Chapter 9

Exercise Solutions

E9.1

$A_{CL} = -\frac{R_2}{R_1} = \frac{-100\text{ k}\Omega}{10\text{ k}\Omega} \Rightarrow \underline{A_{CL} = -10}$

$v_I = 0.25\text{ V} \Rightarrow \underline{v_O = -2.5\text{ V}}$

$i_1 = \frac{v_I}{R_1} = \frac{0.25}{10\text{ k}\Omega} = 0.025\text{ mA} \Rightarrow \underline{i_1 = 25\ \mu\text{A}}$

$\underline{i_2 = i_1 = 25\ \mu\text{A}}$

$\underline{R_i = R_1 = 10\text{ k}\Omega}$

E9.2

$A_{CL} = -\frac{R_2}{R_1} = -15$

$R_i = \underline{R_1 = 20\text{ k}\Omega} \Rightarrow R_2 = (15)(20\text{ k}\Omega)$

$\underline{R_2 = 300\text{ k}\Omega}$

E9.3

(a) $A_v = \frac{-R_2}{R_1 + R_S}$

$A_v(\min) = \frac{-100}{19 + 1.3} = -4.926$

$A_v(\max) = \frac{-100}{19 + 0.7} = -5.076$

so $\underline{4.926 \le |A_v| \le 5.076}$

(b) $i_1(\max) = \frac{0.1}{19 + 0.7} = 5.076\ \mu A$

$i_1(\min) = \frac{0.1}{19 + 1.3} = 4.926\ \mu A$

so $\underline{4.926 \le i_1 \le 5.076\ \mu A}$

(c) Maximum current specification is violated.

E9.4

We can write

$A_{CL} = -\frac{R_2}{R_1}\left(1 + \frac{R_3}{R_4}\right) - \frac{R_3}{R_1}$

$R_i = \underline{R_1 = 10\text{ k}\Omega}$

Want $A_{CL} = -50$ Set $\underline{R_2 = R_3 = 50\text{ k}\Omega}$

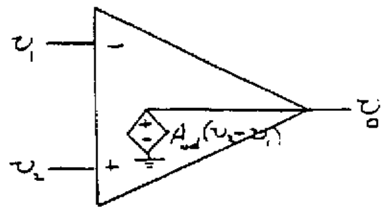
$A_{CL} = -50 = -5\left(1 + \frac{R_3}{R_4}\right) - 5$

$1 + \frac{R_3}{R_4} = 9 \Rightarrow \frac{R_3}{R_4} = 8 = \frac{50}{R_4}$

$\underline{R_4 = 6.25\text{ k}\Omega}$

E9.5

$v_0 = A_d(v_2 - v_1) \qquad A_d = 10^3$



a. $v_2 = 0,\ v_0 = 5$

$v_1 = -\frac{v_0}{A_d} = -\frac{5}{10^3} \Rightarrow \underline{v_1 = -5\text{ mV}}$

b. $v_1 = 5,\ v_0 = -10$

$\frac{v_0}{A_d} = v_2 - v_1$

$\frac{-10}{10^3} = v_2 - 5 \Rightarrow \underline{v_2 = 4.99\text{ V}}$

c. $v_1 = 0.001,\ v_2 = -0.001$

$v_0 = 10^3(-0.001 - 0.001)$

$\underline{v_0 = -2\text{ V}}$

d. $v_2 = 3,\ v_0 = 3$

$v_0 = A_d(v_2 - v_1)$

$\frac{v_0}{A_d} = v_2 - v_1$

$\frac{3}{10^3} = 3 - v_1 \Rightarrow \underline{v_1 = 2.997\text{ V}}$

E9.6

We have

$A_{CL} = -\frac{R_2}{R_1} \cdot \frac{1}{\left[1 + \frac{1}{A_d}\left(1 + \frac{R_2}{R_1}\right)\right]}$

$\underline{R_i = R_1 = 25\text{ k}\Omega}$ Let $\frac{R_2}{R_1} = x$

$-12 = -\frac{x}{1 + \frac{1}{5 \times 10^3}(1 + x)}$

$= \frac{-x}{1.0002 + \frac{x}{5 \times 10^3}}$

$12\left(1.0002 + \frac{x}{5 \times 10^3}\right) = x$

$12.0024 = x - (2.4 \times 10^{-3})x$

$x = \frac{12.0024}{0.9976} = 12.0313 = \frac{R_2}{25\text{ k}\Omega}$

$\underline{R_2 = 300.78\text{ k}\Omega}$

E9.7

$$v_0 = -\left(\frac{R_4}{R_1}v_{I1} + \frac{R_4}{R_2}v_{I2} + \frac{R_4}{R_3}v_{I3}\right)$$

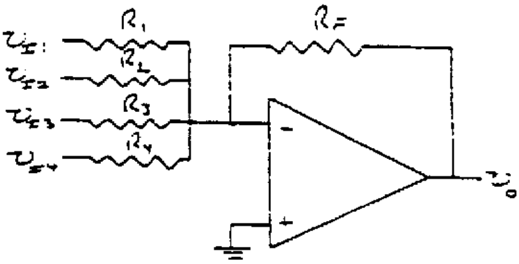
$$v_0 = -\left[\left(\frac{40}{10}\right)(250) + \left(\frac{40}{20}\right)(200) + \left(\frac{40}{30}\right)(75)\right]$$

$$v_0 = -[1000 + 400 + 100]$$

$$\underline{v_0 = -1500\ \mu\text{V} = -1.5\text{ mV}}$$

E9.8

$$v_0 = -\left(\frac{R_F}{R_1}v_{I1} + \frac{R_F}{R_2}v_{I2} + \frac{R_F}{R_3}v_{I3} + \frac{R_F}{R_4}v_{I4}\right)$$



We need

$$\frac{R_F}{R_1} = 7,\ \frac{R_F}{R_2} = 14,\ \frac{R_F}{R_3} = 3.5,\ \frac{R_F}{R_4} = 10$$

Set $R_F = 280\text{ k}\Omega$

Then $R_1 = \frac{280}{7} = 40\text{ k}\Omega$

$R_2 = \frac{280}{14} = 20\text{ k}\Omega$

$R_3 = \frac{280}{3.5} = 80\text{ k}\Omega$

$R_4 = \frac{280}{10} = 28\text{ k}\Omega$

E9.9

$$|v_O| = \frac{v_{I1} + v_{I2} + v_{I3}}{3} = \frac{R_F}{R}(v_{I1} + v_{I2} + v_{I3})$$

$$\frac{R_F}{R} = \frac{1}{3} \Rightarrow R_1 = R_2 = R_3 \equiv R = 1\ M\Omega$$

Then $R_F = \frac{1}{3}\ M\Omega = 333\ k\Omega$

E9.10

$$A_v = \frac{v_O}{v_I} = \left(1 + \frac{R_2}{R_1}\right) = 5$$

so that $\frac{R_2}{R_1} = 4$

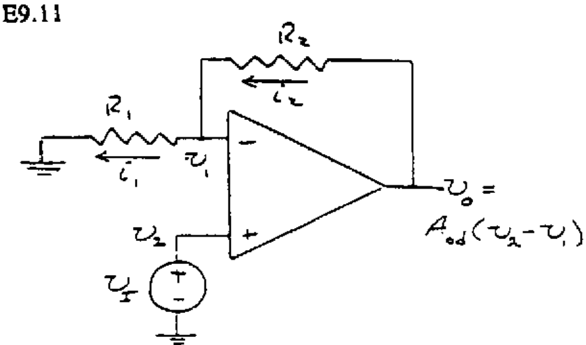
For $v_O = 10$ V, $v_I = 2$ V

Then $i_1 = \frac{2}{R_1} = 50\ \mu\text{A} \Rightarrow \underline{R_1 = 40\text{ k}\Omega}$

Then $\underline{R_2 = 160\text{ k}\Omega}$ we find

$$i_2 = \frac{v_O - v_I}{R_2} = \frac{10 - 2}{160} = 50\ \mu\text{A}$$

E9.11



$$v_0 = A_{od}(v_2 - v_1) = A_{od}(v_I - v_1)$$

$$\frac{v_0}{A_{od}} - v_I = -v_1 \text{ or } v_1 = v_I - \frac{v_0}{A_{od}}$$

$$i_1 = \frac{v_1}{R_1} = i_2 \text{ and } i_2 = \frac{v_0 - v_1}{R_2}$$

Then $v_1\left(\frac{1}{R_1}\right) = \frac{v_0 - v_1}{R_2}$

$$v_1\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = \frac{v_0}{R_2}$$

$$v_0\left(1 + \frac{R_2}{R_1}\right)v_1 = \left(1 + \frac{R_2}{R_1}\right)\left(v_I - \frac{v_0}{A_{od}}\right)$$

$$\text{So } A_v = \frac{v_0}{v_I} = \frac{\left(1 + \frac{R_2}{R_1}\right)}{1 + \frac{1}{A_{od}}\left(1 + \frac{R_2}{R_1}\right)}$$

E9.12

For $v_{I2} = 0$, $v_2 = \left(\frac{R_b}{R_b + R_a}\right)v_{I1}$ and

$$v_0(v_{I1}) = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_b}{R_b + R_a}\right)v_{I1}$$

$$= \left(1 + \frac{70}{5}\right)\left(\frac{50}{50 + 25}\right)v_{I1}$$

$$= 10v_{I1}$$

For $v_{I1} = 0$,

$$v_2 = \left(\frac{R_a}{R_b + R_a}\right)v_{I2}$$

$$v_0(v_{I2}) = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_a}{R_b + R_a}\right)v_{I2}$$

$$= \left(1 + \frac{70}{5}\right)\left(\frac{25}{25 + 50}\right)v_{I2}$$

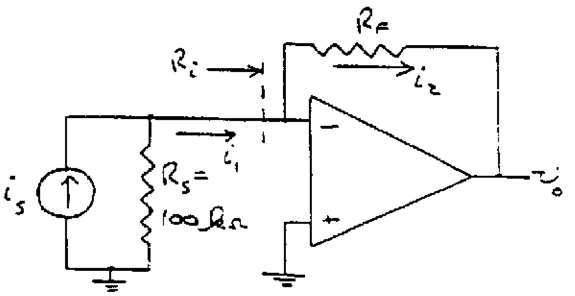
$$= 5v_{I2}$$

Then

$$v_0 = v_0(v_{I1}) + v_0(v_{I2})$$

$$\underline{v_0 = 10v_{I1} + 5v_{I2}}$$

E9.13



$R_S \gg R_i$ so $i_1 = i_2 = i_S = 100\ \mu A$

$v_O = -i_S R_F$

We want $-10 = -(100 \times 10^{-6}) R_F$

$\Rightarrow \underline{R_F = 100\ k\Omega}$

E9.14

We may note that

$\frac{R_3}{R_2} = \frac{3}{1.5} = 2$ and $\frac{R_F}{R_1} = \frac{20}{10} = 2$

so that

$$\frac{R_3}{R_2} = \frac{R_F}{R_1}$$

Then

$$i_L = \frac{-v_I}{R_2} = \frac{-(-3)}{1.5\ k\Omega}$$

$\Rightarrow \underline{i_L = 2\ mA}$

$v_L = i_L Z_L = (2 \times 10^{-3})(200) = 0.4\ V$

$i_4 = \frac{v_L}{R_2} = \frac{0.4}{1.5\ k\Omega} = 0.267\ mA$

$i_3 = i_4 + i_L = 0.267 + 2 = 2.267\ mA$

$v_O = i_3 R_3 + v_L = (2.267 \times 10^{-3})(3 \times 10^3) - 0.4$

$\Rightarrow \underline{v_O = 7.2\ V}$

E9.15

We want $i_L = 1\ mA$ when $v_I = -5\ V$

$i_L = \frac{-v_I}{R_2} \Rightarrow R_2 = \frac{-v_I}{i_2} = \frac{-(-5)}{10^{-3}}$

$\Rightarrow \underline{R_2 = 5\ k\Omega}$

$v_L = i_L Z_L = (10^{-3})(500)$

$\Rightarrow v_L = 0.5\ V$

$i_4 = \frac{v_L}{R_2} = \frac{0.5}{5\ k\Omega} \Rightarrow i_4 = 0.1\ mA$

$i_3 = i_4 + i_L = 0.1 + 1 = 1.1\ mA$

If op-amp is biased at $\pm 10\ V$, output must be limited to $\approx 8\ V$.

So $v_O = i_3 R_3 + v_L$

$8 = (1.1 \times 10^{-3}) R_3 + 0.5$

$\Rightarrow R_3 = 6.82\ k\Omega$

Let $\underline{R_3 = 7.0\ k\Omega}$

Then we want

$\frac{R_3}{R_2} = \frac{R_F}{R_1} = \frac{7}{5} = 1.4$

Can choose $\underline{R_1 = 10\ k\Omega}$ and $\underline{R_F = 14\ k\Omega}$

E9.16

Refer to Fig. 9.24

$R_i = 2R_1 = 5\ k\Omega$

Let $\underline{R_1 = R_3 = 2.5\ k\Omega}$

Set $R_2 = R_4$

Differential Gain $= \frac{v_O}{v_d} = \frac{R_2}{R_1} = 100 = \frac{R_2}{2.5\ k\Omega}$

$\Rightarrow \underline{R_2 = R_4 = 250\ k\Omega}$

E9.17

We have the general relation that

$v_O = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{[R_4/R_3]}{1 + [R_4/R_3]}\right) v_{I2} - \frac{R_2}{R_1} v_{I1}$

$R_1 = R_3 = 10\ k\Omega,\ R_2 = 20\ k\Omega,\ R_4 = 21\ k\Omega$

$v_O = \left(1 + \frac{20}{10}\right)\left(\frac{[21/10]}{1 + [21/10]}\right) v_{I2} - \left(\frac{20}{10}\right) v_{I1}$

$v_O = 2.0323 v_{I2} - 2.0 v_{I1}$

a. $v_{I1} = 1,\ v_{I2} = -1$

$v_O = -2.0323 - 2.0 \Rightarrow \underline{v_O = -4.032\ V}$

b. $v_{I1} = v_{I2} = 1\ V$

$v_O = 2.0323 - 2.0 \Rightarrow \underline{v_O = 0.0323\ V}$

c. $v_{cm} = v_{I1} = v_{I2}$ so common-mode gain

$\underline{A_{cm} = \frac{v_O}{v_{cm}} = 0.0323}$

d. $CMRR_{dB} = 20 \log_{10}\left(\frac{A_d}{A_{cm}}\right)$

$A_d = \frac{2.0323}{2} - (2.0)\left(-\frac{1}{2}\right) = 2.016$

$CMRR_{dB} = 20 \log_{10}\left(\frac{2.016}{0.0323}\right) = 35.9\ dB$

E9.18

$$v_O = -\frac{R_4}{R_3}\left(1+\frac{2R_2}{R_1}\right)(v_{I1}-v_{I2})$$

Differential gain (magnitude) $= \dfrac{R_4}{R_3}\left(1+\dfrac{2R_2}{R_1}\right)$

Minimum Gain $\Rightarrow$ Maximum $R_1 = 1 + 50 = 51$ kΩ

So $A_d = \dfrac{20}{20}\left(1+\dfrac{2(100)}{51}\right) \Rightarrow A_d = 4.92$

Maximum Gain $\Rightarrow$ Minimum $R_1 = 1$ kΩ

$A_d = \dfrac{20}{20}\left(1+\dfrac{2(100)}{1}\right) \Rightarrow A_d = 201$

Range of Differential Gain = $\underline{4.92-201}$

E9.19

a. $i_1 = \dfrac{v_{I1}-v_{I2}}{R_1}$

$v_{O1} = v_{I1} + i_1 R_2',\quad v_{O2} = v_{I2} - i_1 R_2$ and

$$v_O = \frac{R_4}{R_3}(v_{O2}-v_{O1})$$

$$v_O = \frac{R_4}{R_3}[v_{I2} - i_1 R_2 - v_{I1} - i_1 R_2']$$

$$v_O = \frac{R_4}{R_3}[(v_{I2}-v_{I1}) - i_1(R_2+R_2')]$$

$$v_O = \frac{R_4}{R_3}\left[(v_{I2}-v_{I1}) - \left(\frac{v_{I2}-v_{I1}}{R_1}\right)(R_2+R_2')\right]$$

For common-mode input $v_{I2} = v_{I1}$

$\Rightarrow v_O = 0 \Rightarrow$ $\underline{\text{Common Gain} = 0}$, $\underline{CMRR = \infty}$

b. $A_d(\text{min}) \Rightarrow R_2'$ min, R_1 max

$$A_d = \left(\frac{20}{20}\right)\left[1+\frac{100+95}{51}\right] = 4.82$$

$$A_d(\text{max}) = \left(\frac{20}{20}\right)\left[1+\frac{100+105}{1}\right] = 206$$

c. $CMRR = \left|\dfrac{A_d}{A_{cm}}\right|$

$A_{cm} = 0 \Rightarrow \underline{CMRR = \infty}$

E9.20

Differential Gain $= \dfrac{R_4}{R_3}\left(1+\dfrac{2R_2}{R_1}\right)$

Let $R_3 = R_4$ so the difference amplifier gain is unity.

Minimum Gain $\Rightarrow$ Maximum R_1

So $\left(1+\dfrac{2R_2}{R_1(\text{max})}\right) = 2$

We want $2R_2 = R_1(\text{max})$

Maximum Gain $\Rightarrow$ Minimum R_1

So $\left(1+\dfrac{2R_2}{R_1(\text{min})}\right) = 1000$ or $2R_2 = 999R_1(\text{min})$

If $R_2 = 50$ kΩ, let $R_1(\text{min}) = 100\ \Omega$ fixed resistor

and let $R_1(\text{max}) = \underbrace{100\text{ k}\Omega}_{\text{pot}} + 100\ \Omega = 100.1$

Then actual differential gain is in the range of

$\underline{1.999-1001}$

E9.21

Time constant $= \tau = R_1C_2 = (10^4)(0.1\times10^{-6})$

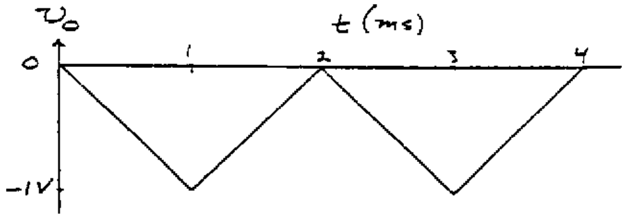
$= 1$ m sec

$0 \le t \le 1 \Rightarrow v_O = \dfrac{-1}{R_1C_2}\times t$

At $t = 1$ m sec $\Rightarrow v_O = -1$ V

$0 \le t \le 2 \Rightarrow v_O = -1 + \dfrac{1}{R_1C_2}\times(t-1)$

At $t = 2$ m sec $\Rightarrow v_O = -1 + \dfrac{(2-1)}{1} = 0$



E9.22

End of 1st pulse:

$$v_O = \frac{-1}{\tau}\times t\Big|_0^{10\ \mu\text{sec}} = \frac{-10\times10^{-6}}{\tau}$$

After 10 pulses:

$$v_O = -5 = \frac{-(10)(10\times10^{-6})}{\tau}$$

So $\tau = \dfrac{100\times10^{-6}}{5} = \underline{20\ \mu\text{sec} = \tau}$

$\tau = R_1C_2 = 20\ \mu$sec $= 20\times10^{-6}$

For example,

$\underline{C_2 = 0.01\times10^{-6} = 0.01\ \mu\text{F}} \Rightarrow \underline{R_1 = 2\text{ k}\Omega}$

E9.23

$$v_0 = v_{I1} + 10v_{I2} - 25v_{I3} - 80v_{I4}$$

From Figure 9.37, v_{I3} input to R_1, v_{I4} input to R_2, v_{I1} input to R_A, and v_{I2} input to R_B.
From Equation (9.87)

$\frac{R_F}{R_1} = 25$ and $\frac{R_F}{R_2} = 80$

Set $\underline{R_F = 500\text{ k}\Omega}$, then $\underline{R_1 = 20\text{ k}\Omega}$, and $\underline{R_2 = 6.25\text{ k}\Omega}$.

Also $\left(1 + \frac{R_F}{R_N}\right)\left(\frac{R_P}{R_A}\right) = 1$

and $\left(1 + \frac{R_F}{R_N}\right)\left(\frac{R_P}{R_B}\right) = 10$

where $R_N = R_1 \| R_2 = 20 \| 6.25 = 4.76\text{ k}\Omega$

and $R_P = R_A \| R_B \| R_C$

We find that $\frac{R_A}{R_B} = 10$

Let $\underline{R_A = 200\text{ k}\Omega}$, $\underline{R_B = 20\text{ k}\Omega}$

Now $\left(1 + \frac{500}{4.76}\right)\left(\frac{R_P}{R_A}\right) = 1 = (106)\left(\frac{R_P}{200}\right)$

Then $R_P = 1.89\text{ k}\Omega$

$R_A \| R_B = 200 \| 20 = 18.2\text{ k}\Omega$

So $R_P = 1.89 = \frac{18.2R_C}{18.2 + R_C} \Rightarrow \underline{R_C = 2.11\text{ k}\Omega}$

E9.25

$$v_{01} = \left[\frac{R - \Delta R}{(R - \Delta R) + (R + \Delta R)} - \frac{R + \Delta R}{(R + \Delta R) + (R - \Delta R)}\right]V^+$$

$$= \left[\frac{R - \Delta R}{2R} - \frac{R + \Delta R}{2R}\right]V^+$$

$$= \left(\frac{R - \Delta R - R - \Delta R}{2R}\right)V^+$$

$$v_{01} = -\left(\frac{\Delta R}{R}\right)V^+$$

For $V^+ = 3.5$ V, $\Delta R = 50$, $R = 10 \times 10^3$

$$v_{01} = -\left(\frac{50}{10^4}\right)(3.5) = -1.75 \times 10^{-2}$$

Need an amplifier with a gain of

$$A_d = \frac{v_0}{v_i} = \frac{5}{-1.75 \times 10^{-2}} \Rightarrow A_d = -285.7$$

Use instrumentation amplifier, Fig. 9-25.

Connect v_{01} to v_{I1} and $(-v_{01})$ to v_{I2}.

$$|A_d| = \left(\frac{R_4}{R_3}\right)\left(1 + \frac{2R_2}{R_1}\right) = 285.7$$

Let $\underline{R_4 = 150\text{ k}\Omega}$, $\underline{R_3 = 10\text{ k}\Omega}$ Then $\frac{R_2}{R_1} = 9.02$

Let $\underline{R_2 = 100\text{ k}\Omega}$, $\underline{R_1 = 11.1\text{ k}\Omega}$

E9.26

$$v_{01} = \left[\frac{1}{2} - \frac{R}{R + R(1+\delta)}\right]V^+$$

$$= \left[\frac{R + R(1+\delta) - 2R}{2(R + R(1+\delta))}\right]V^+$$

$$= \frac{R\delta}{2R(2+\delta)} \times V^+$$

$$v_{01} \approx \left(\frac{\delta}{4}\right)V^+$$

$V^+ = 5$ For $\delta = 0.01$

$$v_{01} = \left(\frac{0.01}{4}\right)(5) = 0.0125$$

Need a gain

$$A_d = \frac{v_0}{v_{01}} = \frac{5}{0.0125} = 400$$

Use an instrumentation amplifier

$$A_d = 400 = \left(\frac{R_4}{R_3}\right)\left(1 + \frac{2R_2}{R_1}\right)$$

Let $\underline{R_4 = 150\text{ k}\Omega}$, $\underline{R_3 = 10\text{ k}\Omega}$, then $\frac{R_2}{R_1} = 12.8$

Let $\underline{R_2 = 150\text{ k}\Omega}$, $\underline{R_1 = 11.7\text{ k}\Omega}$

Chapter 9

Problem Solutions

9.1

$$\left.\begin{array}{l} A_v = -\frac{200}{20} = -10 \\ \text{and} \\ R_i = 20 \text{ k}\Omega \end{array}\right\} \text{for each case}$$

9.2

a. $A_v = -\frac{100}{10} = -10$

$R_i = R_1 = 10 \text{ k}\Omega$

b. $A_v = -\frac{100\|100}{10} = -5$

$R_i = R_1 = 10 \text{ k}\Omega$

c. $A_v = -\frac{100}{10\|10} = -20$

$R_i = 10\|10 = 5 \text{ k}\Omega$

9.3

$A_v = -\frac{R_2}{R_1} = -12 \Rightarrow R_2 = 12R_1$

$R_i = \underline{R_1 = 25 \text{ k}\Omega}$

$\Rightarrow \underline{R_2 = (12)(25) = 300 \text{ k}\Omega}$

9.4

$A_v = -\frac{R_2}{R_1} = -8 \Rightarrow R_2 = 8R_1$

For $v_I = -1$, $i_1 = \frac{1}{R_1} = 15\ \mu\text{A} \Rightarrow \underline{R_1 = 66.7 \text{ k}\Omega}$

$\Rightarrow \underline{R_2 = 533.3 \text{ k}\Omega}$

9.5

$A_v = -\frac{R_2}{R_1} = -30 \Rightarrow R_2 = 30R_1$

Set $\underline{R_2 = 1 \text{ M}\Omega}$

$\Rightarrow \underline{R_1 = 33.3 \text{ k}\Omega}$

9.6

a. $A_v = \frac{R_2}{R_1} \Rightarrow \frac{1.05R_2}{0.95R_1} = 1.105\left(\frac{R_2}{R_1}\right)$

$\frac{0.95R_2}{1.05R_1} = 0.905\left(\frac{R_2}{R_1}\right)$

Deviation in gain is +10.5% and −9.5%

b. $A_v \Rightarrow \frac{1.01R_2}{0.99R_1} = 1.02\left(\frac{R_2}{R_1}\right)$

$\Rightarrow \frac{0.99R_2}{1.01R_1} = 0.98\left(\frac{R_2}{R_1}\right)$

Deviation in gain = ±2%

9.7

(a) $A_v = \frac{v_O}{v_I} = \frac{-15}{1} = -15$

$v_O = -15v_I \Rightarrow \underline{v_O = -150\sin\omega t\ (mV)}$

(b) $\underline{i_2 = i_1 = \frac{v_I}{R_1} = 10\sin\omega t\ (\mu A)}$

$i_L = \frac{v_O}{R_L} \Rightarrow \underline{i_L = -37.5\sin\omega t\ (\mu A)}$

$i_O = i_L - i_2$

$\underline{i_O = -47.5\sin\omega t\ (\mu A)}$

9.8

$A_v = -\frac{R_2}{R_1 + R_S}$

$A_v = -30 \pm 2.5\% \Rightarrow 29.25 \le |A_v| \le 30.75$

So $\frac{R_2}{R_1 + 2} = 29.25$ and $\frac{R_2}{R_1 + 1} = 30.75$

We have $29.25(R_1 + 2) = 30.75(R_1 + 1)$

Which yields $\underline{R_1 = 18.5\ k\Omega}$ and $\underline{R_2 = 599.6\ k\Omega}$

For $v_I = 25\, mV$, then

$\underline{0.731 \le |v_O| \le 0.769\ V}$

9.9

$v_{O1} = -\left(\frac{50}{10}\right)v_I = (-5)(0.15) \Rightarrow \underline{v_{O1} = -0.75 \text{ V}}$

$v_O = -\frac{150}{25} \cdot v_{O1} = (-6)(-0.75) \Rightarrow \underline{v_O = 4.5 \text{ V}}$

$i_1 = i_2 = \frac{0.15}{10} \Rightarrow \underline{i_1 = i_2 = 15\ \mu\text{A}}$

$i_3 = i_4 = \frac{v_{O1}}{R_3} = -\frac{0.75}{25} \Rightarrow \underline{i_3 = i_4 = -30\ \mu\text{A}}$

First op-amp must sink $15 + 30 = 45\ \mu$A

9.10

(a) $A_v = -\frac{R_2}{R_1} = -\frac{22}{1} \Rightarrow \underline{A_v = -22}$

(b) $A_v = -\frac{R_2}{R_1} \cdot \frac{1}{\left[1+\frac{1}{A_{od}}\left(1+\frac{R_2}{R_1}\right)\right]}$

$= -\frac{22}{1} \cdot \frac{1}{\left[1+\frac{1}{15x10^5}\left(1+\frac{22}{1}\right)\right]} = -\frac{22}{1} \cdot \frac{1}{1.000153} \Rightarrow$

$\underline{A_v = -21.99663}$

(c) $|A_v| = 22 - 1\% = 22 - 0.22 = 21.78$

Then $21.78 = \frac{22}{1} \cdot \frac{1}{\left[1+\frac{1}{A_{od}}(23)\right]} \Rightarrow \underline{A_{od} = 2277}$

9.11

$A_v = -\frac{R_2}{R_1}\left(1 + \frac{R_3}{R_4} + \frac{R_3}{R_2}\right)$

a. $-10 = -\frac{R_2}{100}\left(1 + \frac{100}{100} + \frac{100}{R_2}\right)$

$10 = \frac{2R_2}{100} + 1 \Rightarrow \underline{R_2 = 450 \text{ k}\Omega}$

b. $100 = \frac{2R_2}{100} + 1 \Rightarrow \underline{R_2 = 4.95 \text{ M}\Omega}$

9.12

a. $A_v = -\frac{R_2}{R_1}\left(1 + \frac{R_3}{R_4} + \frac{R_3}{R_2}\right)$

$R_1 = 500 \text{ k}\Omega$

$80 = \frac{R_2}{500}\left(1 + \frac{R_3}{R_4} + \frac{R_3}{R_2}\right)$

Set $\underline{R_2 = R_3 = 500 \text{ k}\Omega}$

$80 = 1\left(1 + \frac{500}{R_4} + 1\right) = 2 + \frac{500}{R_4}$

$\Rightarrow \underline{R_4 = 6.41 \text{ k}\Omega}$

b. For $v_I = -0.05$ V

$i_1 = i_2 = \frac{-0.05}{500 \text{ k}\Omega} \Rightarrow \underline{i_1 = i_2 = -0.1\ \mu\text{A}}$

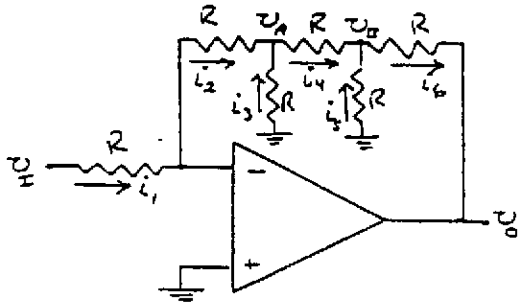
$v_X = -i_2 R_2 = -(-0.1 \times 10^{-6})(500 \times 10^3)$

$= 0.05$

$i_4 = -\frac{v_X}{R_4} = -\frac{0.05}{6.41} \Rightarrow \underline{i_4 = -7.80\ \mu\text{A}}$

$i_3 = i_2 + i_4 = -0.1 - 7.80 \Rightarrow \underline{i_3 = -7.90\ \mu\text{A}}$

9.13



$i_1 = \frac{v_I}{R} = i_2$

$v_A = -i_2 R = -\left(\frac{v_I}{R}\right)R = -v_I$

$i_3 = -\frac{v_A}{R} = \frac{v_I}{R}$

$i_4 = i_2 + i_3 = -\frac{v_A}{R} - \frac{v_A}{R} = -\frac{2v_A}{R} = \frac{2v_I}{R}$

$v_B = v_A - i_4 R = -v_I - \left(\frac{2v_I}{R}\right)(R) = -3v_I$

$i_5 = -\frac{v_B}{R} = -\frac{(-3v_I)}{R} = \frac{3v_I}{R}$

$i_6 = i_4 + i_5 = \frac{2v_I}{R} + \frac{3v_I}{R} = \frac{5v_I}{R}$

$v_0 = v_B - i_6 R = -3v_I - \left(\frac{5v_I}{R}\right)R$

$\Rightarrow \underline{\frac{v_0}{v_I} = -8}$

From Figure 9.11 $\Rightarrow \underline{A_v = -3}$

9.14

(a) $A_v = -\frac{R_2}{R_1} \cdot \frac{1}{\left[1+\frac{1}{A_{od}}\left(1+\frac{R_2}{R_1}\right)\right]}$

$= -\frac{50}{10} \cdot \frac{1}{\left[1+\frac{1}{2x10^5}\left(1+\frac{50}{10}\right)\right]} \Rightarrow \underline{A_v = -4.99985}$

(b) $v_O = -(4.99985)(100x10^{-3}) \Rightarrow$

$\underline{v_O = -499.985\, mV}$

(c) Error $= \frac{0.5 - 0.499985}{0.5} x100\% \Rightarrow \underline{0.003\%}$

9.15

a. From Equation (9.23)

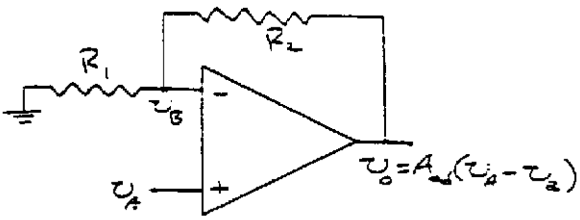
$$A_\nu = -\frac{R_2}{R_1}\cdot\frac{1}{\left[1+\frac{1}{A_{od}}\left(1+\frac{R_2}{R_1}\right)\right]}$$

$$= -\frac{100}{100}\cdot\frac{1}{\left[1+\frac{1}{10^3}\left(1+\frac{100}{100}\right)\right]} = -0.9980$$

Then $\nu_0 = A_\nu \cdot \nu_I = (-0.9980)(2)$

$\Rightarrow \underline{\nu_0 = -1.9960}$

b.



$$\nu_0 = A_{od}(\nu_A - \nu_B)$$

$$\frac{\nu_B}{R_1} = \frac{\nu_0-\nu_B}{R_2} \Rightarrow \nu_B\left(\frac{1}{R_1}+\frac{1}{R_2}\right) = \frac{\nu_0}{R_2}$$

$$\nu_B = \frac{\nu_0}{\left(1+\frac{R_2}{R_1}\right)}$$

Then $\nu_0 = A_{od}\nu_A - \dfrac{A_{od}\nu_0}{\left(1+\frac{R_2}{R_1}\right)}$

$$\nu_0\left[1+\frac{A_{od}}{\left(1+\frac{R_2}{R_1}\right)}\right] = A_{od}\nu_A$$

$$\nu_0\left[\frac{\left(1+\frac{R_2}{R_1}\right)+A_{od}}{\left(1+\frac{R_2}{R_1}\right)}\right] = A_{od}\nu_A$$

$$\nu_0 = \frac{A_{od}\left(1+\frac{R_2}{R_1}\right)\nu_A}{A_{od}+\left(1+\frac{R_2}{R_1}\right)}$$

$$\nu_0 = \frac{\left(1+\frac{R_2}{R_1}\right)\nu_A}{1+\frac{1}{A_{od}}\left(1+\frac{R_2}{R_1}\right)}$$

So

$$\nu_0 = \frac{\left(1+\frac{10}{10}\right)\left(\frac{\nu_I}{2}\right)}{1+\frac{1}{10^3}\left(1+\frac{10}{10}\right)} = 0.9980\nu_I$$

For $\nu_I = 2$ V

$\underline{\nu_0 = 1.9960 \text{ V}}$

9.16

(a) $i_i = \dfrac{v_I}{R_1} = i_2 = -\dfrac{v_O}{R_2} \Rightarrow \quad \dfrac{v_O}{v_I} = -\dfrac{R_2}{R_1}$

(b) $i_2 = i_1 = \dfrac{v_I}{R_1} = i_3 + \dfrac{v_O}{R_L} = i_3 + \dfrac{1}{R_L}\left(-\dfrac{R_2}{R_1}\cdot v_I\right)$

Then $\underline{i_3 = \dfrac{v_I}{R_1}\left(1+\dfrac{R_2}{R_L}\right)}$

9.17

$$V_{X,\max} = \left(\frac{R_3\|R_1}{R_3\|R_1+R_4}\right)\cdot V^+ = \left(\frac{0.1\|1}{0.1\|1+10}\right)(10) \Rightarrow$$

$$V_{X,\max} = 0.09008\ V$$

$$|v_O| = \frac{R_2}{R_1}\cdot V_{X,\max}$$

$$10 = \frac{R_2}{R_1}(0.09008) \Rightarrow \frac{R_2}{R_1} = 111$$

So $\underline{R_2 = 111\ k\Omega}$

9.18

$$\nu_0 = A_{oL}(\nu_2 - \nu_1)$$

a. $A_{oL} = \dfrac{1}{[1-(-1)]\times 10^{-3}} \Rightarrow \underline{A_{oL} = 500}$

b. $1 = 500(\nu_2 - 1\times 10^{-3}) \Rightarrow \underline{\nu_2 = 3 \text{ mV}}$

c. $5 = 500(1-\nu_1) \Rightarrow \underline{\nu_1 = 0.99 \text{ V}}$

d. $\nu_0 = 500(-1-(-1)) \Rightarrow \underline{\nu_0 = 0}$

e. $-3 = 500(\nu_2 - (-0.5)) \Rightarrow \underline{\nu_2 = -0.506 \text{ V}}$

9.19

a. $\nu_0 = -\dfrac{R_F}{R_1}\cdot\nu_{I1} - \dfrac{R_F}{R_2}\cdot\nu_{I2} - \dfrac{R_F}{R_3}\cdot\nu_{I3}$

$$\nu_0 = -\frac{80}{20}(0.5) - \frac{80}{40}(-1) - \frac{80}{60}(2)$$

$$= -4(0.5) - 2(-1) - 1.33(2)$$

$\underline{\nu_0 = -2.667 \text{ V}}$

b. $-5.2 = -4(1) - 2(0.25) - 1.33\nu_{I3}$

$\underline{\nu_{I3} = 0.525}$

9.20

$$v_O = -8v_{I1} - 2v_{I2} - 5v_{I3}$$
$$= -\frac{R_F}{R_1}v_{I1} - \frac{R_F}{R_2}v_{I2} - \frac{R_F}{R_3}v_{I3}$$
$$\frac{R_F}{R_1} = 8 \quad \frac{R_F}{R_2} = 2 \quad \frac{R_F}{R_3} = 5$$

Let $R_F = 500\text{ k}\Omega \Rightarrow R_1 = 62.5\text{ k}\Omega$

$R_2 = 250\text{ k}\Omega$

$R_3 = 100\text{ k}\Omega$

9.21

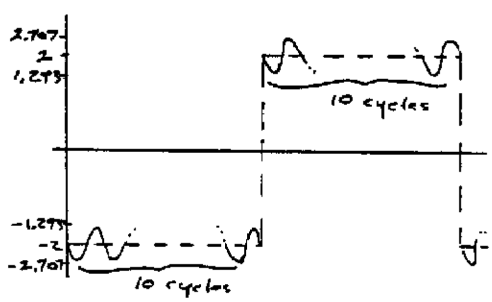
$$v_O = -4v_{I1} - 0.5v_{I2} = -\frac{R_F}{R_1}v_{I1} - \frac{R_F}{R_2}v_{I2}$$
$$\frac{R_F}{R_1} = 4 \qquad \frac{R_F}{R_2} = 0.5$$

$\Rightarrow R_1$ is the smallest resistor

$$|i| = 100\ \mu\text{A} = \frac{v_I}{R_1} = \frac{2}{R_1} \Rightarrow \underline{R_1 = 20\text{ k}\Omega}$$
$$\Rightarrow \underline{R_F = 80\text{ k}\Omega}$$
$$\Rightarrow \underline{R_2 = 160\text{ k}\Omega}$$

9.22

$$v_{I1} = (0.05)\sqrt{2}\sin(2\pi ft) = 0.0707\sin(2\pi ft)$$
$$f = 1\ kHz \Rightarrow T = \frac{1}{10^3} \Rightarrow 1\ ms$$
$$v_{I2} \Rightarrow T_2 = \frac{1}{100} \Rightarrow 10\ ms$$
$$v_O = -\frac{R_F}{R_1}\cdot v_{I1} - \frac{R_F}{R_2}\cdot v_{I2} = -\frac{10}{1}\cdot v_{I1} - \frac{10}{5}\cdot v_{I2}$$
$$v_O = -(10)(0.0707\sin(2\pi ft)) - (2)(\pm 1\ V)$$
$$v_O = -0.707\sin(2\pi ft) - (\pm 2\ V)$$



9.23

$$v_O = -\frac{R_F}{R_1}\cdot v_{I1} - \frac{R_F}{R_2}\cdot v_{I2} - \frac{R_F}{R_3}\cdot v_{I3}$$
$$v_O = -\frac{20}{10}\cdot v_{I1} - \frac{20}{5}\cdot v_{I2} - \frac{20}{2}\cdot v_{I3}$$
$$K\sin\omega t = -2v_{I1} - 4[2 + 100\sin\omega t] - 0$$

Set $\underline{v_{I1} = -4}$

9.24

a.

$$v_O = -\frac{R_F}{R_3}\cdot a_3(-5) - \frac{R_F}{R_2}\cdot a_2(-5) - \frac{R_F}{R_1}\cdot a_1(-5) - \frac{R_F}{R_0}\cdot a_0(-5)$$

So $v_O = \frac{R_F}{10}\left[\frac{a_3}{2} + \frac{a_2}{4} + \frac{a_1}{8} + \frac{a_0}{16}\right](5)$

b. $v_O = 2.5 = \frac{R_F}{10}\cdot\frac{1}{2}\cdot 5 \Rightarrow \underline{R_F = 10\text{ k}\Omega}$

c. i. $v_O = \frac{10}{10}\cdot\frac{1}{16}\cdot 5 \Rightarrow \underline{v_O = 0.3125\text{ V}}$

ii. $v_O = \frac{10}{10}\left[\frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \frac{1}{16}\right](5)$

$\Rightarrow \underline{v_O = 4.6875\text{ V}}$

9.25

(a) $v_{O1} = -\frac{10}{1}\cdot v_{I1}$

$$v_O = -\frac{20}{1}\cdot v_{O1} - \frac{20}{1}\cdot v_{I2} = -(20)(-10)v_{I1} - (20)v_{I2}$$
$$\underline{v_O = 200v_{I1} - 20v_{I2}}$$

(b) $v_{I1} = 1 + 2\sin\omega t\ (mV)$

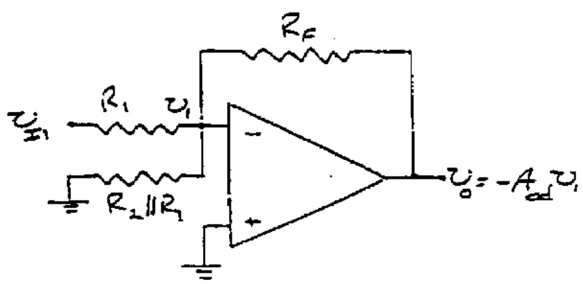
$v_{I2} = -10\ mV$

Then $v_O = 200(1 + 2\sin\omega t) - 20(-10)$

So $\underline{v_O = 0.4 + 0.4\sin\omega t\ (V)}$

9.26

For one-input



$$v_1 = -\frac{v_O}{A_{od}}$$
$$\frac{v_{I1} - v_1}{R_1} = \frac{v_1}{R_2\|R_3} + \frac{v_1 - v_O}{R_F}$$
$$\frac{v_{I1}}{R_1} = v_1\left[\frac{1}{R_1} + \frac{1}{R_2\|R_3} + \frac{1}{R_F}\right] - \frac{v_O}{R_F}$$
$$= -\frac{v_O}{A_{od}}\left[\frac{1}{R_1} + \frac{1}{R_2\|R_3} + \frac{1}{R_F}\right] - \frac{v_O}{R_F}$$
$$= -v_O\left\{\frac{1}{A_{od}R_F} + \frac{1}{R_F} + \frac{1}{A_{od}}\left(\frac{1}{R_1} + \frac{1}{R_2\|R_3}\right)\right\}$$
$$= -\frac{v_O}{R_F}\left\{\frac{1}{A_{od}} + 1 + \frac{1}{A_{od}}\cdot\frac{R_F}{R_1\|R_2\|R_3}\right\}$$

$$v_O = -\frac{R_F}{R_1}\cdot v_{I1}\cdot\left\{\frac{1}{1+\frac{1}{A_{od}}\left(1+\frac{R_F}{R_P}\right)}\right\}$$

where $R_P = R_1\|R_2\|R_3$

Therefore, for three-inputs

$$v_O = \frac{-1}{1+\frac{1}{A_{od}}\left(1+\frac{R_F}{R_P}\right)} \times\left(\frac{R_F}{R_1}\cdot v_{I1}+\frac{R_F}{R_2}\cdot v_{I2}+\frac{R_F}{R_3}\cdot v_{I3}\right)$$

9.27

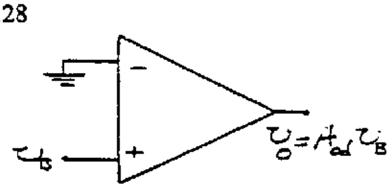
$$A_v = \left(1+\frac{R_2}{R_1}\right) = 10$$

$$\frac{R_2}{R_1} = 9$$

$$|i| = \frac{v_I}{R_1} = \frac{0.8}{R_1} = 100\ \mu\text{A}$$

$$\Rightarrow \underline{R_1 = 8\ \text{k}\Omega},\ \underline{R_2 = 72\ \text{k}\Omega}$$

9.28



$$v_B = \left(\frac{1}{1+500}\right)v_I,\quad v_O = A_{od}\left(\frac{1}{501}\right)v_I$$

a. $2.5 = A_{od}\left(\frac{1}{501}\right)(5) \Rightarrow \underline{A_{od} = 250.5}$

b. $v_O = 5000\left(\frac{1}{501}\right)(5) \Rightarrow \underline{v_O = 49.9\ \text{V}}$

9.29

$$v_O = \left(1+\frac{50}{50}\right)\left[\left(\frac{20}{20+40}\right)v_{I2}+\left(\frac{40}{20+40}\right)v_{I1}\right]$$

$$\underline{v_O = 1.33v_{I1}+0.667v_{I2}}$$

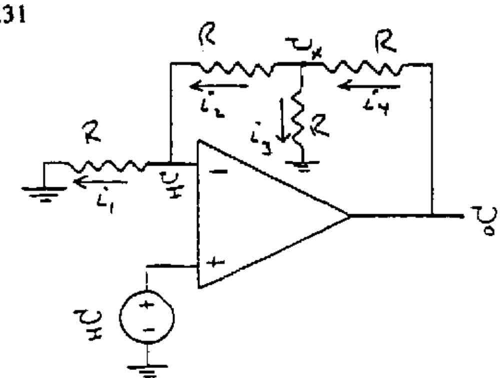
9.30

$$v_O = \left(1+\frac{100}{50}\right) \times\left[\left(\frac{10\|40}{10\|40+20}\right)v_{I1}+\left(\frac{10\|20}{10\|20+40}\right)v_{I2}\right]$$

$$v_O = 3\left[\left(\frac{8}{8+20}\right)v_{I1}+\left(\frac{6.67}{6.67+40}\right)v_{I2}\right]$$

$$\underline{v_O = 0.857v_{I1}+0.429v_{I2}}$$

9.31



$$i_1 = \frac{v_I}{R} = i_2$$

$$v_X = i_2R+v_I = \left(\frac{v_I}{R}\right)R+v_I = 2v_I$$

$$i_3 = \frac{v_X}{R} = \frac{2v_I}{R}$$

$$i_4 = i_2+i_3 = \frac{v_I}{R}+\frac{2v_I}{R} = \frac{3v_I}{R}$$

$$v_O = i_4R+v_X = \left(\frac{3v_I}{R}\right)R+2v_I$$

$$\underline{\frac{v_O}{v_I} = 5}$$

9.32

(a) $\frac{v_O}{v_I} = 1$

(b) From Exercise 9.11

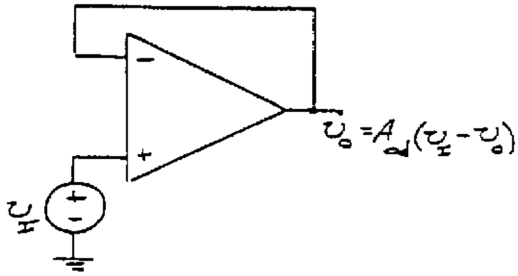
$$\frac{v_O}{v_I} = \frac{\left(1+\frac{R_2}{R_1}\right)}{\left[1+\frac{1}{A_{od}}\left(1+\frac{R_2}{R_1}\right)\right]}$$

But $R_2 = 0$, $R_1 = \infty$

$$\frac{v_O}{v_I} = \frac{1}{1+\frac{1}{A_{od}}} = \frac{1}{1+\frac{1}{1.5\text{x}10^5}} \Rightarrow \underline{\frac{v_O}{v_I} = 0.99999}$$

(b) Want $\frac{v_O}{v_I} = 0.990 = \frac{1}{1+\frac{1}{A_{od}}} \Rightarrow \underline{A_{od} = 99}$

9.33



$$v_O = A_{od}(v_I - v_O)$$
$$\left(\frac{1}{A_{od}} + 1\right) v_O = v_I$$
$$v_O = \frac{v_I}{\left(1 + \frac{1}{A_{od}}\right)}$$

$A_{od} = 10^4;\ \frac{v_O}{v_I} = 0.99990$
$A_{od} = 10^3;\ \frac{v_O}{v_I} = 0.9990$
$A_{od} = 10^2;\ \frac{v_O}{v_I} = 0.990$
$A_{od} = 10;\ \frac{v_O}{v_I} = 0.909$

9.34

$$v_{OA} = \left(1 + \frac{R_2}{R_1}\right) v_I$$
$$\underline{v_{O1} = \left(1 + \frac{R_2}{R_1}\right) v_I}, \quad \underline{v_{O2} = -\left(1 + \frac{R_2}{R_1}\right) v_I}$$

So $\underline{v_{O1} = -v_{O2}}$

9.35

(a) $i_L = \frac{v_I}{R_1}$

(b) $v_{O1} = i_L R_L + v_I = i_L R_L + i_L R_1$
$v_{O1}(\max) \cong 8\ V = i_L(1+9) = 10 i_L$
So $\underline{i_L(\max) \cong 0.8\ mA}$
Then $v_I(\max) \cong i_L R_1 = (0.8)(9) \Rightarrow$ $\underline{v_I(\max) \cong 7.2\ V}$

9.36

(a) $v_X = \left(\frac{20}{20+40}\right) \cdot v_I = \left(\frac{20}{60}\right)(6) = 2$
$\underline{v_O = 2\ V}$

(b) Same as (a)

(c) $v_X = \left(\frac{6}{6+48}\right)(6) = 0.666\ V$

$v_O = \left(1 + \frac{10}{10}\right) \cdot v_X \Rightarrow$ $\underline{v_O = 1.33\ V}$

9.37

a. $R_{in} = \frac{v_1}{i_1}$ and $\frac{v_1 - v_O}{R_F} = i_1$ and $v_O = -A_{od} v_1$

So $i_1 = \frac{v_1 - (-A_{od} v_1)}{R_F} = \frac{v_1(1 + A_{od})}{R_F}$

Then $\underline{R_{in} = \frac{v_1}{i_1} = \frac{R_F}{1 + A_{od}}}$

b. $i_1 = \left(\frac{R_S}{R_S + R_{in}}\right) i_S$ and $v_O = -A_{od} \cdot \frac{R_F}{1 + A_{od}} \cdot i_1$

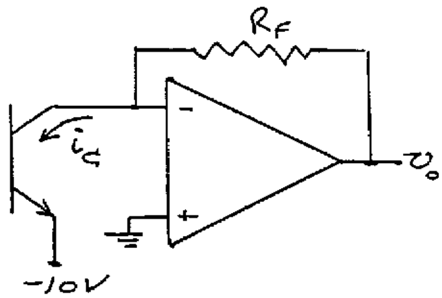
So $v_O = -R_F \left(\frac{A_{od}}{1 + A_{od}}\right)\left(\frac{R_S}{R_S + R_{in}}\right) i_S$

$R_{in} = \frac{R_F}{1 + A_{od}} = \frac{10}{1001} = 0.009990$

$v_O = -R_F \left(\frac{1000}{1001}\right)\left(\frac{R_S}{R_S + 0.009990}\right) i_S$

Want $\left(\frac{1000}{1001}\right)\left(\frac{R_S}{R_S + 0.009990}\right) \geq 0.990$
which yields $\underline{R_S \geq 1.099\ k\Omega}$

9.38



$v_O = i_C R_F$, $\quad 0 \leq i_C \leq 8\ mA$
For $v_O(\max) = 8\ V$, Then
$\underline{R_F = 1\ k\Omega}$

9.39

$i = \frac{v_I}{R}$ so $1 = \frac{10}{R} \Rightarrow \underline{R = 10\ k\Omega}$

In the ideal op-amp, R_1 has no influence.

Output voltage: $v_O = \left(1 + \frac{R_2}{R}\right) v_I$

v_O must remain within the bias voltages of the op-amp; the larger the R_2, the smaller the range of input voltage v_I in which the output is valid.

9.40

$i_L = \frac{-\nu_I}{R_2} \Rightarrow 10 = -\frac{(-10)}{R_2} \Rightarrow \underline{R_2 = 1\text{ k}\Omega}$

$i_4 = \frac{\nu_L}{R_2}$ and $\nu_L = i_L Z_L = (0.010)(100) = 1\text{ V}$

$i_4 = \frac{1}{1\text{ k}\Omega} = 1\text{ mA}$

$i_3 = i_4 + i_L = 1 + 10 = 11\text{ mA}$

For $\nu_0(\max) \approx 12\text{ V} = i_3 R_3 + \nu_L = (11)R_3 + 1$

$\Rightarrow \underline{R_3 = 1\text{ k}\Omega}$

We need

$\frac{R_3}{R_2} = \frac{R_F}{R_1} = \frac{1\text{ k}\Omega}{1\text{ k}\Omega} \Rightarrow \underline{R_1 = R_F}$

9.41

(a) $i_1 = i_2$ and $i_2 = \frac{v_X}{R_2} + i_D$, $v_X = -i_2 R_F$

Then $i_1 = -i_1\left(\frac{R_F}{R_2}\right) + i_D$

Or $\underline{i_D = i_1\left(1 + \frac{R_F}{R_2}\right)}$

(b) $R_1 = \frac{v_I}{i_1} = \frac{5}{1} \Rightarrow$ $\underline{R_1 = 5\,k\Omega}$

$12 = (1)\left(1 + \frac{R_F}{R_2}\right) \Rightarrow$ $\underline{\frac{R_F}{R_2} = 11}$

For example, $\underline{R_2 = 5\,k\Omega,\quad R_F = 55\,k\Omega}$

9.42

(1) $I_X = \frac{V_X}{R_2} + \frac{V_X - v_O}{R_3}$

(2) $\frac{V_X}{R_1} + \frac{V_X - v_O}{R_F} = 0$

From (2) $v_O = V_X\left(1 + \frac{R_F}{R_1}\right)$

Then (1) $I_X = V_X\left(\frac{1}{R_2} + \frac{1}{R_3}\right) - \frac{1}{R_3}\cdot V_X\left(1 + \frac{R_F}{R_1}\right)$

$\frac{I_X}{V_X} = \frac{1}{R_o} = \frac{1}{R_2} + \frac{1}{R_3} - \frac{1}{R_3} - \frac{R_F}{R_1 R_3} = \frac{1}{R_2} - \frac{R_F}{R_1 R_3}$

$= \frac{R_1 R_3 - R_2 R_F}{R_1 R_2 R_3}$

or

$\underline{R_o = \frac{R_1 R_2 R_3}{R_1 R_3 - R_2 R_F}}$

Note: If $\frac{R_F}{R_1 R_3} = \frac{1}{R_2} \Rightarrow R_2 R_F = R_1 R_3$

then $R_o = \infty$, which corresponds to an ideal current source.

9.43

$A_d = \frac{R_2}{R_1} = \frac{R_4}{R_3} = 5$

Minimum resistance seen by ν_{I1} is R_1.

Set $\underline{R_1 = R_3 = 25\text{ k}\Omega}$ Then $\underline{R_2 = R_4 = 125\text{ k}\Omega}$

$i_L = \frac{\nu_O}{R_L} \Rightarrow \nu_O = i_L R_L = (0.5)(5) = 2.5\text{ V}$

$\nu_O = 5(\nu_{I2} - \nu_{I1})$

$2.5 = 5(\nu_{I2} - 2) \Rightarrow \underline{\nu_{I2} = 2.5\text{ V}}$

9.44

a. From superposition:

$\nu_{O1} = -\frac{R_2}{R_1}\cdot \nu_{I1}$

$\nu_{O2} = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4}{R_3 + R_4}\right)\nu_{I2}$

Setting $\nu_{I1} = \nu_{I2} = \nu_{cm}$

$$\nu_O = \nu_{O1} + \nu_{O2} = \left[\left(1 + \frac{R_2}{R_1}\right)\left(\frac{1}{1 + \frac{R_3}{R_4}}\right) - \frac{R_2}{R_1}\right]\nu_{cm}$$

$$A_{cm} = \frac{\nu_O}{\nu_{cm}} = \frac{R_4}{R_3}\cdot\left(1 + \frac{R_2}{R_1}\right)\left(\frac{1}{1 + \frac{R_3}{R_4}}\right) - \frac{R_2}{R_1}$$

$$= \frac{\frac{R_4}{R_3}\left(1 + \frac{R_2}{R_1}\right) - \frac{R_2}{R_1}\left(1 + \frac{R_4}{R_3}\right)}{\left(1 + \frac{R_4}{R_3}\right)}$$

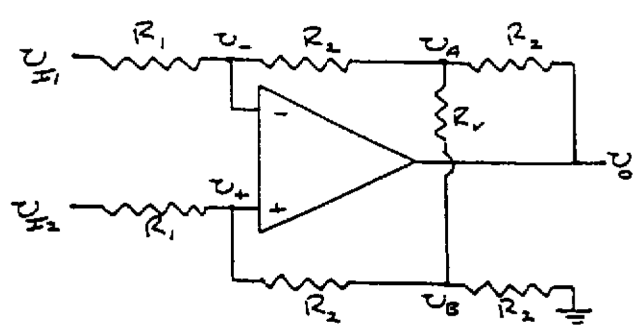
$$\underline{A_{cm} = \frac{\frac{R_4}{R_3} - \frac{R_2}{R_1}}{\left(1 + \frac{R_4}{R_3}\right)}}$$

b. Max. $|A_{cm}| \Rightarrow$ Min. $\frac{R_4}{R_3}$ and Max. $\frac{R_2}{R_1}$

$$\text{Max. } |A_{cm}| = \frac{\frac{47.5}{10.5} - \frac{52.5}{9.5}}{1 + \frac{47.5}{10.5}} = \frac{4.5238 - 5.5263}{1 + 4.5238}$$

$\Rightarrow \underline{|A_{cm}|_{max} = 0.1815}$

9.45



$$\frac{v_{I1}-v_A}{R_1+R_2}=\frac{v_A-v_B}{R_V}+\frac{v_A-v_0}{R_2} \quad (1)$$

$$\frac{v_{I2}-v_B}{R_1+R_2}=\frac{v_B-v_A}{R_V}+\frac{v_B}{R_2} \quad (2)$$

$$v_-=\left(\frac{R_1}{R_1+R_2}\right)v_A+\left(\frac{R_2}{R_1+R_2}\right)v_{I1} \quad (3)$$

$$v_+=\left(\frac{R_1}{R_1+R_2}\right)v_B+\left(\frac{R_2}{R_1+R_2}\right)v_{I2} \quad (4)$$

Now $v_-=v_+ \Rightarrow R_1v_A+R_2v_{I1}=R_1v_B+R_2v_{I2}$

So that $v_A=v_B+\frac{R_2}{R_1}(v_{I2}-v_{I1})$

$$\frac{v_{I1}}{R_1+R_2}=v_A\left(\frac{1}{R_1+R_2}+\frac{1}{R_V}+\frac{1}{R_2}\right)-\frac{v_B}{R_V}-\frac{v_0}{R_2} \quad (1)$$

$$\frac{v_{I2}}{R_1+R_2}=v_B\left(\frac{1}{R_1+R_2}+\frac{1}{R_V}+\frac{1}{R_2}\right)-\frac{v_A}{R_V} \quad (2)$$

Then

$$\frac{v_{I1}}{R_1+R_2} \quad (1)$$
$$=v_B\left(\frac{1}{R_1+R_2}+\frac{1}{R_V}+\frac{1}{R_2}\right)-\frac{v_B}{R_V}-\frac{v_0}{R_2}+\left(\frac{R_2}{R_1}\right)\left(\frac{1}{R_1+R_2}+\frac{1}{R_V}+\frac{1}{R_2}\right)(v_{I2}-v_{I1})$$

$$\frac{v_{I2}}{R_1+R_2}=v_B\left(\frac{1}{R_1+R_2}+\frac{1}{R_V}+\frac{1}{R_2}\right)-\frac{1}{R_V}\left[v_B+\frac{R_2}{R_1}(v_{I2}-v_{I1})\right] \quad (2)$$

Substitute (1)-(2)

$$\frac{1}{R_1+R_2}(v_{I1}-v_{I2})=\left(\frac{R_2}{R_1}\right)\left(\frac{1}{R_1+R_2}+\frac{1}{R_V}+\frac{1}{R_2}\right)(v_{I2}-v_{I1})-\frac{v_0}{R_2}+\frac{1}{R_V}\cdot\frac{R_2}{R_1}(v_{I2}-v_{I1})$$

$$\frac{v_0}{R_2}=(v_{I2}-v_{I1})\left\{\left(\frac{R_2}{R_1}\right)\left(\frac{1}{R_1+R_2}+\frac{1}{R_V}+\frac{1}{R_2}\right)+\frac{1}{R_1+R_2}+\frac{1}{R_V}\cdot\frac{R_2}{R_1}\right\}$$

$$v_0=(v_{I2}-v_{I1})\left(\frac{R_2}{R_1}\right)\left\{\frac{R_2}{R_1+R_2}+\frac{R_2}{R_V}+1+\frac{R_1}{R_1+R_2}+\frac{R_2}{R_V}\right\}$$

$$\underline{v_0=\frac{2R_2}{R_1}\left(1+\frac{R_2}{R_V}\right)(v_{I2}-v_{I1})}$$

9.46

$$v_{01}=\left(1+\frac{R_2}{R_1}\right)v_{I1}-\frac{R_2}{R_1}\cdot v_{I2}$$
$$=\left(1+\frac{50}{10}\right)(-25\sin\omega t)-\frac{50}{10}(25\sin\omega t)$$

$\underline{v_{01}=-275\sin\omega t\text{ mV}}$

$$v_{02}=\left(1+\frac{R_2}{R_1}\right)v_{I2}-\frac{R_2}{R_1}\cdot v_{I1}$$
$$=\left(1+\frac{50}{10}\right)(25\sin\omega t)-\frac{50}{10}(-25\sin\omega t)$$

$\underline{v_{02}=275\sin\omega t\text{ mV}}$

$$v_0=\frac{R_4}{R_3}\left(1+\frac{2R_2}{R_1}\right)(v_{I2}-v_{I1})$$
$$=\frac{30}{20}\left(1+2\left[\frac{50}{10}\right]\right)(25-[-25])\sin\omega t$$

$\underline{v_0=825\sin\omega t\text{ mV}}$

Current in R_1 and R_2:

$$i_1=\frac{v_{I1}-v_{I2}}{R_1}=\frac{(-25-25)\sin\omega t\text{ mV}}{10\text{ k}\Omega}$$

$\underline{|i_1|=5\sin\omega t\ \mu\text{A}}$

Current in bottom R_3 and R_4:

$$i_3=\frac{v_{02}}{R_3+R_4}=\frac{275\sin\omega t\text{ mV}}{(20+30)\text{ k}\Omega}$$

$\underline{|i_3|=5.5\sin\omega t\ \mu\text{A}}$

Current in top R_3 and R_4:

$$i_3'=\frac{v_{01}-\left(\frac{R_4}{R_3+R_4}\right)v_{02}}{R_3}=\frac{\left[-275-\left(\frac{30}{30+20}\right)(275)\right]\sin\omega t\text{ mV}}{20\text{ k}\Omega}$$

$\underline{|i_3'|=22\sin\omega t\ \mu\text{A}}$

9.47

$$v_0=\frac{30}{20}\left(1+\frac{2(50)}{R_1}\right)(25-(-25))\sin\omega t\text{ mV}$$

$$|v_0|=(1.5)(50)\left(1+\frac{100}{R_1}\right)\text{ mV}$$

For

$$|v_0|=0.1\text{ V}=(1.5)(0.050)\left(1+\frac{100}{R_1}\right)$$

$\Rightarrow \underline{R_1=300\text{ k}\Omega}$

For

$$|v_O| = 5\ \text{V} = (1.5)(0.050)\left(1 + \frac{100}{R_1}\right)$$

$\Rightarrow \underline{R_1 = 1.52\ \text{k}\Omega}$

So $\underline{R_{1f} = 1.52\ \text{k}\Omega} \Rightarrow \underline{\text{Potentiometer} \approx 300\ \text{k}\Omega}$

9.48

$$A_d = \frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_1}\right)$$

For $A_d(\max)$, $R_1 = R_1(\min) = R_{1f}$

$$200 = \frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_{1f}}\right)$$

For $A_d(\min)$, $R_1 = R_1(\max) \approx 50\ \text{k}\Omega$

$$0.5 = \frac{R_4}{R_3}\left(1 + \frac{2R_2}{50}\right)$$

Let $\underline{\dfrac{R_4}{R_3} = 0.4}$

Then $0.5 = 0.4\left(1 + \dfrac{2R_2}{50}\right) \Rightarrow \underline{R_2 = 6.25\ \text{k}\Omega}$

and

$$200 = (0.4)\left(1 + \frac{2(6.25)}{R_{1f}}\right) \Rightarrow \underline{R_{1f} = 25.05\ \Omega}$$

9.49

For a common-mode gain, $v_{cm} = v_{I1} = v_{I2}$

Then

$$v_{01} = \left(1 + \frac{R_2}{R_1}\right)v_{cm} - \frac{R_2}{R_1}v_{cm} = v_{cm}$$

$$v_{02} = \left(1 + \frac{R_2}{R_1}\right)v_{cm} - \frac{R_2}{R_1}v_{cm} = v_{cm}$$

From Problem 9.41, we can write

$$A_{cm} = \frac{\dfrac{R_4}{R_3} - \dfrac{R_4}{R_3'}}{\left(1 + \dfrac{R_4}{R_3}\right)}$$

$R_3 = R_4 = 20\ \text{k}\Omega$, $R_3' = 20\ \text{k}\Omega \pm 5\%$

$$A_{cm} = \frac{1 - \dfrac{20}{R_3'}}{(1+1)} = \frac{1}{2}\left(1 - \frac{20}{R_3'}\right)$$

For $R_3' = 20\ \text{k}\Omega - 5\% = 19\ \text{k}\Omega$

$$A_{cm} = \frac{1}{2}\left(1 - \frac{20}{19}\right) = -0.0263$$

For $R_3' = 20\ \text{k}\Omega + 5\% = 21\ \text{k}\Omega$

$$A_{cm} = \frac{1}{2}\left(1 - \frac{20}{21}\right) = 0.0238$$

So $\underline{|A_{cm}|_{\max} = 0.0263}$

9.50

a. $v_O = \dfrac{1}{R_1C_2} \cdot \displaystyle\int v_I(t')\,dt'$

$$\int 0.5 \sin \omega t\, dt = -\frac{0.5}{\omega}\cos \omega t$$

$$|v_O| = 0.5 = \frac{1}{R_1C_2} \cdot \frac{(0.5)}{\omega} = \frac{0.5}{2\pi R_1C_2 f}$$

$$f = \frac{1}{2\pi R_1C_2} = \frac{1}{2\pi(50 \times 10^3)(0.1 \times 10^{-6})}$$

$\Rightarrow \underline{f = 31.8\ \text{Hz}}$

Output signal lags input signal by 90°

b. i. $f = \dfrac{0.5}{2\pi(50 \times 10^3)(0.1 \times 10^{-6})} \Rightarrow \underline{f = 15.9\ \text{Hz}}$

ii. $f = \dfrac{0.5}{(0.1)(2\pi)(50 \times 10^3)(0.1 \times 10^{-6})}$

$\Rightarrow \underline{f = 159\ \text{Hz}}$

9.51

(a) $v_O = -\dfrac{1}{RC}\displaystyle\int v_I(t')dt'$

$v_O = -\dfrac{1}{0.2}(0.5)(2) \Rightarrow \underline{v_O = -5\,V}$

(b) $-15 = -\dfrac{1}{0.2}(0.5)t \Rightarrow \underline{t = 6\,s}$

9.52

a. $$\frac{v_O}{v_I} = \frac{-R_2 \parallel \dfrac{1}{j\omega C_2}}{R_1} = -\frac{R_2 \cdot \dfrac{1}{j\omega C_2}}{R_1\left(R_2 + \dfrac{1}{j\omega C_2}\right)}$$

$$\underline{\frac{v_O}{v_I} = -\frac{R_2}{R_1} \cdot \frac{1}{1 + j\omega R_2C_2}}$$

b. $\underline{\dfrac{v_O}{v_I} = -\dfrac{R_2}{R_1}}$

c. $\underline{f = \dfrac{1}{2\pi R_2C_2}}$

9.53

a. $$\frac{v_O}{v_I} = \frac{-R_2}{R_1 + \dfrac{1}{j\omega C_1}} = -\frac{R_2(j\omega C_1)}{1 + j\omega R_1C_1}$$

$$\underline{\frac{v_O}{v_I} = -\frac{R_2}{R_1} \cdot \frac{j\omega R_1C_1}{1 + j\omega R_1C_1}}$$

b. $\underline{\dfrac{v_O}{v_I} = -\dfrac{R_2}{R_1}}$

c. $\underline{f = \dfrac{1}{2\pi R_1C_1}}$

9.54

Assuming the Zener diode is in breakdown,

$v_O = -\frac{R_2}{R_1}\cdot V_Z = -\frac{1}{1}(6.8) \Rightarrow \quad v_O = -6.8\,V$

$i_2 = \frac{0 - v_O}{R_2} = \frac{0-(-6.8)}{1} \Rightarrow \quad i_2 = 6.8\,mA$

$i_Z = \frac{10 - V_Z}{R_S} - i_2 = \frac{10-6.8}{5.6} - 6.8 \Rightarrow \quad i_Z = -6.2\,mA!!!$

Circuit is not in breakdown. Now

$\frac{10-0}{R_S + R_1} = i_2 = \frac{10}{5.6+1} \Rightarrow \quad \underline{i_2 = 1.52\,mA}$

$v_O = -i_2 R_2 = -(1.52)(1) \Rightarrow \quad \underline{v_O = -1.52\,V}$

$\underline{i_Z = 0}$

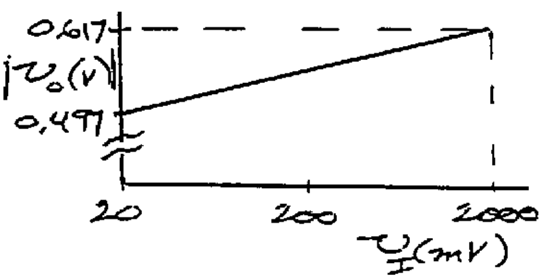
9.55

$v_O = -V_T \ln\left(\frac{v_I}{I_S R_1}\right) = -(0.026)\ln\left[\frac{v_I}{(10^{-14})(10^4)}\right] \Rightarrow$

$v_O = -0.026\ln\left(\frac{v_I}{10^{-10}}\right)$

For $v_I = 20\,mV$, $|v_O| = 0.497\,V$

For $v_I = 2\,V$, $|v_O| = 0.617\,V$



9.56

$v_0 = \left(\frac{333}{20}\right)(v_{01} - v_{02}) = 16.65(v_{01} - v_{02})$

$v_{01} = -v_{BE1} = -V_T \ln\left(\frac{i_{C1}}{I_S}\right)$

$v_{02} = -v_{BE2} = -V_T \ln\left(\frac{i_{C2}}{I_S}\right)$

$v_{01} - v_{02} = -V_T \ln\left(\frac{i_{C1}}{i_{C2}}\right) = V_T \ln\left(\frac{i_{C2}}{i_{C1}}\right)$

$i_{C2} = \frac{v_2}{R_2}, \quad i_{C1} = \frac{v_1}{R_1}$

So $v_{01} - v_{02} = V_T \ln\left(\frac{v_2}{R_2}\cdot\frac{R_1}{v_1}\right)$

Then

$v_0 = (16.65)(0.026)\ln\left(\frac{v_2}{v_1}\cdot\frac{R_1}{R_2}\right)$

$v_0 = 0.4329\ln\left(\frac{v_2}{v_1}\cdot\frac{R_1}{R_2}\right)$

$\ln(x) = \log_e(x) = [\log_{10}(x)]\cdot[\log_e(10)]$

$= 2.3026\log_{10}(x)$

Then

$\underline{v_0 \cong (1.0)\log_{10}\left(\frac{v_2}{v_1}\cdot\frac{R_1}{R_2}\right)}$

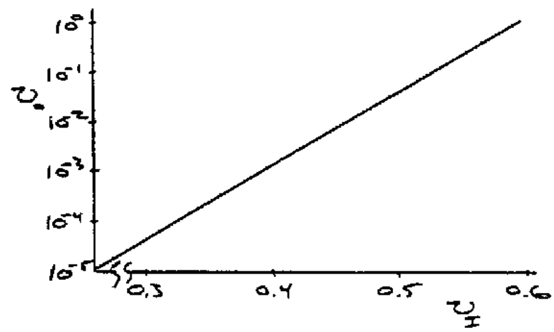
9.57

$v_O = -I_S R\left(e^{v_I/V_T}\right) = -(10^{-14})(10^4)e^{v_I/V_T}$

$|v_O| = (10^{-10})e^{v_I/0.026}$

For $v_I = 0.30\,V$, $|v_O| = 1.03\text{x}10^{-5}\,V$

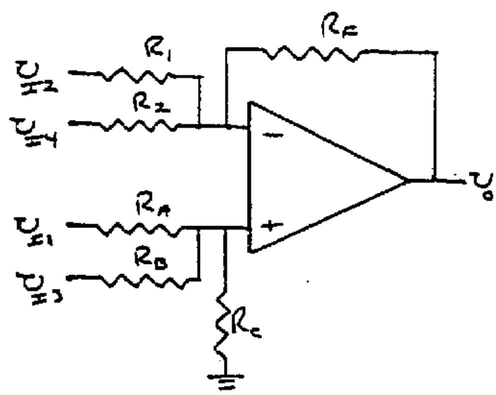
For $v_I = 0.60\,V$, $|v_O| = 1.05\,V$



9.58

$v_O = 2v_{I1} - 10v_{I2} + 3v_{I3} - v_{I4}$

From Figure 9. 37



From Equation (9.110), we can write

$$v_0 = -\frac{R_F}{R_1}\cdot v_{I2} - \frac{R_F}{R_2}\cdot v_{I4} + \left(1+\frac{R_F}{R_N}\right)\left[\frac{R_P}{R_A}\cdot v_{I1} + \frac{R_P}{R_B}\cdot v_{I3}\right]$$

where $R_N = R_1 \| R_2$, $R_P = R_A \| R_B \| R_C$

Then $\frac{R_F}{R_1} = 10; \quad \frac{R_F}{R_2} = 1$

Set $R_F = 500$ kΩ, then $R_1 = 50$ kΩ, $R_2 = 500$ kΩ

Now $R_N = R_1 \| R_2 = 50 \| 500 = 45.45$ kΩ

$$\left(1+\frac{R_F}{R_N}\right) = \left(1+\frac{500}{45.45}\right) = 12$$

Then $(12)\left(\frac{R_P}{R_A}\right) = 2;\ (12)\left(\frac{R_P}{R_B}\right) = 3$

Now $\frac{12(R_P/R_A)}{12(R_P/R_B)} = \frac{2}{3} = \frac{R_B}{R_A}$

R_A is the largest resistor

Set $\underline{R_A = 500\text{ k}\Omega}$, then $\underline{R_B = 333.3\text{ k}\Omega}$

Then $\frac{12R_P}{R_A} = 2 = \frac{12R_P}{500} = 2 \Rightarrow R_P = 83.33$ kΩ

$R_P = R_A \| R_B \| R_C$ and $R_A \| R_B = 500 \| 333.3$

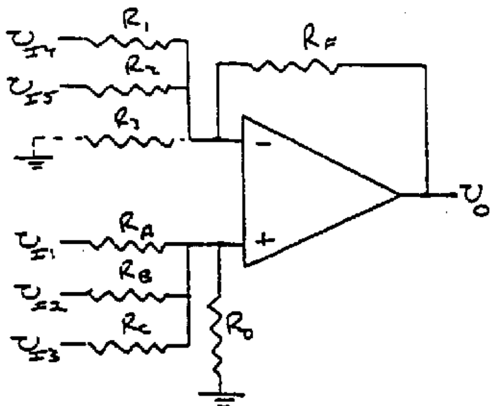
$= 200$ kΩ

Then $200 \| R_C = 83.33$ so $\underline{R_C = 142.8\text{ k}\Omega}$

9.59

$v_O = 6v_{I1} + 3v_{I2} + 5v_{I3} - v_{I4} - 2v_{I5}$

From Figure 9.37



$$v_O = -\frac{R_F}{R_1}\cdot v_{I4} - \frac{R_F}{R_2}\cdot v_{I5} + \left(1+\frac{R_F}{R_N}\right)\left[\frac{R_P}{R_A}\cdot v_{I1} + \frac{R_P}{R_B}\cdot v_{I2} + \frac{R_P}{R_C}\cdot v_{I3}\right]$$

where

$R_N = R_1 \| R_2$, $R_P = R_A \| R_B \| R_C \| R_D$

Then $\frac{R_F}{R_1} = 1;\ \frac{R_F}{R_2} = 2$

Let $R_F = 250$ kΩ, then $R_1 = 250$ kΩ, $R_2 = 125$ kΩ

Then $R_N = R_1 \| R_2 = 250 \| 125 = 83.33$ kΩ

$$\left(1+\frac{R_F}{R_N}\right) = \left(1+\frac{250}{83.33}\right) = 4$$

Now $4\left(\frac{R_P}{R_A}\right) = 6;\ 4\left(\frac{R_P}{R_B}\right) = 3;\ 4\left(\frac{R_P}{R_C}\right) = 5$

$$\frac{4(R_P/R_A)}{4(R_P/R_B)} = \frac{6}{3} = 2 = \frac{R_B}{R_A}$$

$$\frac{4(R_P/R_C)}{4(R_P/R_B)} = \frac{5}{3} = 1.667 = \frac{R_B}{R_C}$$

Set $R_B = 250$ kΩ, then

$R_A = 125$ kΩ, $R_C = 150$ kΩ

Then $\frac{4R_P}{R_A} = 6 = \frac{4R_P}{125} = 6 \Rightarrow R_P = 187.5$ kΩ

$\Rightarrow$ won't work since

$R_P = R_A \| R_B \| R_C \| R_D > R_A$ and R_C

Add a resistor R_3 in parallel with R_1 and R_2 to decrease R_N (but with zero input to R_3).

Set $R_D = \infty \Rightarrow R_P = R_A \| R_B \| R_C = 53.57$ kΩ

Then

$$\left(1+\frac{R_F}{R_N}\right)\cdot\frac{R_P}{R_A} = 6 = \left(1+\frac{R_F}{R_N}\right)\cdot\left(\frac{53.57}{125}\right)$$

$$\Rightarrow \frac{R_F}{R_N} = 13.0$$

So

$R_N = \frac{250}{13} = 19.23 = R_1 \| R_2 \| R_3 = 83.33 \| R_3$

So $\underline{R_3 = 25\text{ k}\Omega}$

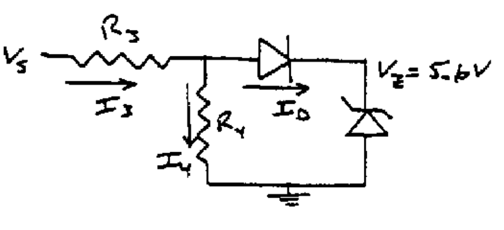
9.60

$$\frac{V_0}{V_Z} = \left(1+\frac{R_2}{R_1}\right)$$

$$\frac{9}{5.6} = 1 + \frac{R_2}{R_1} \Rightarrow \underline{\frac{R_2}{R_1} = 0.607}$$

$$I_F = \frac{V_0 - V_Z}{R_F}$$

Set $I_F = 0.8\text{ mA} = \frac{9-5.6}{R_F} \Rightarrow \underline{R_F = 4.25\text{ k}\Omega}$



$V_Z' = 5.6 + 0.7 = 6.3$ V

$I_4 = \frac{V_Z'}{R_4} = \frac{6.3}{R_4},\ I_3 = \frac{V_S - V_Z'}{R_3}$

If $V_S = 10$ V, $I_3 = \frac{10-6.3}{R_3} = \frac{3.7}{R_3}$

Want $I_{D1} = 0.1$ mA; if we set $I_4 = 0.1\text{ mA} = \frac{6.3}{R_4}$

$\Rightarrow \underline{R_4 = 63\text{ k}\Omega}$

Then $I_3 = 0.2\text{ mA} = \frac{3.7}{R_3} \Rightarrow \underline{R_3 = 18.5\text{ k}\Omega}$

9.61

For $I_Z = 1$ mA

$$I_Z = \frac{V_0 - V_Z}{R_1} = \frac{10 - 5.6}{R_1} = 1 \text{ mA} \Rightarrow \underline{R_1 = 4.4\ \text{k}\Omega}$$

$$V_Z = \left(\frac{R_3}{R_2 + R_3}\right) \cdot V_0 \Rightarrow 5.6 = \frac{R_3}{R_2 + R_3} \cdot 10$$

$$= \frac{10}{\left(1 + \frac{R_2}{R_3}\right)}$$

$$1 + \frac{R_2}{R_3} = \frac{10}{5.6} \Rightarrow \underline{\frac{R_2}{R_3} = 0.786}$$

Let $\dfrac{V_0}{R_2 + R_3} = 1 \text{ mA} = \dfrac{10}{R_2 + R_3} = 1 \text{ mA}$

$\Rightarrow R_2 + R_3 = 10\ \text{k}\Omega$

$R_2 = 0.786 R_3 \Rightarrow 0.786 R_3 + R_3 = 10$

$\Rightarrow \underline{R_3 = 5.6\ \text{k}\Omega}$, $\underline{R_2 = 4.4\ \text{k}\Omega}$

Let $\dfrac{V_{in} - V_0}{R_4} = 2 \text{ mA} = \dfrac{12 - 10}{R_4} \Rightarrow \underline{R_4 = 1\ \text{k}\Omega}$

In this case, the op-amp must supply the load current.

9.62

For $v_{01} - v_{02} = 0$ at $T = 250°$ K, set

$R_1 = R_2 = R_2 = R_T$ @ $250°$ K $= 12$ kΩ

Assuming v_{01} and v_{02} look into an open circuit.

$$v_{02} = \left(\frac{R_T}{R_T + R_2}\right) V^+ \text{ and}$$

$$v_{01} = \left(\frac{R_3}{R_1 + R_3}\right) \cdot V^+ = \frac{V^+}{2}$$

As temperature increases, R_T decreases. Let $R_T = 12(1 - \delta)$ where δ is positive.

$R_T = 10$ kΩ @ $300° \Rightarrow \underline{\delta = 0.1667}$

$$v_{02} = \left(\frac{12(1-\delta)}{12(1-\delta) + 12}\right) V^+$$

Consider

$$v_{02} - v_{01} = \left(\frac{12(1-\delta)}{12(1-\delta)+12} - \frac{1}{2}\right)(10)$$

$$= \left(\frac{12(1-\delta) - 6[(1-\delta)+1]}{12[(1-\delta)+1]}\right)(10)$$

$$= \left(\frac{6(1-\delta) - 6}{12[(1-\delta)+1]}\right)(10) = \frac{60\delta}{12[(1-\delta)+1]}$$

Now consider $v_{01} - v_{02} = \dfrac{5\delta}{2-\delta} \approx \dfrac{5}{2} \cdot \delta$

Connect v_{01} to the v_{I2} terminal of the instrumentation amplifier and v_{02} to the v_{I1} terminal.

Now $v_0 = \dfrac{R_4}{R_3}\left(1 + \dfrac{2R_2}{R_1}\right)\left(\dfrac{5}{2}\right) \cdot \delta$

For $\delta = 0.1667$, $v_0 = 5$

$$\frac{5}{0.1667} = 30 = \frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_1}\right)\left(\frac{5}{2}\right) \text{ or}$$

$$\frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_1}\right) = 12$$

Set $\underline{\dfrac{R_4}{R_3} = 4}$ Then $\underline{\dfrac{2R_2}{R_1} = 3}$ If $R_2 = 30$ kΩ

$R_1 = 20$ kΩ

Resistor R_1 can be a fixed resistor in series with a potentiometer for more precise control.

9.63

Using the bridge circuit shown in Figure 9.44

$$v_{01} = \left[\frac{1}{2} - \frac{R}{R + R(1+\delta)}\right] V^+ = \left[\frac{1}{2} - \frac{1}{2+\delta}\right](10)$$

$$= \left(\frac{2 + \delta - 2}{2(2+\delta)}\right)(10)$$

$$\Rightarrow v_{01} \cong \frac{10\delta}{4} = 2.5\delta$$

Connect v_{01} to an instrumentation amplifier.

$$v_0 = \frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_1}\right)(2.5\delta)$$

When $\delta = 0.02$, $v_0 = 5$

$$\frac{5}{(2.5)(0.02)} = 100 = \frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_1}\right)$$

Set $\underline{\dfrac{R_4}{R_3} = 10}$ Then $\underline{\dfrac{2R_2}{R_1} = 9}$