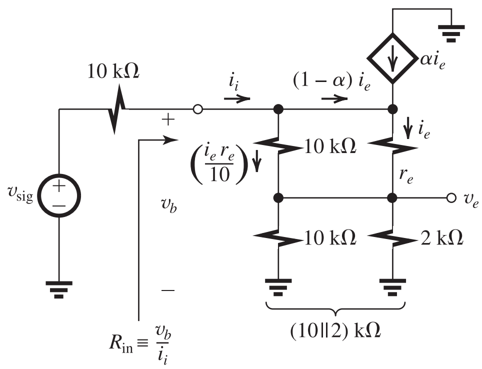


Figure 2

From Fig. 2 we see that

$$v_e = \left(i_e + i_e \frac{r_e}{10}\right)(10 \parallel 2)$$

$$v_b = v_e + i_e r_e = i_e(10 \parallel 2)\left(1 + \frac{r_e}{10}\right) + i_e r_e$$

$$i_i = (1-\alpha)i_e + i_e \frac{r_e}{10}$$

$$= \frac{i_e}{\beta+1} + i_e \frac{r_e}{10}$$

We can now obtain R_{in} from

$$R_{in} \equiv \frac{v_b}{i_i} = \frac{(10 \parallel 2)\left(1 + \frac{r_e}{10}\right) + r_e}{\frac{1}{\beta+1} + \frac{r_e}{10}}$$

$$= \frac{(\beta+1)(10 \parallel 2)\left(1 + \frac{r_e}{10}\right) + (\beta+1)r_e}{1 + (\beta+1)\frac{r_e}{10}}$$

$$= \frac{101 \times (10 \parallel 2) \times (1 + 0.00145) + 101 \times 0.0145}{1 + 101 \times 0.00145}$$

$$= \frac{168.577 + 1.4645}{1 + 0.14645} = 148.3 \text{ k}\Omega$$

$$\frac{v_b}{v_{sig}} = \frac{R_{in}}{R_{in} + R_{sig}} = \frac{148.3}{148.3 + 10} = 0.937$$

$$\frac{v_o}{v_b} = \frac{v_e}{v_b} = \frac{i_e\left(1 + \frac{r_e}{10}\right)(10 \parallel 2)}{i_e\left(1 + \frac{r_e}{10}\right)(10 \parallel 2) + i_e r_e}$$

$$= \frac{1.00145 \times (10 \parallel 2)}{1.00145 \times (10 \parallel 2) + 0.0145}$$

$$= 0.991 \text{ V/V}$$

$$G_v \equiv \frac{v_o}{v_{sig}} = 0.937 \times 0.991 = 0.93 \text{ V/V}$$

(c) When C_B is open-circuited, the equivalent circuit becomes that shown in Fig. 3.

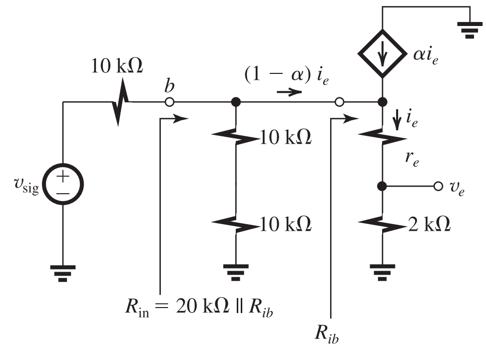


Figure 3

Thus,

$$R_{in} = 20 \text{ k}\Omega \parallel R_{ib}$$

$$= 20 \text{ k}\Omega \parallel (\beta+1)(R_e + 2)$$

$$= 20 \parallel 101 \times 2.0145$$

$$= 18.21 \text{ k}\Omega$$

which is greatly reduced because of the absence of bootstrapping. The latter causes the lower node of the 10-kΩ base-biasing resistor to rise with the output voltage, thus causing a much reduced signal current in the 10-kΩ resistor and a correspondingly larger effective resistance across the amplifier input.

The reduced R_{in} will result in a reduction in v_b/v_{sig},

$$\frac{v_b}{v_{sig}} = \frac{R_{in}}{R_{in} + R_{sig}} = \frac{18.21}{28.21}$$

$$= 0.646 \text{ V/V}$$

$$\frac{v_o}{v_b} = \frac{2}{2 + 0.0145} = 0.993$$

$$G_v \equiv \frac{v_o}{v_{sig}} = 0.646 \times 0.993$$

$$= 0.64 \text{ V/V}$$

which is much reduced relative to the value obtained with bootstrapping.

7.137

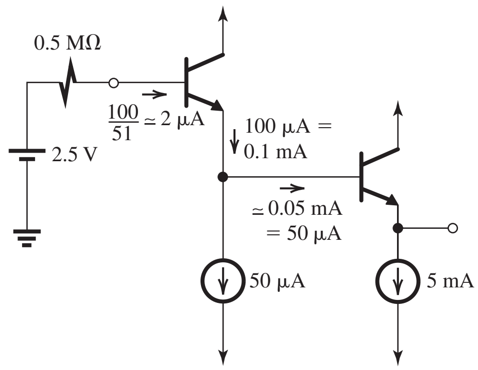
(a) Applying Thévenin's theorem to the base-biasing circuit of Q_1 results in the dc circuit shown below. From our partial analysis on the figure, we can write

$$I_{E1} = 0.1 \text{ mA}$$

$$I_{E2} = 5 \text{ mA}$$

V_{B1} can be obtained as

$$V_{B1} = 2.5 - 2\ \mu\text{A} \times 0.5\ \text{M}\Omega = 1.5 \text{ V}$$



and V_{B2} can be found as

$$V_{B2} = V_{B1} - 0.7 = 0.8 \text{ V}$$

(b) Refer to the circuit in Fig. P7.137. With a load resistance $R_L = 1 \text{ k}\Omega$ connected to the output terminal, the voltage gain v_o/v_{b2} can be found as

$$\frac{v_o}{v_{b2}} = \frac{R_L}{R_L + r_{e1}}$$

where

$$r_{e2} = \frac{25 \text{ mV}}{5 \text{ mA}} = 5 \ \Omega$$

$$\frac{v_o}{v_{b2}} = \frac{1000}{1000 + 5} = 0.995 \text{ V/V}$$

$$R_{ib2} = (\beta_2 + 1)(r_{e2} + R_L)$$

$$= 101 \times 1.005 = 101.5 \text{ k}\Omega$$

(c) $R_{\text{in}} = 1 \text{ M}\Omega \parallel 1 \text{ M}\Omega \parallel (\beta + 1)(r_{e1} + R_{ib2})$

where

$$r_e = \frac{V_T}{I_{E1}} = \frac{25 \text{ mV}}{0.1 \text{ mA}} = 250 \ \Omega = 0.25 \text{ k}\Omega$$

$$R_{\text{in}} = 0.5 \text{ M}\Omega \parallel [51 \times (0.25 + 101.5)] \text{ k}\Omega$$

$$= 0.5 \text{ M}\Omega \parallel 5.2 \text{ M}\Omega$$

$$= 456 \text{ k}\Omega$$

$$\frac{v_{e1}}{v_{b1}} = \frac{R_{ib}}{R_{ib} + r_{e1}} = \frac{101.5}{101.5 + 0.25}$$

$$= 0.9975 \text{ V/V}$$

(d) $\dfrac{v_{b1}}{v_{\text{sig}}} = \dfrac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} = \dfrac{456}{456 + 100} = 0.82 \text{ V/V}$

(e) $\dfrac{v_o}{v_{\text{sig}}} = 0.82 \times 0.9975 \times 0.995 = 0.814 \text{ V/V}$

7.138 We need to raise f_H by a factor of

$$\frac{2 \text{ MHz}}{500 \text{ kHz}} = 4. \text{ Thus}$$

$$1 + g_m R_e = 4$$

$$\Rightarrow R_e = \frac{3}{g_m}$$

Since

$$g_m = \frac{I_C}{V_T} = \frac{1 \text{ mA}}{0.025 \text{ V}} = 40 \text{ mA/V}$$

$$R_e = \frac{3}{0.04} = 75 \ \Omega$$

The new value of f_L will be

$$f_L = \frac{100 \text{ Hz}}{1 + g_m R_e} = \frac{100}{4} = 25 \text{ Hz}$$

and the midband gain will become

$$|A_M| = \frac{100}{1 + g_m R_e} = \frac{100}{4} = 25 \text{ V/V}$$