EXAMPLE 5.1 For the network of Fig. 5.25:

a. Determine r_e.
b. Find Z_i (with $r_o = \infty\,\Omega$).
c. Calculate Z_o (with $r_o = \infty\,\Omega$).
d. Determine A_v (with $r_o = \infty\,\Omega$).
e. Repeat parts (c) and (d) including $r_o = 50\text{ k}\Omega$ in all calculations and compare results.

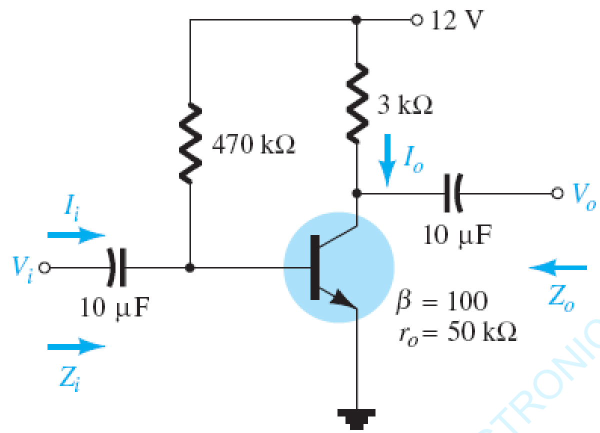
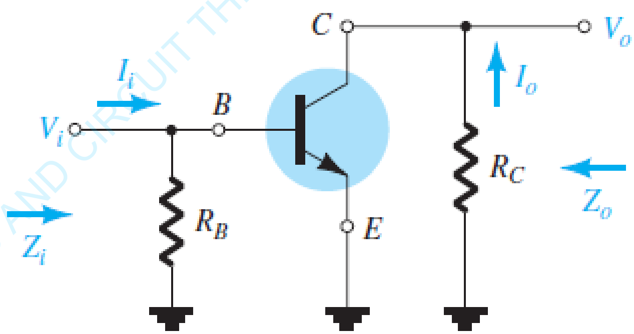
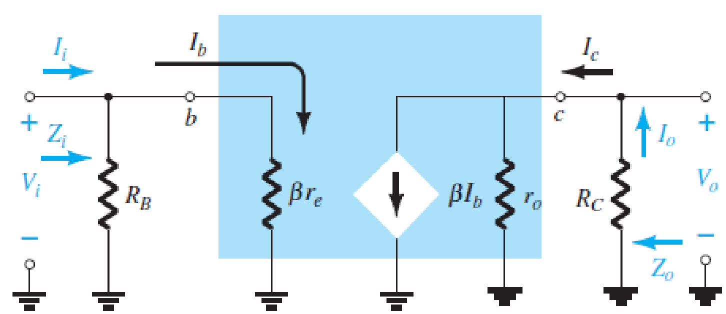


FIG. 5.25





a. DC analysis:

$$I_B = \frac{V_{CC} - V_{BE}}{R_B} = \frac{12\text{ V} - 0.7\text{ V}}{470\text{ k}\Omega} = 24.04\ \mu\text{A}$$

$$I_E = (\beta + 1)I_B = (101)(24.04\ \mu\text{A}) = 2.428\text{ mA}$$

$$r_e = \frac{26\text{ mV}}{I_E} = \frac{26\text{ mV}}{2.428\text{ mA}} = \mathbf{10.71\ \Omega}$$

b. $\beta r_e = (100)(10.71\ \Omega) = 1.071\text{ k}\Omega$

$$Z_i = R_B \| \beta r_e = 470\text{ k}\Omega \| 1.071\text{ k}\Omega = \mathbf{1.07\text{ k}\Omega}$$

c. $Z_o = R_C = \mathbf{3\text{ k}\Omega}$

d. $$A_v = -\frac{R_C}{r_e} = -\frac{3\text{ k}\Omega}{10.71\ \Omega} = \mathbf{-280.11}$$

$$V_o = -\beta I_b (R_C \| r_o)$$

$$I_b = \frac{V_i}{\beta r_e}$$

$$V_o = -\beta\left(\frac{V_i}{\beta r_e}\right)(R_C \| r_o)$$

$$\boxed{A_v = \frac{V_o}{V_i} = \frac{-R_C \| r_o}{r_e}}$$

e. $Z_o = r_o \| R_C = 50\text{ k}\Omega \| 3\text{ k}\Omega = \mathbf{2.83\text{ k}\Omega}$ vs. $3\text{ k}\Omega$

$$A_v = -\frac{r_o \| R_C}{r_e} = \frac{2.83\text{ k}\Omega}{10.71\ \Omega} = \mathbf{-264.24} \text{ vs. } -280.11$$

EXAMPLE 5.2 For the network of Fig. 5.28, determine:

a. r_e.
b. Z_i.
c. Z_o ($r_o = \infty\,\Omega$).
d. A_v ($r_o = \infty\,\Omega$).
e. The parameters of parts (b) through (d) if $r_o = 50\text{ k}\Omega$ and compare results.

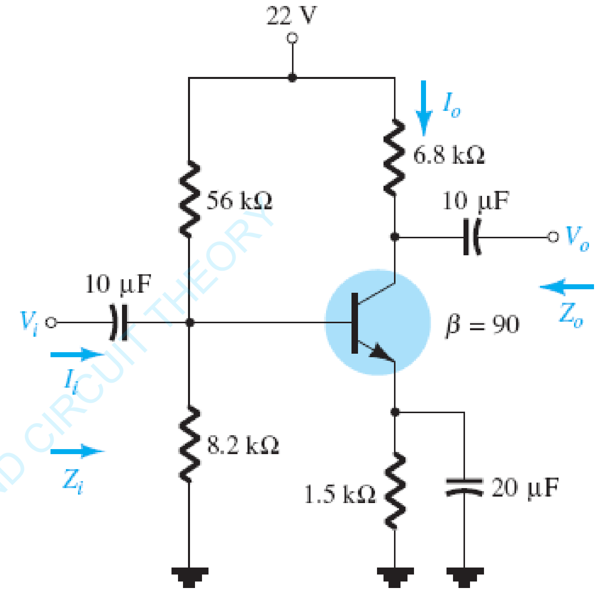


FIG. 5.28

Solution:

a. DC: Testing $\beta R_E > 10R_2$,

$$(90)(1.5\text{ k}\Omega) > 10(8.2\text{ k}\Omega)$$
$$135\text{ k}\Omega > 82\text{ k}\Omega\ (\textit{satisfied})$$

Using the approximate approach, we obtain

$$V_B = \frac{R_2}{R_1 + R_2}V_{CC} = \frac{(8.2\text{ k}\Omega)(22\text{ V})}{56\text{ k}\Omega + 8.2\text{ k}\Omega} = 2.81\text{ V}$$
$$V_E = V_B - V_{BE} = 2.81\text{ V} - 0.7\text{ V} = 2.11\text{ V}$$
$$I_E = \frac{V_E}{R_E} = \frac{2.11\text{ V}}{1.5\text{ k}\Omega} = 1.41\text{ mA}$$
$$r_e = \frac{26\text{ mV}}{I_E} = \frac{26\text{ mV}}{1.41\text{ mA}} = \mathbf{18.44\ \Omega}$$

b. $R' = R_1 \| R_2 = (56\text{ k}\Omega) \| (8.2\text{ k}\Omega) = 7.15\text{ k}\Omega$

$$Z_i = R' \| \beta r_e = 7.15\text{ k}\Omega \| (90)(18.44\ \Omega) = 7.15\text{ k}\Omega \| 1.66\text{ k}\Omega$$
$$= \mathbf{1.35\ k\Omega}$$

c. $Z_o = R_C = \mathbf{6.8\ k\Omega}$

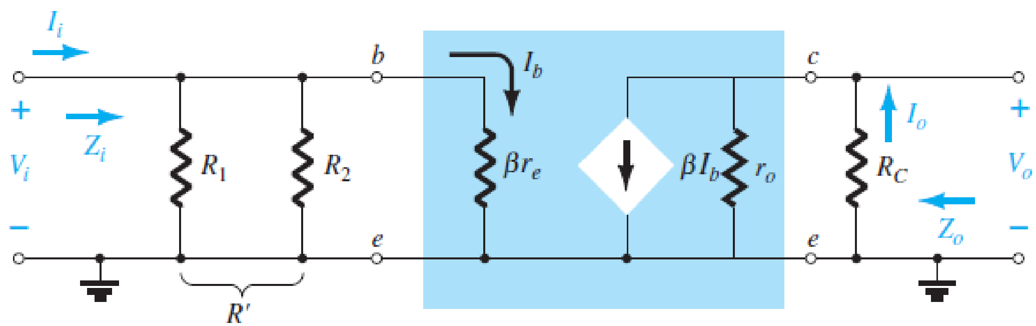
d. $A_v = -\dfrac{R_C}{r_e} = -\dfrac{6.8\text{ k}\Omega}{18.44\ \Omega} = \mathbf{-368.76}$

e. $Z_i = \mathbf{1.35\ k\Omega}$

$$Z_o = R_C \| r_o = 6.8\text{ k}\Omega \| 50\text{ k}\Omega = \mathbf{5.98\ k\Omega}\text{ vs. }6.8\text{ k}\Omega$$
$$A_v = -\frac{R_C \| r_o}{r_e} = -\frac{5.98\text{ k}\Omega}{18.44\ \Omega} = \mathbf{-324.3}\text{ vs. }-368.76$$

$$V_o = -\beta I_b(R_C \| r_o)$$
$$I_b = \frac{V_i}{\beta r_e}$$
$$V_o = -\beta\left(\frac{V_i}{\beta r_e}\right)(R_C \| r_o)$$

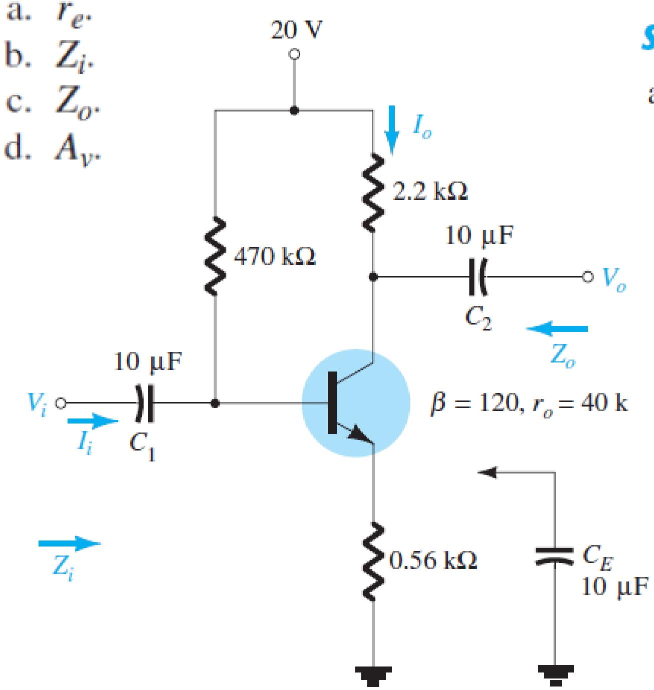
$$\boxed{A_v = \frac{V_o}{V_i} = \frac{-R_C \| r_o}{r_e}}$$



There was a measurable difference in the results for Z_o and A_v, because the condition $r_o \geq 10R_C$ was *not* satisfied.

EXAMPLE 5.3 For the network of Fig. 5.32, without C_E (unbypassed), determine:

a. r_e.
b. Z_i.
c. Z_o.
d. A_v.



Solution:

a. DC:

$$I_B = \frac{V_{CC} - V_{BE}}{R_B + (\beta + 1)R_E} = \frac{20\text{ V} - 0.7\text{ V}}{470\text{ k}\Omega + (121)0.56\text{ k}\Omega} = 35.89\ \mu\text{A}$$

$$I_E = (\beta + 1)I_B = (121)(35.89\ \mu\text{A}) = 4.34\text{ mA}$$

and
$$r_e = \frac{26\text{ mV}}{I_E} = \frac{26\text{ mV}}{4.34\text{ mA}} = \mathbf{5.99\ \Omega}$$

b. Testing the condition $r_o \geq 10(R_C + R_E)$, we obtain

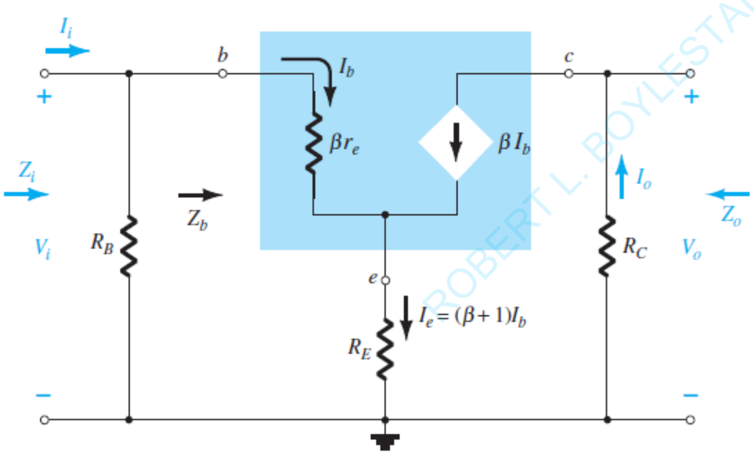
$$40\text{ k}\Omega \geq 10(2.2\text{ k}\Omega + 0.56\text{ k}\Omega)$$
$$40\text{ k}\Omega \geq 10(2.76\text{ k}\Omega) = 27.6\text{ k}\Omega\ (\textit{satisfied})$$

$$V_i = I_b\beta r_e + I_e R_E$$
$$V_i = I_b\beta r_e + (\beta + 1)I_b R_E$$
$$Z_b = \frac{V_i}{I_b} = \beta r_e + (\beta + 1)R_E$$

Because β is normally much greater than 1, the approximate equation is

$$Z_b \cong \beta(r_e + R_E) = 120(5.99\ \Omega + 560\ \Omega) = 67.92\text{ k}\Omega$$

and
$$Z_i = R_B \| Z_b = 470\text{ k}\Omega \| 67.92\text{ k}\Omega = \mathbf{59.34\ k\Omega}$$



c. $Z_o = R_C = \mathbf{2.2\ k\Omega}$

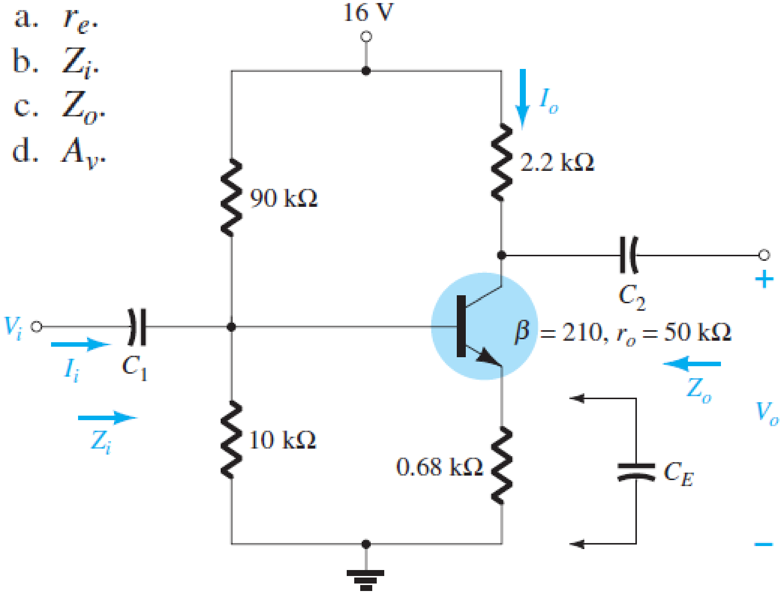
d. $r_o \geq 10R_C$ is satisfied. Therefore,

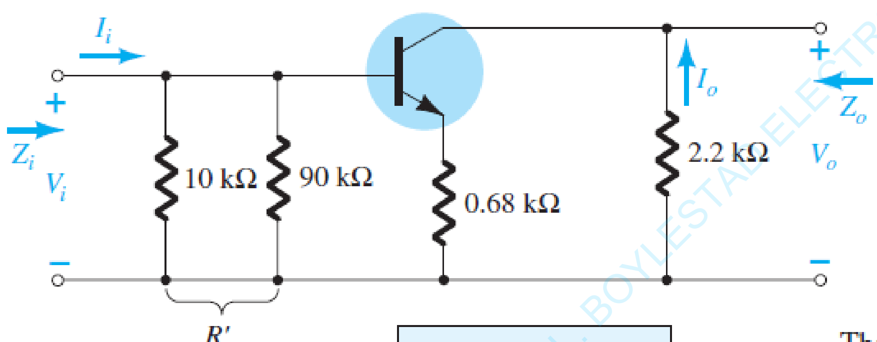
$$I_b = \frac{V_i}{Z_b}$$
$$V_o = -I_o R_C = -\beta I_b R_C = -\beta\left(\frac{V_i}{Z_b}\right)R_C$$

$$A_v = \frac{V_o}{V_i} \cong -\frac{\beta R_C}{Z_b} = -\frac{(120)(2.2\text{ k}\Omega)}{67.92\text{ k}\Omega} = \mathbf{-3.89}$$

EXAMPLE 5.5 For the network of Fig. 5.33 (with C_E unconnected), determine (using appropriate approximations):

a. r_e.
b. Z_i.
c. Z_o.
d. A_v.





$$I_b = \frac{V_i}{Z_b}$$

$$V_o = -I_o R_C = -\beta I_b R_C$$

$$= -\beta\left(\frac{V_i}{Z_b}\right)R_C$$

$$\boxed{A_v = \frac{V_o}{V_i} = -\frac{\beta R_C}{Z_b}}$$

Substituting $Z_b \cong \beta(r_e + R_E)$

$$\boxed{A_v = \frac{V_o}{V_i} \cong -\frac{R_C}{r_e + R_E}}$$

for the approximation $Z_b \cong \beta R_E$,

$$\boxed{A_v = \frac{V_o}{V_i} \cong -\frac{R_C}{R_E}}$$

Solution:

a. Testing $\beta R_E > 10R_2$,

$$(210)(0.68\text{ k}\Omega) > 10(10\text{ k}\Omega)$$
$$142.8\text{ k}\Omega > 100\text{ k}\Omega\ \textit{(satisfied)}$$

we have

$$V_B = \frac{R_2}{R_1 + R_2}V_{CC} = \frac{10\text{ k}\Omega}{90\text{ k}\Omega + 10\text{ k}\Omega}(16\text{ V}) = 1.6\text{ V}$$

$$V_E = V_B - V_{BE} = 1.6\text{ V} - 0.7\text{ V} = 0.9\text{ V}$$

$$I_E = \frac{V_E}{R_E} = \frac{0.9\text{ V}}{0.68\text{ k}\Omega} = 1.324\text{ mA}$$

$$r_e = \frac{26\text{ mV}}{I_E} = \frac{26\text{ mV}}{1.324\text{ mA}} = \mathbf{19.64\ \Omega}$$

b. The ac equivalent circuit is provided in Fig. 5.34. The resulting configuration is different from Fig. 5.30 only by the fact that now

$$R_B = R' = R_1 \| R_2 = 9\text{ k}\Omega$$

$$V_i = I_b \beta r_e + I_e R_E$$

$$V_i = I_b \beta r_e + (\beta + I)I_b R_E$$

$$Z_b = \frac{V_i}{I_b} = \beta r_e + (\beta + 1)R_E$$

Because β is normally much greater than 1, the approximate equation is

$$Z_b \cong \beta r_e + \beta R_E$$

The testing conditions of $r_o \geq 10(R_C + R_E)$ and $r_o \geq 10R_C$ are both satisfied the appropriate approximations yields

$$Z_b \cong \beta R_E = 142.8\text{ k}\Omega$$

$$Z_i = R_B \| Z_b = 9\text{ k}\Omega \| 142.8\text{ k}\Omega$$

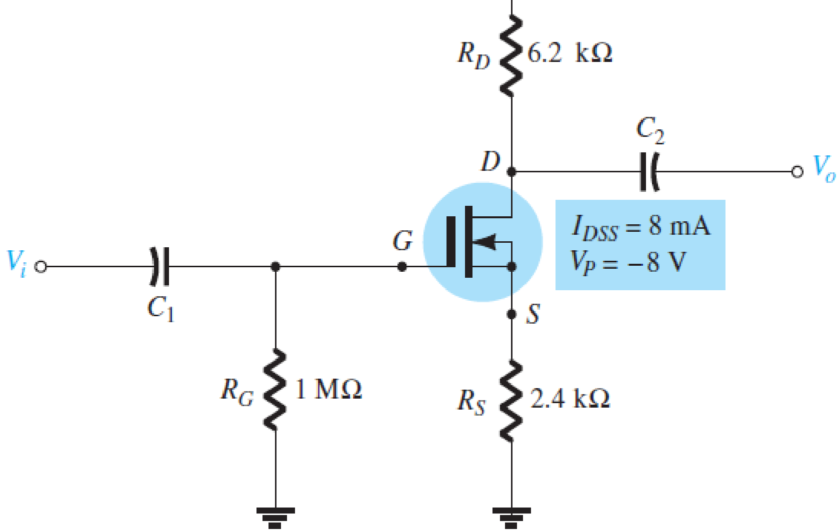
$$= \mathbf{8.47\ k\Omega}$$

c. $Z_o = R_C = \mathbf{2.2\ k\Omega}$

d. $A_v = -\dfrac{R_C}{R_E} = -\dfrac{2.2\text{ k}\Omega}{0.68\text{ k}\Omega} = \mathbf{-3.24}$

EXAMPLE 7.8 Determine the following for the network of Fig. 7.33:

a. I_{D_Q} and V_{GS_Q}.
b. V_D.



Solution:

a. The self-bias configuration results in

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

as obtained for the JFET configuration, establishing the fact that V_{GS} must be less than 0 V. There is therefore no requirement to plot the transfer curve for positive values of V_{GS}, although it was done on this occasion to complete the transfer characteristics. A plot point for the transfer characteristics for $V_{GS} < 0$ V is

$$I_D = \frac{I_{DSS}}{4} = \frac{8\text{ mA}}{4} = 2\text{ mA}$$

and

$$V_{GS} = \frac{V_P}{2} = \frac{-8\text{ V}}{2} = -4\text{ V}$$

and for $V_{GS} > 0$ V, since $V_P = -8$ V, we will choose

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

and

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 = 8\text{ mA}\left(1 - \frac{+2\text{ V}}{-8\text{ V}}\right)^2$$
$$= 12.5\text{ mA}$$

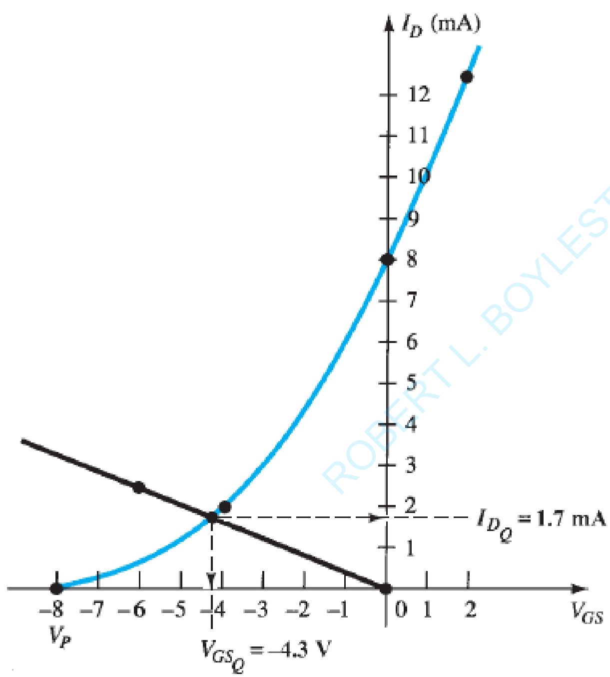
The resulting transfer curve appears in Fig. 7.34. For the network bias line, at $V_{GS} = 0$ V, $I_D = 0$ mA. Choosing $V_{GS} = -6$ V gives

$$I_D = -\frac{V_{GS}}{R_S} = -\frac{-6\text{ V}}{2.4\text{ k}\Omega} = 2.5\text{ mA}$$

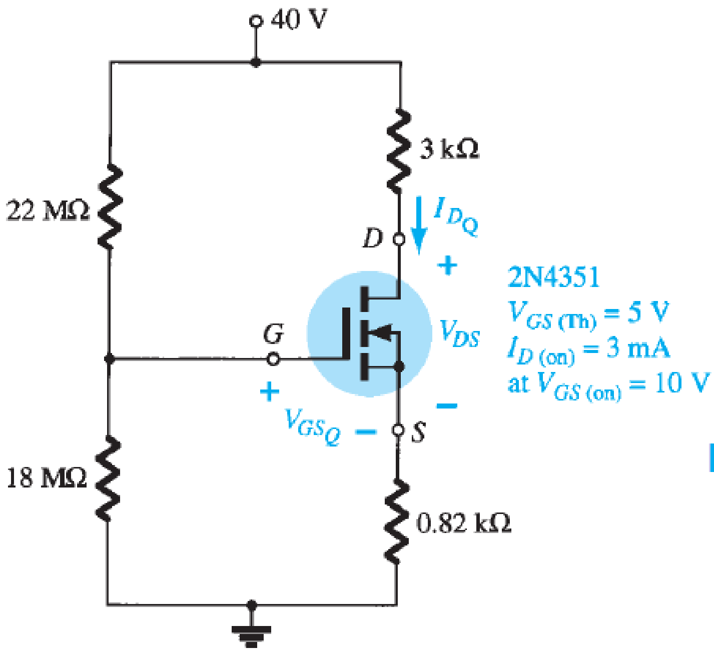
The resulting Q-point is given by

$$I_{D_Q} = \mathbf{1.7\text{ mA}}$$
$$V_{GS_Q} = \mathbf{-4.3\text{ V}}$$

b. $V_D = V_{DD} - I_D R_D$
$= 20\text{ V} - (1.7\text{ mA})(6.2\text{ k}\Omega)$
$= \mathbf{9.46\text{ V}}$



EXAMPLE 7.11 Determine I_{D_Q}, V_{GS_Q}, and V_{DS} for the network of Fig. 7.44.



When $I_D = 0$ mA,

$$V_{GS} = 18\text{ V} - (0\text{ mA})(0.82\text{ k}\Omega) = 18\text{ V}$$

as appearing on Fig. 7.45. When $V_{GS} = 0$ V,

$$V_{GS} = 18\text{ V} - I_D(0.82\text{ k}\Omega)$$

$$0 = 18\text{ V} - I_D(0.82\text{ k}\Omega)$$

$$I_D = \frac{18\text{ V}}{0.82\text{ k}\Omega} = 21.95\text{ mA}$$

Device

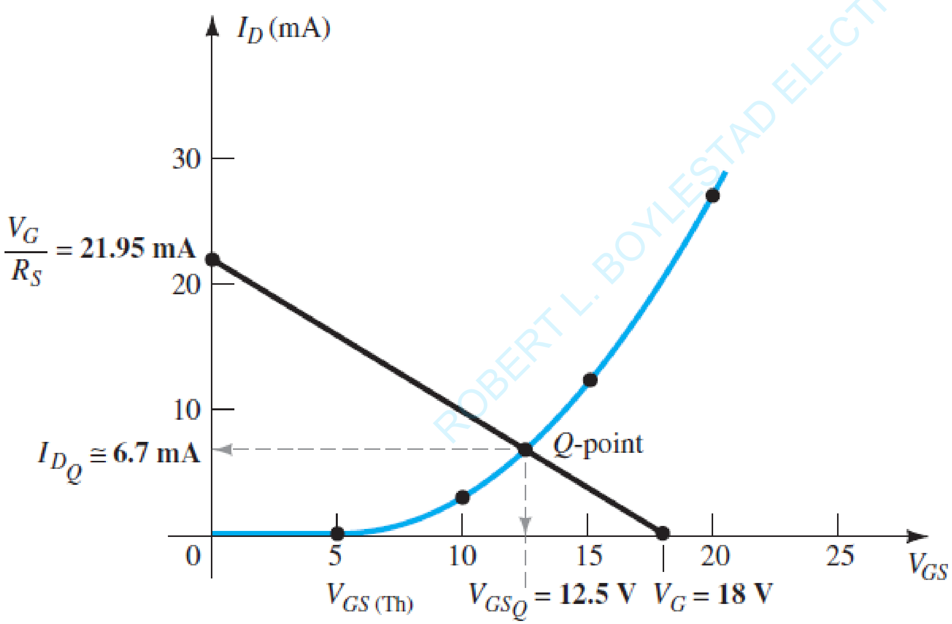
$$V_{GS(\text{Th})} = 5\text{ V}, \qquad I_{D(\text{on})} = 3\text{ mA with } V_{GS(\text{on})} = 10\text{ V}$$

$$\text{Eq. (7.34):}\quad k = \frac{I_{D(\text{on})}}{(V_{GS(\text{on})} - V_{GS(\text{Th})})^2}$$

$$= \frac{3\text{ mA}}{(10\text{ V} - 5\text{ V})^2} = 0.12 \times 10^{-3}\text{ A/V}^2$$

$$I_D = k(V_{GS} - V_{GS(\text{Th})})^2$$

$$= 0.12 \times 10^{-3}(V_{GS} - 5)^2$$



$$I_{D_Q} \cong \mathbf{6.7\text{ mA}}$$

$$V_{GS_Q} = \mathbf{12.5\text{ V}}$$

$$V_{DS} = V_{DD} - I_D(R_S + R_D)$$

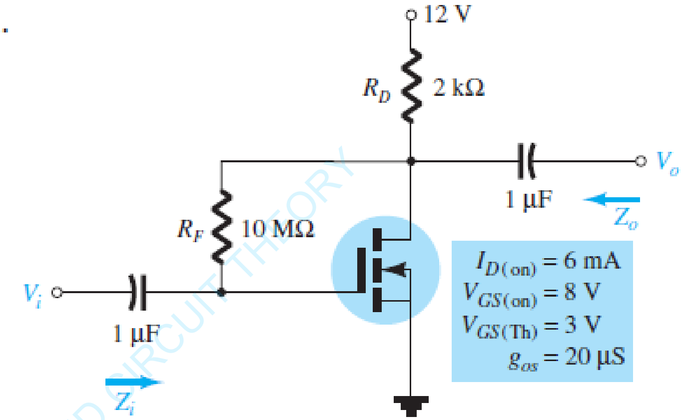
$$= 40\text{ V} - (6.7\text{ mA})(0.82\text{ k}\Omega + 3.0\text{ k}\Omega)$$

$$= 40\text{ V} - 25.6\text{ V}$$

$$= \mathbf{14.4\text{ V}}$$

EXAMPLE 8.12 The E-MOSFET of Fig. 8.40 was analyzed in Example 7.10, with the result that $k = 0.24 \times 10^{-3}\ \text{A/V}^2$, $V_{GS_Q} = 6.4\ \text{V}$, and $I_{D_Q} = 2.75\ \text{mA}$.

a. Determine g_m.
b. Find r_d.
c. Calculate Z_i with and without r_d. Compare results.
d. Find Z_o with and without r_d. Compare results.
e. Find A_v with and without r_d. Compare results.



Solution:

a. $g_m = 2k(V_{GS_Q} - V_{GS(\text{Th})}) = 2(0.24 \times 10^{-3}\ \text{A/V}^2)(6.4\ \text{V} - 3\ \text{V})$
$= \mathbf{1.63\ mS}$

b. $r_d = \dfrac{1}{g_{os}} = \dfrac{1}{20\ \mu\text{S}} = \mathbf{50\ k\Omega}$

c. With r_d,

$$Z_i = \frac{R_F + r_d \| R_D}{1 + g_m(r_d \| R_D)} = \frac{10\ \text{M}\Omega + 50\ \text{k}\Omega \| 2\ \text{k}\Omega}{1 + (1.63\ \text{mS})(50\ \text{k}\Omega \| 2\ \text{k}\Omega)}$$
$$= \frac{10\ \text{M}\Omega + 1.92\ \text{k}\Omega}{1 + 3.13} = \mathbf{2.42\ M\Omega}$$

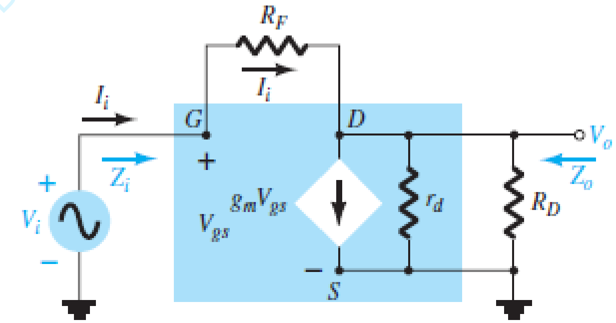
Without r_d,

$$Z_i \cong \frac{R_F}{1 + g_m R_D} = \frac{10\ \text{M}\Omega}{1 + (1.63\ \text{mS})(2\ \text{k}\Omega)} = \mathbf{2.53\ M\Omega}$$

which shows that since the condition $r_d \geq 10R_D = 50\ \text{k}\Omega \geq 40\ \text{k}\Omega$ is results for Z_o with or without r_d will be quite close.

d. With r_d,

$$Z_o = R_F \| r_d \| R_D = 10\ \text{M}\Omega \| 50\ \text{k}\Omega \| 2\ \text{k}\Omega = 49.75\ \text{k}\Omega \| 2\ \text{k}\Omega$$
$$= \mathbf{1.92\ k\Omega}$$



Without r_d,

$$Z_o \cong R_D = \mathbf{2\ k\Omega}$$

again providing very close results.

e. With r_d,

$$A_v = -g_m(R_F \| r_d \| R_D)$$
$$= -(1.63\ \text{mS})(10\ \text{M}\Omega \| 50\ \text{k}\Omega \| 2\ \text{k}\Omega)$$
$$= -(1.63\ \text{mS})(1.92\ \text{k}\Omega)$$
$$= \mathbf{-3.21}$$

Without r_d,

$$A_v = -g_m R_D = -(1.63\ \text{mS})(2\ \text{k}\Omega)$$
$$= \mathbf{-3.26}$$

which is very close to the above result.

EXAMPLE 11.1 Determine the output voltage for the circuit of Fig. 11.2 with a sinusoidal input of 2.5 mV.

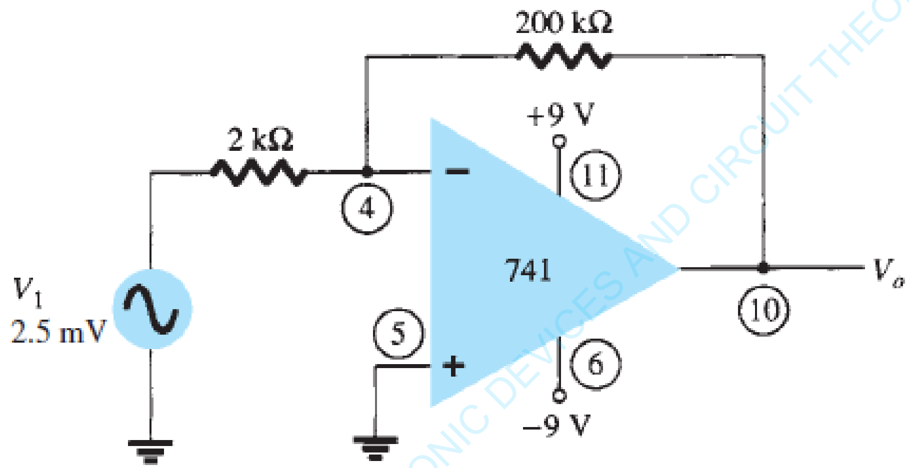


FIG. 11.2
Circuit for Example 11.1.

Solution: The circuit of Fig. 11.2 uses a 741 op-amp to provide a constant or fixed gain, calculated from Eq. (11.1) to be

$$A = -\frac{R_f}{R_1} = -\frac{200\text{ k}\Omega}{2\text{ k}\Omega} = -100$$

The output voltage is then

$$V_o = AV_i = -100(2.5\text{ mV}) = -250\text{ mV} = \mathbf{-0.25\ V}$$

EXAMPLE 11.2 Calculate the output voltage from the circuit of Fig. 11.4 for an input of 120 μV.

Solution: The gain of the op-amp circuit is calculated using Eq. (11.2) to be

$$A = 1 + \frac{R_f}{R_1} = 1 + \frac{240\ \text{k}\Omega}{2.4\ \text{k}\Omega} = 1 + 100 = 101$$

The output voltage is then

$$V_o = AV_i = 101(120\ \mu\text{V}) = \mathbf{12.12\ mV}$$

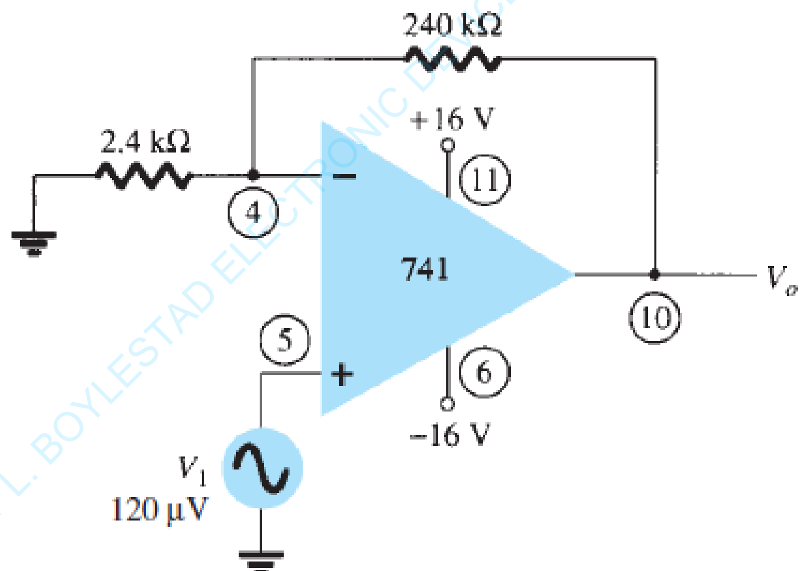


FIG. 11.4
Circuit for Example 11.2.

EXAMPLE 11.3 Calculate the output voltage using the circuit of Fig. 11.5 for resistor components of value $R_f = 470\ \text{k}\Omega$, $R_1 = 4.3\ \text{k}\Omega$, $R_2 = 33\ \text{k}\Omega$, and $R_3 = 33\ \text{k}\Omega$ for an input of $80\ \mu\text{V}$.

Solution: The amplifier gain is calculated to be

$$A = A_1A_2A_3 = \left(1 + \frac{R_f}{R_1}\right)\left(-\frac{R_f}{R_2}\right)\left(-\frac{R_f}{R_3}\right)$$

$$= \left(1 + \frac{470\ \text{k}\Omega}{4.3\ \text{k}\Omega}\right)\left(-\frac{470\ \text{k}\Omega}{33\ \text{k}\Omega}\right)\left(-\frac{470\ \text{k}\Omega}{33\ \text{k}\Omega}\right)$$

$$= (110.3)(-14.2)(-14.2) = 22.2 \times 10^3$$

so that

$$V_o = AV_i = 22.2 \times 10^3(80\ \mu\text{V}) = \mathbf{1.78\ V}$$

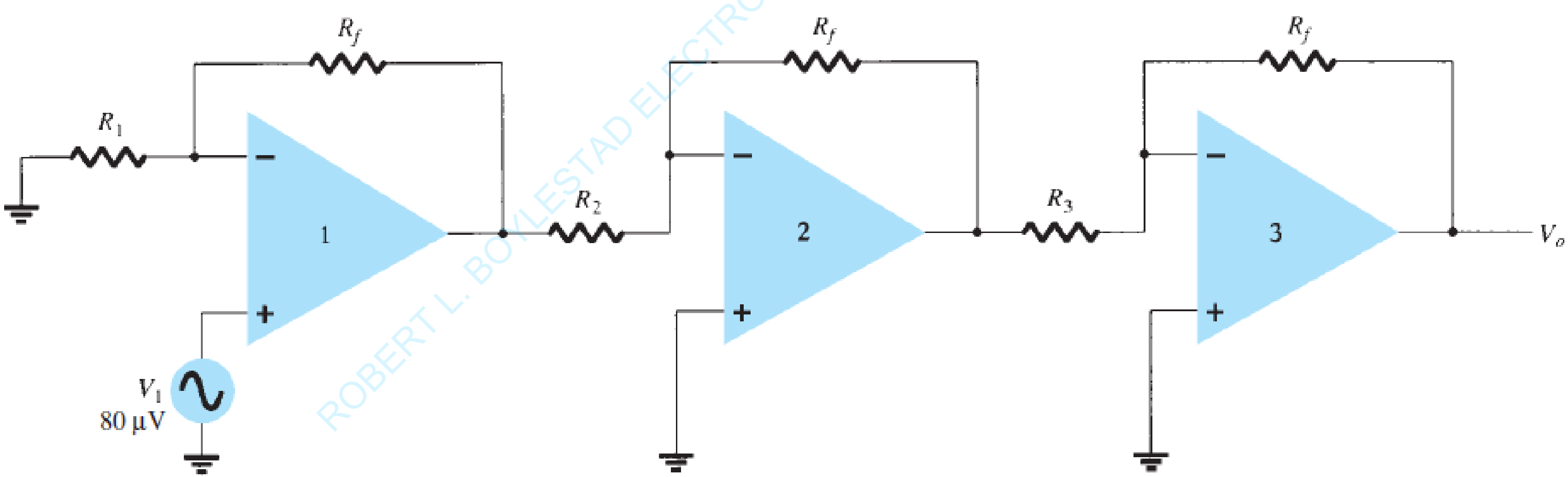


FIG. 11.5
Constant-gain connection with multiple stages.

EXAMPLE 11.6 Calculate the output voltage for the circuit of Fig. 11.9. The inputs are $V_1 = 50$ mV sin(1000t) and $V_2 = 10$ mV sin(3000t).

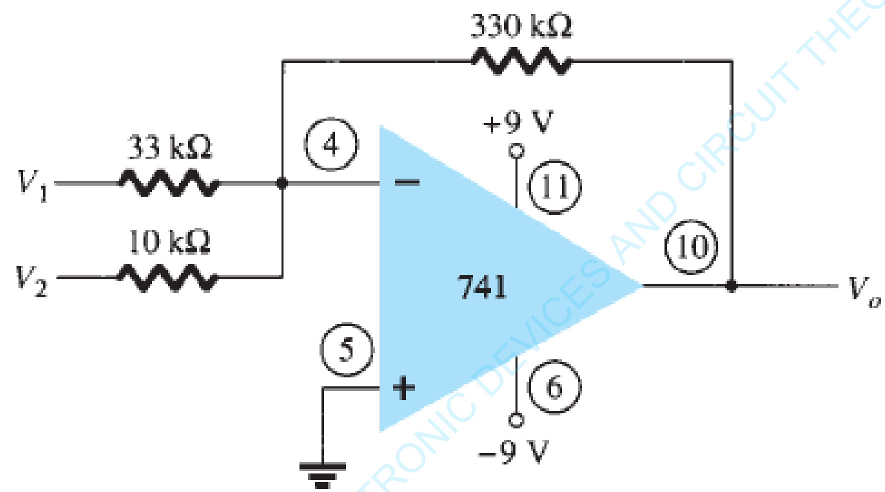


FIG. 11.9
Circuit for Example 11.6.

Solution: The output voltage is

$$V_o = -\left(\frac{330\text{ k}\Omega}{33\text{ k}\Omega}V_1 + \frac{330\text{ k}\Omega}{10\text{ k}\Omega}V_2\right) = -(10\,V_1 + 33\,V_2)$$

$$= -[10(50\text{ mV})\sin(1000t) + 33(10\text{ mV})\sin(3000t)]$$

$$= \mathbf{-[0.5\sin(1000t) + 0.33\sin(3000t)]}$$

EXAMPLE 11.7 Determine the output for the circuit of Fig. 11.10 with components $R_f = 1\ \text{M}\Omega$, $R_1 = 100\ \text{k}\Omega$, $R_2 = 50\ \text{k}\Omega$, and $R_3 = 500\ \text{k}\Omega$.

Solution: The output voltage is calculated to be

$$V_o = -\left(\frac{1\ \text{M}\Omega}{50\ \text{k}\Omega}V_2 - \frac{1\ \text{M}\Omega}{500\ \text{k}\Omega}\,\frac{1\ \text{M}\Omega}{100\ \text{k}\Omega}V_1\right) = -(20\ V_2 - 20\ V_1) = \mathbf{-20(V_2 - V_1)}$$

The output is seen to be the difference of V_2 and V_1 multiplied by a gain factor of -20.

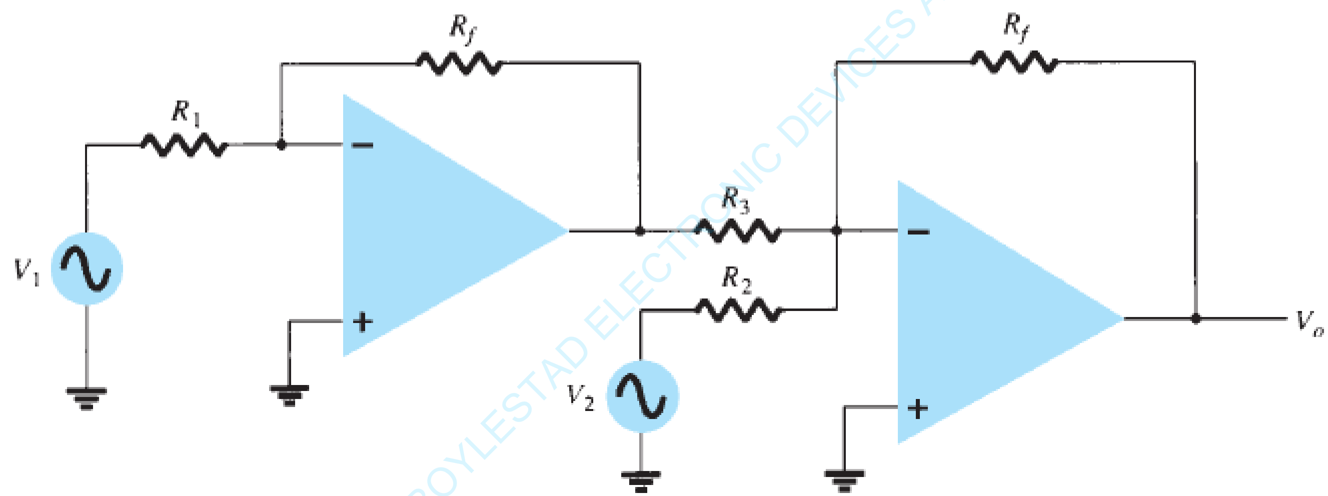


FIG. 11.10
Circuit for subtracting two signals.