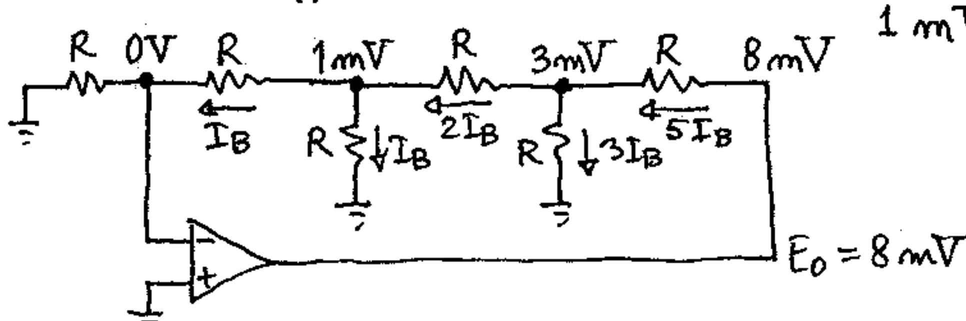
5.1 By Eq. (5.7), doubling I_A will double g_{m1}, thus increasing the open-loop gain a. This will also double the input bias currents I_P & I_N, and halve the input resistance r_d and the first-stage output resistance r_{o1}. The reduction in r_{o1} will affect loading of the first stage by the second stage, thus affecting a. Furthermore, the first-stage output-current saturation levels will also double; in Ch. 6 we'll see that this doubles the slew rate.

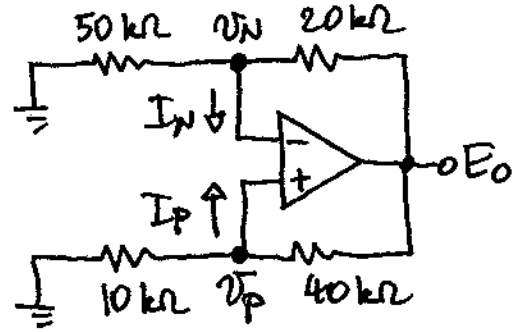
5.2 $R_2 = 10R_1$. With $R_p = R_1 /\!/ R_2 = 0.91R_1$ in place, $E_{O(max)} = (1+R_2/R_1)(R_1/\!/R_2)I_{OS(max)} = 11 \times 0.91R_1 \times 200\times10^{-9} = 10\times10^{-3}$. This yields $R_1 = 5\,k\Omega$. Use $R_1 = 4.99\,k\Omega$, $R_2 = 49.9\,k\Omega$, and $R_p = 45.3\,k\Omega$, all 1%.

5.3 (a) Suppress v_I and find E_O. $RI_B = 10^5\times10^{-8} = 1\,mV$.



(b) We readily find the noise gain to be $1/\beta = 13$ V/V. We thus need $R_pI_B = (8\,mV)/13$ $\Rightarrow R_p = 61.5\,k\Omega$ (Use $62\,k\Omega$).

5.4

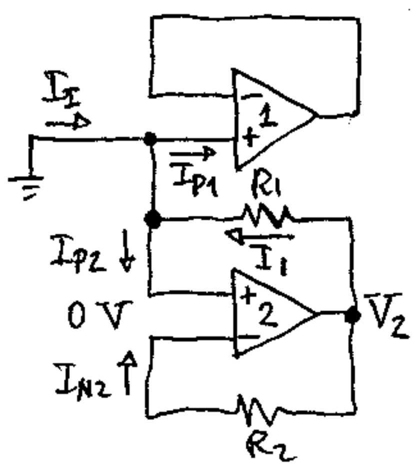


$v_N = v_P$; $\dfrac{E_0 - v_N}{20\,k\Omega} = I_N + \dfrac{v_N}{50\,k\Omega}$; $\dfrac{E_0 - v_P}{40\,k\Omega} = I_P + \dfrac{v_P}{10\,k\Omega}$

$$\Rightarrow E_0 = \frac{250\times10^3 I_N - 140\times10^3 I_P}{9}$$

With $I_P = 105$ nA and $I_N = 95$ nA we get $E_0 = 1.00\overline{5}$ mV; with $I_P = 95$ nA and $I_N = 105$ nA we get $E_0 = 1.43\overline{8}$ mV. We thus expect E_0 within the range of $1.00\overline{5}$ mV to $1.43\overline{8}$ mV. With $I_{OS} = 0$, $E_0 = 1.\overline{2}$ mV.

5.5



$$\begin{aligned} I_I &= I_{P1} + I_{P2} - I_1 \\ &= I_{P1} + I_{P2} - V_2/R_1 \\ &= I_{P1} + I_{P2} - R_2 I_{N2}/R_1. \end{aligned}$$

(a) For matched op amps,

$$\begin{aligned} I_I &= 2I_P - (R_2/R_1) I_N \\ &= (2 - R_2/R_1) I_B \end{aligned}$$

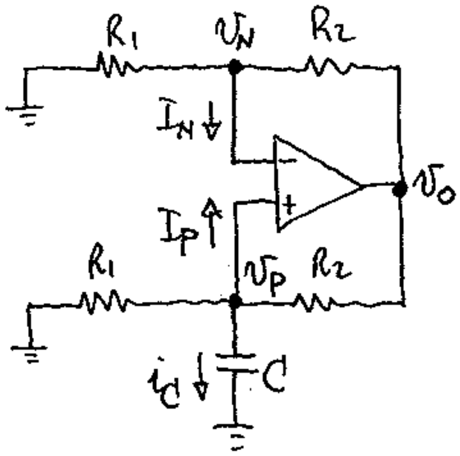
$$\Rightarrow R_2 = 2R_1.$$

(b) Assume $I_{P1} = I_B$, $I_{P2} = I_{N2} = I_B(1 \pm 0.01)$.

Then $I_I = I_B + I_B(1\pm0.01) - 2I_B(1\pm0.01) = \mp 0.01 I_B$, indicating an input current on the order of the mismatch itself.

(5.3)

5.6 (a)



$$\frac{v_O - v_N}{R_2} = I_N + \frac{v_N}{R_1}$$

$$\frac{v_O - v_P}{R_2} = I_P + i_C + \frac{v_P}{R_1}$$

$v_N = v_P$. Combining,

$i_C = I_N - I_P = -I_{OS}$

regardless of the resistance values. Consequently,

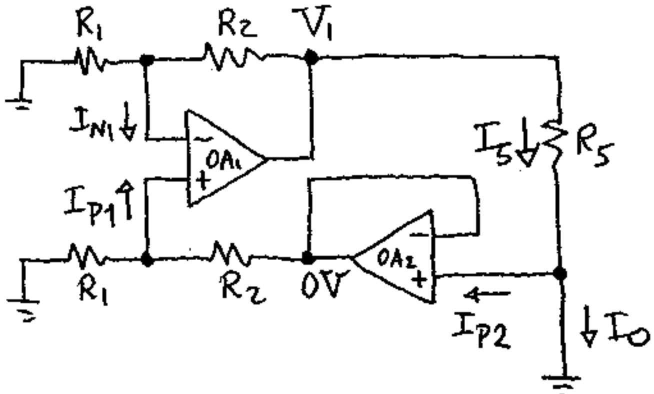
$$v_O(t) = \left(1 + \frac{R_2}{R_1}\right) v_P = -\left(1 + \frac{R_2}{R_1}\right)\frac{I_{OS}}{C} t + v_O(0).$$

(b) $v_O(t) = \mp 2 \times \frac{10^{-9}}{10^{-9}} t + 1 = \mp 2t + 1$ V.

Depending on whether $I_{OS} > 0$ or $I_{OS} < 0$, v_O will

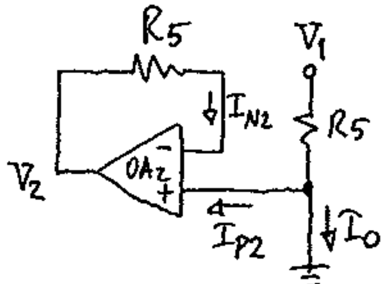
(5.4)

5.8



The presence of the bias and offset currents does not affect the resistances, so we expect $i_O = A(v_2 - v_1) - v_L/R_o + I_O$, $A = R_2/R_1R_5$, $R_o = \infty$.
To find the error I_O, consider the case of a short-circuit load for simplicity. Then,
$V_1 = R_2 I_{N1} + (1 + R_2/R_1)[-(R_1 // R_2) I_{P1}] = -R_2 I_{OS1}$.
$I_O = I_5 - I_{P2} = V_1/R_5 - I_{P2} = -(R_2/R_5)I_{OS1} - I_{P2}$.
Writing $I_O = A \times [-(R_1 I_{OS1} + R_1 I_{P2} R_5/R_2)]$ indicates the presence of an equivalent input voltage error $E_I = -R_1[I_{OS1} + (R_5/R_2) I_{B2}]$.

To make the second term proportional to I_{OS2} rather than I_{B2}, install a dummy feedback resistance R_5, as shown.

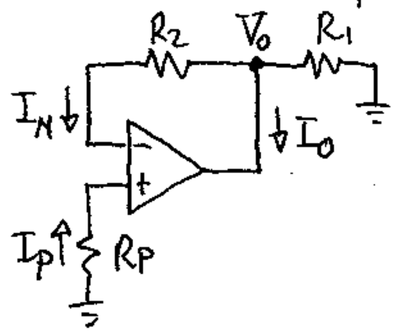


Then, $V_1 = -R_2 I_{OS1} + R_5 I_{N2}$

$$I_O = \frac{-R_2 I_{OS1} + R_5 I_{N2}}{R_5} - I_{P2} = -\frac{R_2}{R_5} I_{OS1} - I_{OS2}$$

$E_I = -R_1[I_{OS1} + (R_2/R_5) I_{OS2}]$.

5.9 Since I_B and I_{OS} do not affect the resistances, we expect $i_O = Ai_I - v_L/R_o + I_O$, $A = 1+R_2/R_1$, $R_o = \infty$. To find I_O, consider a short-circuited load for simplicity.

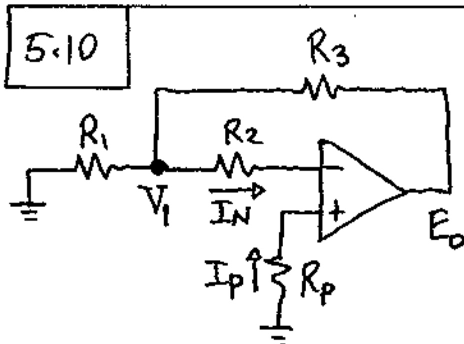


$$\frac{0-V_o}{R_1} = I_N + I_O \Rightarrow I_O = -\left(\frac{V_o}{R_1} + I_N\right)$$

$$V_o = V_N + R_2 I_N = V_P + R_2 I_N = -R_P I_P + R_2 I_N.$$

Eliminating V_o gives $I_O = \frac{R_P}{R_1} I_P - \left(1 + \frac{R_2}{R_1}\right) I_N$. With $R_P = 0$ we get $I_O \cong -(1+R_2/R_1) I_B$, indicating an equivalent input error $I_I = -I_B$. Installing a dummy resistance $R_P = R_1 + R_2$ gives $I_O = (1+R_2/R_1) I_{OS}$, for an equivalent input error $I_I = I_{OS}$.

5.10



At dc caps = open ckts.

$$\frac{E_O - V_1}{R_3} + \frac{0 - V_1}{R_1} = I_N \Rightarrow$$

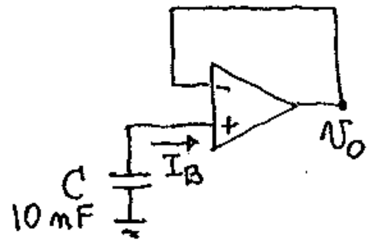
$$E_O = \left(1 + \frac{R_3}{R_1}\right) V_1 + R_3 I_N$$

$$V_1 = R_2 I_N + V_N = R_2 I_N - R_P I_P$$

Eliminating V_1, $E_O = \left(1 + \frac{R_3}{R_1}\right)\left[(R_2 + R_1 \| R_3) I_N - R_P I_P\right]$. Without R_P, $E_o \cong (1 + R_3/R_1)(R_2 + R_1 \| R_3) I_B = 2 \times 150 \times 10^3 \times 50 \times 10^{-9} = 15$ mV. Installing a dummy resistance $R_P = R_2 + R_1 \| R_3 = 150$ kΩ gives $E_o = -\left(1 + \frac{R_3}{R_1}\right)(R_2 + R_1 \| R_3) I_{OS} = -300 \times 10^3 I_{OS}$.

(5.6)

5.11

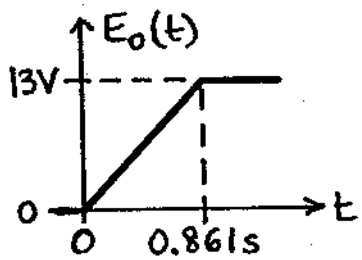


(a) $I_B = C|dv_O/dt| = 10^{-8} \times 10^{-3}/1 = 10$ pA $\Rightarrow$ FET-input op amp.

(b) To increase I_B by a factor of 100 we need $100 = 2^{\Delta T/10} \Rightarrow \Delta T = 66.4°C$.

5.12

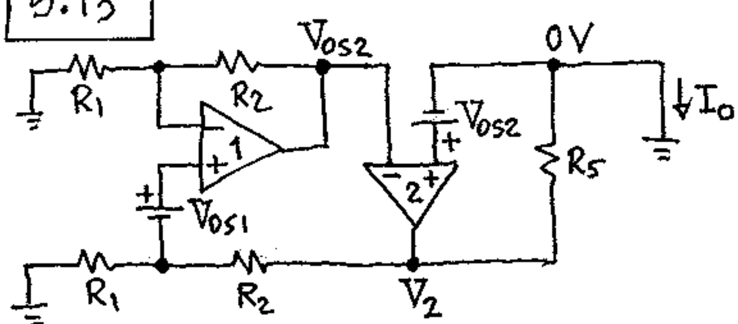
$V_{OS} = E_O/(1+R_2/R_1) = 0.5/(1+33/0.1) = 1.51$ mV.



$E_O(t) = \frac{1}{RC} V_{OS}\, t = \frac{1}{10^5 \times 10^{-9}} \times 1.51 \times 10^{-3} t = 15.1t.$

The output saturates at $t = 13/15.1 = 0.861$ s.

5.13

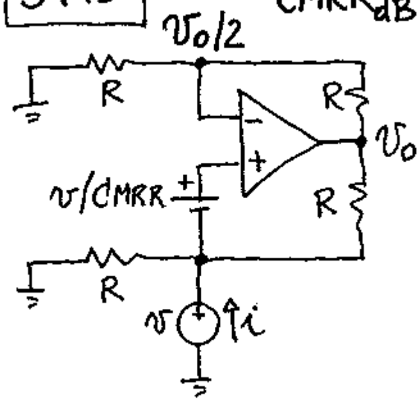


The presence of V_{OS1} and V_{OS2} does not affect the resistances of the circuit, so we expect $i_O = Av_I - v_L/R_o + I_O$, $A = R_2/R_1R_5$, $R_o = \infty$. To find I_O, consider a short-circuit load for simplicity. $I_O = V_2/R_5$; moreover, $V_{N1} = [R_1/(R_1+R_2)]V_{OS2} = V_{P1} = [R_1/(R_1+R_2)]V_2 + V_{OS1}$. This gives $I_O = (\frac{1}{R_5})[V_{OS2} - (1+\frac{R_2}{R_1})V_{OS1}]$, indicating an equivalent input error $I_I = \frac{R_1R_5}{R_2} I_O = \frac{R_1}{R_2}V_{OS2} - (1+\frac{R_1}{R_2})V_{OS1}$.

5.14 (a) $E_O \cong (1+10^5/10)V_{OS} = 10^4 V_{OS}$; $|E_O(0°C)| \cong 10^4(5\times10^{-6}\times 25) = 1.25$ V; $|E_O(25°C)| \cong 10^4(5\times10^{-6})\times(70-25) = 2.25$ V; opposite polarities.

(b) $v_O(t) = \pm(V_{OS}/RC)t + v_O(0) = \pm[5\times10^{-6}\times 25/(10^5\times10^{-9})]t + v_O(0) = \pm 1.25t + v_O(0)$; $v_O(t) = \mp 2.25t + v_O(0)$.

5.15 $CMRR_{dB} = 100\,\text{dB} \Rightarrow 1/CMRR = 10^{-5}$ V/V.



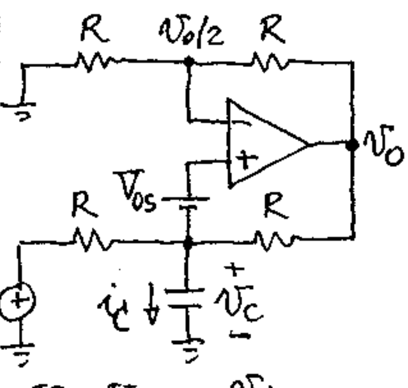
$$\frac{v_O}{2} = v + \frac{v}{CMRR} = \frac{1+CMRR}{CMRR}v$$

$$i = \frac{v}{R} + \frac{v-v_O}{R} = -\frac{2v/R}{CMRR}$$

$$R_o = v/i = -\frac{R}{2}CMRR = -500\ \text{M}\Omega.$$

The output resistance is negative (or positive), depending on whether V_{OS} increases (or decreases) with v_{CM}.

5.16

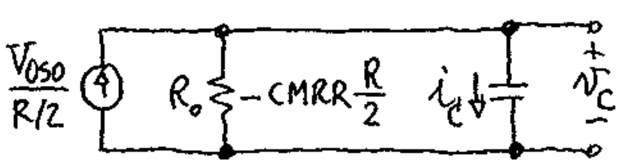


$$v_O = \left(1+\frac{R}{R}\right)(v_C + V_{OS}) = 2(v_C + V_{OS})$$

$$i_C = \frac{v_I - v_C}{R} + \frac{v_O - v_C}{R} = v_I/R + 2V_{OS}/R.$$

Letting $V_{OS} = V_{OS0} + \frac{v_C}{CMRR}$ gives $i_C = \frac{v_I}{R} + \frac{2V_{OS0}}{R} - \frac{v_C}{CMRR\times R/2}$.

For $v_I = 0$, C sees the Norton equivalent:



$V_{OS0}/(R/2) = 2$ mA

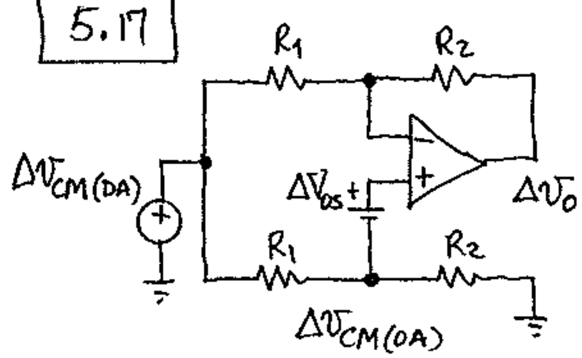
$|R_o| = 5$ GΩ.

Assuming C is initially discharged, we have two cases:

1. V_{OS} decreases with v_{CM}; then $R_o = +5\ \mathrm{G\Omega}$, $\tau = R_oC = +5\ \mathrm{s}$, $v_C(\infty) = 10\ \mathrm{V}$; $v_C(t) = 10(1-e^{-t/5})\ \mathrm{V}$; $v_O = 2(v_C + V_{OS})$. These expressions hold only as long as the op amp is within the linear region.

2. V_{OS} increases with v_{CM}; then $R_o = -5\ \mathrm{G\Omega}$, $\tau = -5\ \mathrm{s}$, $v_C(t) = 10(e^{+t/5}-1)\ \mathrm{V}$, $v_O = 2(v_C + V_{OS})$.

5.17



$$A_{dm} = R_2/R_1$$

$$\Delta v_{CM(OA)} = \frac{R_2}{R_1+R_2}\Delta v_{CM(DA)}$$

$$\Delta V_{OS} = \frac{\Delta v_{CM(OA)}}{CMRR_{OA}}$$

$$\Delta v_O = \left(1+\frac{R_2}{R_1}\right)\Delta V_{OS} = \left(1+\frac{R_2}{R_1}\right)\frac{R_2}{R_1+R_2}\,\frac{\Delta v_{CM(DA)}}{CMRR_{OA}}$$

$$A_{cm} = \frac{\Delta v_O}{\Delta v_{CM(DA)}} = \frac{R_2}{R_1}\,\frac{1}{CMRR_{OA}} = A_{dm}\frac{1}{CMRR_{OA}}$$

$$CMRR_{DA} \triangleq A_{dm}/A_{cm} = CMRR_{OA}\ .$$

5.18 (a) $CMRR_{DA(min)} = CMRR_{OA(min)} = 70\ \mathrm{dB}$.

(b) Applying $\Delta v_{CM(DA)} = 1\ \mathrm{V}$ yields

$$|\Delta v_{O1}|_{max} = A_{dm}\frac{1\ \mathrm{V}}{CMRR_{OA(min)}} = \frac{100\times 1}{10^{70/20}} = 31.6\ \mathrm{mV}$$

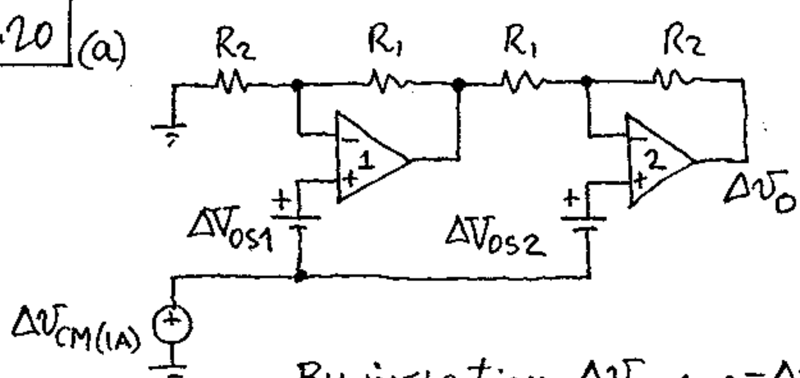
due to the op amp finite CMRR. Moreover, by Eq. (2.24c), bridge imbalance yields

$$|\Delta v_{O2}|_{max} = \frac{R_2}{R_1+R_2}|\varepsilon|_{max}\times(1\ \mathrm{V}) = \frac{100}{1+100}\,0.04\times 1 =$$

39.6 mV. The worst-case scenario occurs when the output terms are maximized and combine additively to give $|\Delta v_O|_{max} = 31.6 + 39.6 = 71.2$ mV. Then, $|A_{cm}|_{max} = |\Delta v_O|_{max} / \Delta v_{CM(DA)} = 0.0712/1 = 0.0712$ V/V, and $CMRR_{net(max)} = 20 \log_{10} \frac{100}{0.0712} = 63$ dB. In the present circuit, a 1% resistance tolerance can degrade the CMRR due to the basic op amp by as much as 7 dB.

5.19 Assuming perfectly matched resistances, we have, by Prob. 5.17, $CMRR_{DA} = CMRR_{741} = 90$ dB at 1 Hz, 76 dB at 1 kHz, and 66 dB at 10 kHz. The corresponding peak variations of V_{OS} are, respectively, $(1\text{ V})/10^{90/20} = 31.6\ \mu V$, $158\ \mu V$, and $501\ \mu V$. Multiplying by the noise gain, which is 101 V/V, gives, respectively, $v_O \cong 3.2 \times \sin 2\pi t$ mV, $16 \sin 2\pi 10^3 t$ mV, $50.6 \sin 2\pi 10^4 t$ mV.

5.20 (a)



By inspection, $\Delta v_{CM(OA)} = \Delta v_{CM(IA)}$;

$\Delta V_{OS1} \cong \Delta V_{OS2} = \frac{\Delta v_{CM(IA)}}{CMRR_{OA}}$; $\Delta v_O = A_{dm}(\Delta V_{OS2} - \Delta V_{OS1})$.

The worst-case scenario occurs when the two terms combine additively to give

(5.10)

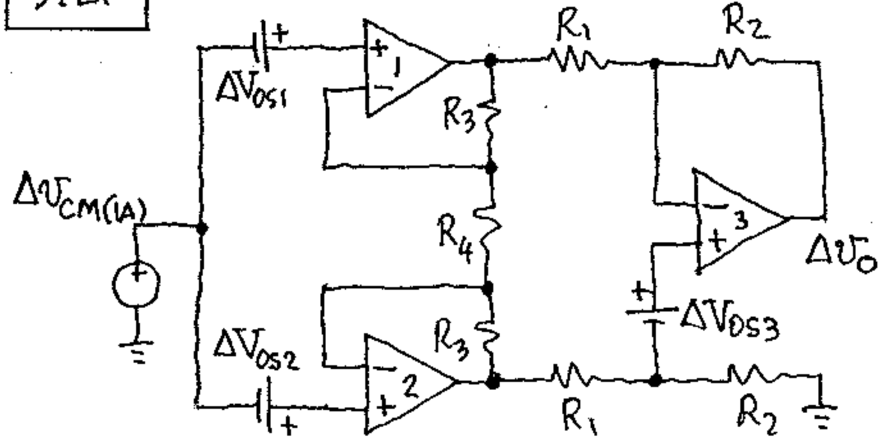
$$|\Delta v_O|_{max} = A_{dm} \times 2 |\Delta V_{OS}|_{max} = 2A_{dm}\, \Delta v_{CM(IA)} / CMRR_{OA(min)} \Rightarrow$$

$$A_{cm(max)} = |\Delta v_O|_{max} / \Delta v_{CM(IA)} = 2A_{dm} / CMRR_{OA(min)} \Rightarrow$$

$$CMRR_{IA(min)} \triangleq \frac{A_{dm}}{A_{cm(max)}} = \frac{1}{2} CMRR_{OA(min)} .$$

(b) $\Delta v_{O(max)} = 100 \times 2 \times \dfrac{10\ \text{V}}{10^{114/20}} \cong 4\ \text{mV}.$

5.21



$$CMRR_{IA} = \left|\frac{A_{dm}}{A_{cm}}\right|; \quad A_{dm} = A_I \times A_{II} = \left(1 + \frac{2R_3}{R_4}\right) \times \left(\frac{R_2}{R_1}\right).$$

By inspection, $\Delta v_{CM(OA_1)} = \Delta v_{CM(OA_2)} = \Delta v_{CM(II)} = \Delta v_{CM(IA)}$.

By Problem 5.17, $CMRR_{II} = CMRR_{OA_3}$, so the contribution of OA_3 to the output is

$$\Delta v_{O(II)} = A_{cm(II)}\, \Delta v_{CM(II)} = A_{II}\, \Delta v_{CM(IA)} / CMRR_{OA_3} .$$

The first-stage contribution to the output is

$$\Delta v_{O(I)} = A_I A_{II} (\Delta V_{OS2} - \Delta V_{OS1})$$

$$= A_I A_{II} \left(\Delta v_{CM(IA)}/CMRR_{OA_1} - \Delta v_{CM(IA)}/CMRR_{OA_2}\right).$$

The worst-case scenario occurs when the contributions are maximized and combine additively:

$$|\Delta v_O|_{max} = |\Delta v_{O(I)}|_{max} + |\Delta v_{O(II)}|_{max}$$

$$= \Delta v_{CM(IA)} \left[A_I A_{II} \left(\frac{1}{CMRR_{OA_1(min)}} + \frac{1}{CMRR_{OA_2(min)}} \right) \right.$$

$$+A_{II}\frac{1}{CMRR_{OA_3(min)}}\Bigg] = A_{dm}\,\Delta v_{CM(IA)}\Bigg[\frac{1}{CMRR_{OA_1(min)}} + \frac{1}{CMRR_{OA_2(min)}} + \frac{1}{A_I\,CMRR_{OA_3(min)}}\Bigg] \Rightarrow$$

$$A_{cm(max)} = |\Delta v_O|_{max}/\Delta v_{CM(IA)} = A_{dm}\times[\cdots].$$

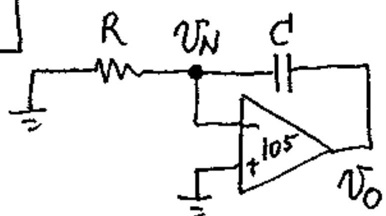
$$\frac{1}{CMRR_{IA(min)}} = \frac{A_{cm(max)}}{A_{dm}} = \frac{1}{CMRR_{OA_1(min)}} + \frac{1}{CMRR_{OA_2(min)}} + \frac{1}{(1+2R_3/R_4)\,CMRR_{OA_3(min)}}.$$

For matched op amps this simplifies to

$$CMRR_{IA(min)} = CMRR_{OA(min)}\Big/\left[2+\frac{1}{1+2R_3/R_4}\right].$$

For a sufficiently high first-stage gain, the second-stage CMRR limitation can be ignored compared to the first stage's.

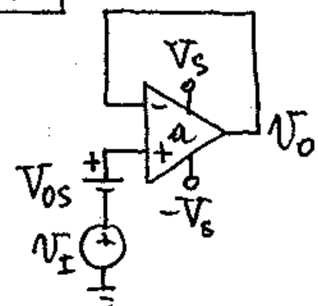
5.22



$v_O(0) = 10$ V;
$a = 10^5$ V/V;
$v_N = -v_O/a$.

$(0-v_N)/R = C\,d(v_N - v_O)/dt$. Eliminating v_N and collecting gives $v_O(t) = -\tau\, dv_O(t)/dt$, where $\tau = (1+a)RC \cong 10^5\times 10^5\times 10^{-8} = 100$ s. The solution is $v_O(t) = 10\,e^{-t/(100\text{ s})}$ V, which represents an exponential decay with a 100-s time constant.

5.23



$v_O = a(v_I + V_{OS} - v_O) \Rightarrow$

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

$v_O - v_I \cong V_{OS} - v_I/a$.

Ideally, $v_O = v_I$; max departure of v_O from v_I is thus $\Delta v_{O(max)} = -[|V_{OS}|_{max} + |v_I|/a]$.

(a) $v_I = 0 \Rightarrow \Delta v_{O(max)} = -V_{OS0} = -3$ mV.

(b) $v_I = 10$ V $\Rightarrow \Delta v_{O(max)} = -(V_{OS0} + 10/10^4 + 10/10^{74/20}) = -(3+1+2)$ mV $= -5$ mV.

(c) $\Delta V_S = 3$V $\Rightarrow \Delta V_{OS} = 3/10^{74/20} = 0.6$ mV.

Thus, in (a) we have $\Delta v_{O(max)} = -3.6$ mV, and in (b) we have $\Delta v_{O(max)} = -5.6$ mV.

5.24 (a) By Eq. (5.32), a 10% mismatch between A_{E1} and A_{E2} yields a 10% mismatch between I_{S1} and I_{S2}. By Eq. (5.30), this gives $\Delta V_{OS} = V_T \ln 1.01 \cong 0.01 \times 26$ mV $=$ 0.26 mV.

(b) A well known rule of thumb states that the voltage drop across a pn junction varies by about 2 mV/°C. We thus anticipate that a 1°C gradient across Q_1 and Q_2 will yield $\Delta V_{OS} \cong 2$ mV.

5.25 Use $R_p = R = 100\ k\Omega$. Then, $E_{I(max)} = 6\ mV + 100\times10^3 \times 200\times10^{-9} = 26\ mV$. Impose $-30\ mV \le V_X \le 30\ mV$ for safety. Use $R_C = 100\ k\Omega$, $R_B = 100\ k\Omega$, $R_A = 200\ \Omega$.

5.26 $R_1 = R_2 = 0 \Rightarrow E_o = (1 + 10^4/10)V_{OS} = 1000 V_{OS} \Rightarrow V_{OS} = 0.48\ mV$. $R_1 = 1\ M\Omega$ and $R_2 = 0 \Rightarrow E_o = 1000\,(V_{OS} + R_1 I_N)$. Thus, $I_N = (0.230/1000 - 0.48\times10^{-3})/10^6 = -0.25\ nA$, indicating that I_N flows out of the op amp. $R_1 = 0$ and $R_2 = 1M\Omega \Rightarrow E_o = 1000 \times (V_{OS} - R_2 I_P) \Rightarrow I_P = -(0.780/1000 - 0.48\times10^{-3})/10^6 = -0.3\ nA$, flowing out of the op amp. Thus, $I_B = -(0.25 + 0.3)/2 = 0.275\ nA$, out of op amp; $I_{OS} = -50\ pA$.

5.27 At dc, the output v_O of DUT is such that $(v_O - 0)/10^5 = (0 - v_1)/10^5$, or $v_O = -v_1$. The inputs are, respectively, $v_N = -R_n I_N$ and $v_P = [100/(100 + 49{,}900)]v_2 - R_p I_p$, where R_n and R_p are the dc resistances presented at DUT's inputs. Imposing $v_N = v_P + V_{OS0} - v_O/a$ gives

$$v_2 = 500\left[R_p I_p - R_n I_N - V_{OS0} - \frac{v_1}{a}\right] \quad \text{Eq.(1)}$$

(a) With $SW_1 = SW_2 =$ closed we have $R_p =$

5.14

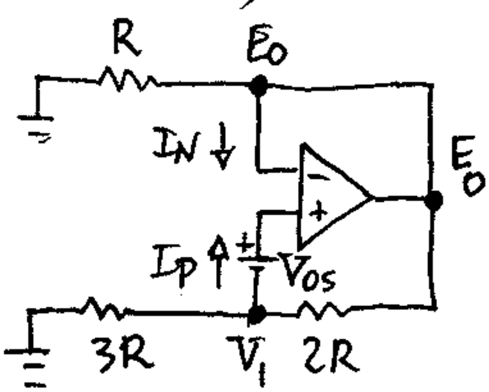
$R_n = 100\,\Omega \cong 0\,\Omega$. With $v_1 = 0$, Eq. (1) reduces to $v_2 = 500(-V_{OSO})$; imposing $-0.75 = 500(-V_{OSO})$ gives $V_{OSO} = 1.5\,\text{mV}$.

(b) We now have $R_p = 10^5\,\Omega$, and Eq. (1) becomes $v_2 = 500(R_pI_p - V_{OSO})$, or $0.30 = 500(10^5 I_p - 1.5\text{m})$, which gives $I_p = 21$ nA.

(c) $R_n = 10^5\,\Omega$, $v_2 = 500(-R_nI_N - V_{OSO})$, $-1.70 = 500(-10^5 I_N - 1.5\,\text{mV})$, $I_N = 19$ nA; $I_{OS} = I_P - I_N = 2$ nA.

(d) $v_2 = [-V_{OSO} - (-10)/a]$, $-0.25 = 500\times[-1.5\,\text{mV} + 10/a] \Rightarrow a = 10^4$ V/V.

$\boxed{5.28}$ (a)



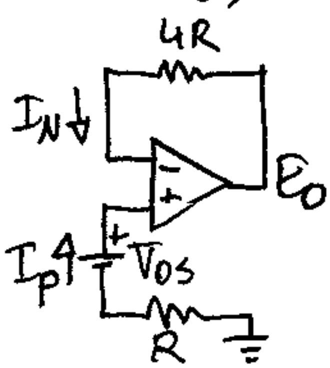
$E_0 = V_1 + V_{OS}$. Summing currents at node V_1,

$$\frac{0 - V_1}{3R} = I_p + \frac{V_1 - E_0}{2R}.$$

Eliminating V_1,

$$E_0 = 2.5\,V_{OS} - 3RI_p.$$

(b)

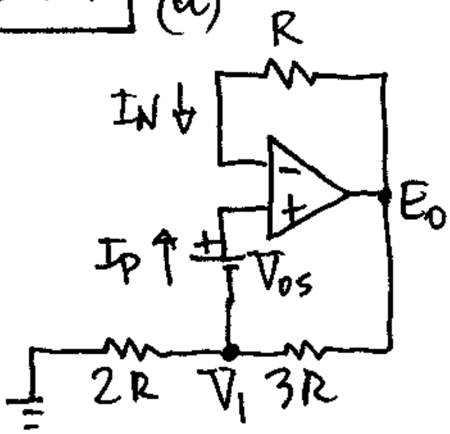


$$E_0 = 4RI_N + V_N = 4RI_N + V_P$$
$$= 4RI_N + (-V_{OS} - RI_P)$$
$$= R(4I_N - I_P) - V_{OS}.$$

(5.15)

5.29

(a)



$E_0 = RI_N + V_N = RI_N + V_P$

$= RI_N + V_{OS} + V_1$.

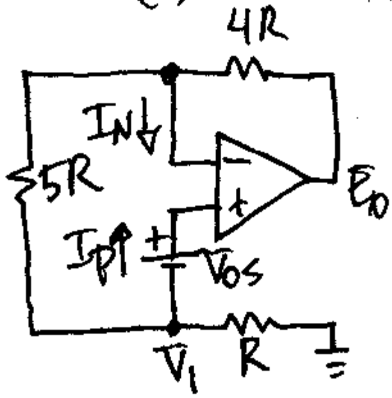
Summing currents @ V_1:

$$\frac{0-V_1}{2R} = I_P + \frac{V_1 - E_0}{3R}$$

Eliminating V_1,

$$E_0 = \frac{1}{3}\left[5V_{OS} + R(5I_N - 6I_P)\right].$$

(b)



KVL: $V_N = V_1 + V_{OS}$; KCL:

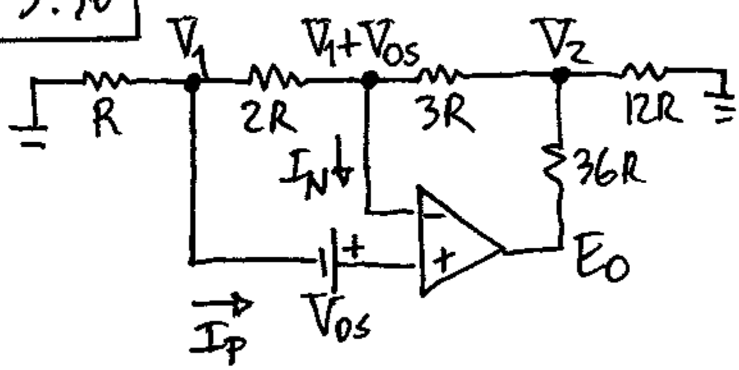
$$\frac{E_0 - (V_1 + V_{OS})}{4R} = \frac{V_{OS}}{5R} + I_N$$

KCL again:

$$\frac{V_{OS}}{5R} = I_P + \frac{V_1}{R}.$$

Eliminating V_1: $E_0 = 2V_{OS} + R(4I_N - I_P)$

5.30



KCL @ V_1: $\dfrac{0-V_1}{R} = I_P + \dfrac{V_1 - (V_1 + V_{OS})}{2R} = I_P - \dfrac{V_{OS}}{2R}$

KCL @ V_N: $\dfrac{V_1 - (V_1 + V_{OS})}{2R} = I_N + \dfrac{V_1 + V_{OS} - V_2}{3R}$

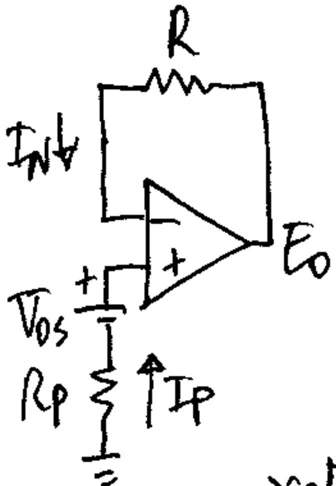
(5.16) KCL @ V_2: $\dfrac{V_1 + V_{OS} - V_2}{3R} = \dfrac{V_2 - E_0}{36R} + \dfrac{V_2}{12R}$

Eliminating V_1 and V_2 gives

$E_0 = 54V_{OS} + 4R(24I_N - 5I_P)$.

$\boxed{5.31}$ (a) With $R_p = 0$, $E_0 = RI_N + V_N$

$\cong RI_B + V_{OS}$



(b) With $R_p = R$,

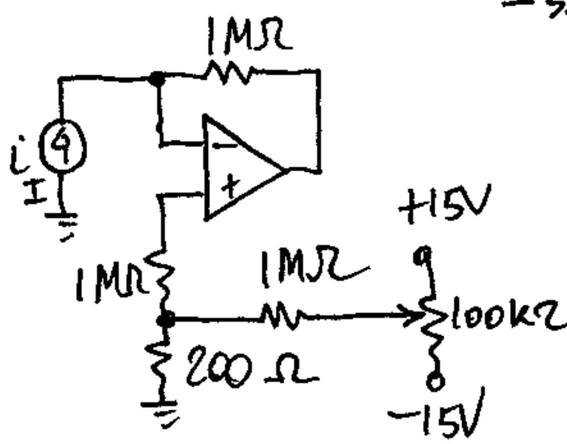
$E_0 = V_{OS} - RI_{OS}$

(c) $E_0(max) = 10^{-3} + 10^{6} \times 10^{-9}$

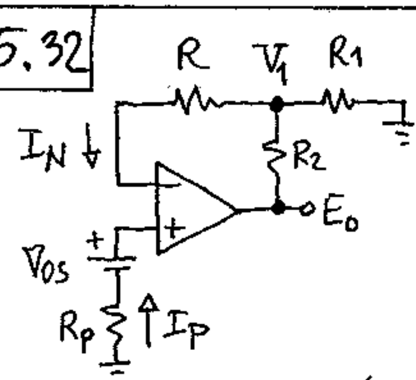
$= 2mV$. To null E_0,

return R_p to a variable voltage

$-3mV \le V_x \le +3mV$.



$\boxed{5.32}$



Superposition and KCL:

$V_1 = V_{OS} + RI_N - R_pI_P$

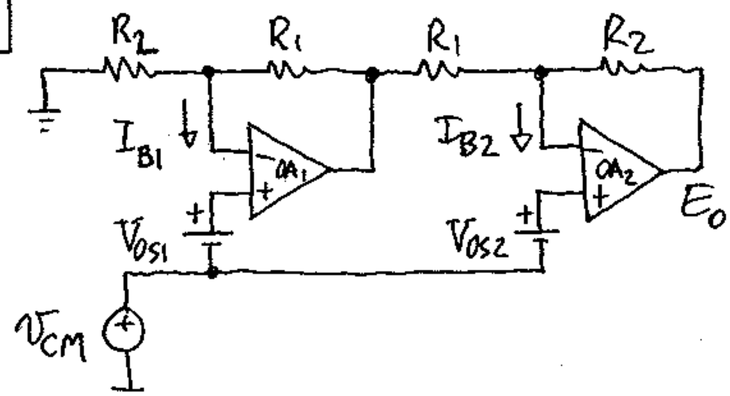
$(E_0 - V_1)/R_2 = I_N + V_1/R_1$.

Eliminating V_1 gives

$E_0 = \left(1 + \frac{R_2}{R_1}\right)\left[V_{OS} - R_pI_P + (R + R_1 \| R_2)I_N\right]$.

To minimize input-bias current errors, use a FET-input op amp, and install a dummy resistance $R_p = R + R_1 /\!/ R_2 \cong 1\ M\Omega$, after which $E_O = (1+R_2/R_1)[V_{OS} - (R + R_1/\!/R_2)I_{OS}] = 101[V_{OS} - 10^6 I_{OS}]$. To null E_O, return R_p to a variable voltage V_X within the range $-V_2 \le V_X \le V_2$, where $V_2 \geq V_{OS(max)} + 10^6 I_{OS(max)}$.

5.33



Since the OP-227 uses input bias-current cancellation, there is no point using dummy resistances at the noninverting inputs. The superposition principle gives, for $v_{CM} = 0$,

$$E_O = \left(1+\frac{R_2}{R_1}\right)(V_{OS2} - V_{OS1}) - \frac{R_2}{R_1}R_1 I_{B1} + R_2 I_{B2}$$

$$= (1+R_2/R_1)[V_{OS2} - V_{OS1} + (R_1 \| R_2)(I_{B2} - I_{B1})]$$

$$E_{O(max)} = 100\,[2V_{OS(max)} + 2(R_1\|R_2)I_{B(max)}]$$

$$= 200\,[V_{OS(max)} + (R_1\|R_2)I_{B(max)}].$$

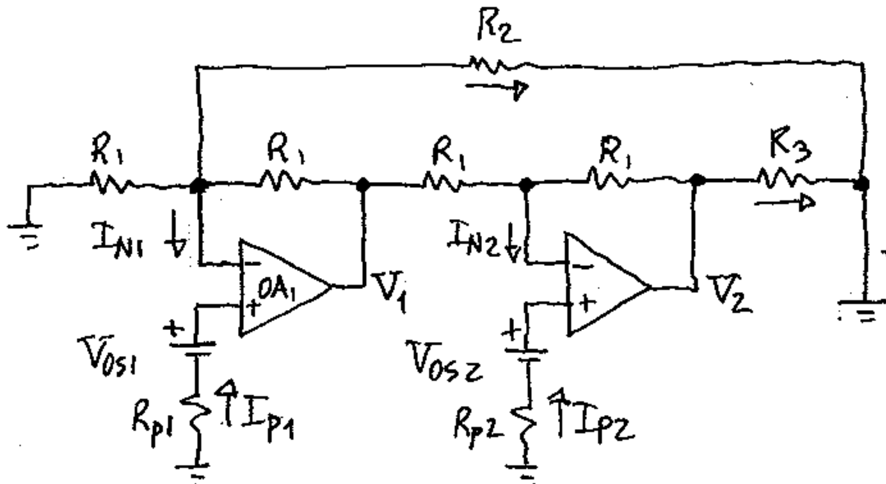
Specify R_1 and R_2 so that $(R_1\|R_2)I_{B(max)} \ll V_{OS(max)}$, or $R_1\|R_2 = R_1\|(99R_1) \cong R_1 \ll (80\ \mu V)/(40\ nA) = 2\ k\Omega$. For instance, use $R_1 = 200\ \Omega$, $R_2 =$

5.18

19.8 kΩ. Then, with $v_{CM} = 0\ \text{V}$, $E_{O(max)} = 17.6\ \text{mV}$.

Rising v_{CM} to 10 V changes V_{OS1} and V_{OS2} by as much as $(10\ \text{V})/10^{114/20} \cong 20\ \mu\text{V}/\text{V}$. Moreover, V_{OS1} experiences an additional change of $v_{O1}/a_{1(min)} = 10/10^6 = 1\ \mu\text{V}$. We thus have, for $v_{CM} = 10\ \text{V}$, $E_{O(max)} \cong 17.6\ \text{mV} + 100(21+20)\ \mu\text{V} = 21.7\ \text{mV}$.

$\boxed{5.34}$ The presence of the bias currents and offset voltages does not affect the resistances of the circuit, so we expect A and R_o to remain the same. The only effect is to produce an output error I_o.



$I_o = V_{N1}/R_2 + V_2/R_3$. In a well-designed circuit we usually have $R_3 \ll R_2$ for efficiency, so we need to minimize V_2. Superposition:

$$V_2 = (1 + R_1/R_1)(V_{OS2} - R_{P2}I_{P2}) + R_1 I_{N2} - (R_1/R_1)V_1.$$

$$= 2\left[V_{OS2} - R_{P2}I_{P2} + (R_1/2)I_{N2}\right] - V_1.$$

$\Rightarrow$ Use $R_{P2} = R_1/2$ to minimize effect of I_{B2}.

$$V_1 = \left[1 + R_1/(R_1 \| R_2)\right](V_{OS1} - R_{P1}I_{P1}) + R_1 I_{N1}$$

(5.19)

$= (2+R_1/R_2)\{V_{OS1} - R_{P1} I_{P1} + [(R_1/2)\|R_2] I_{N1}\}$

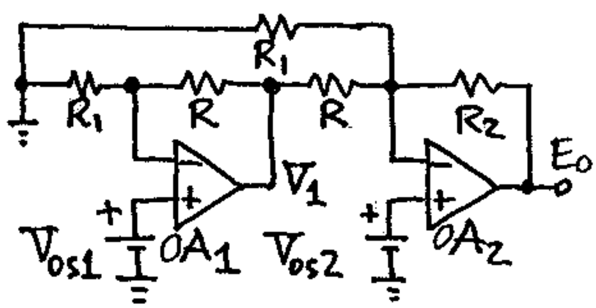
$\Rightarrow$ Use $R_{P1} = (R_1/2)\|R_2$ to minimize effect of I_{B1}.

Worst-case output error is then

$$I_{O(max)} = \frac{V_{OS1} + R_{P1} I_{B1}}{R_2} + \frac{1}{R_3}\Big\{2V_{OS2} + \frac{R_1}{2} I_{OS2} + \left(2+\frac{R_1}{R_2}\right)\left(V_{OS1} + R_{P1} I_{OS1}\right)\Big\}.$$

To null I_O, return R_{P2} to a variable voltage V_X, $-V_3 \le V_X \le V_3$, $V_3 \geq 2\overline{V_{OS2}} + (R_1/2)\overline{I_{OS2}} + 3(\overline{V_{OS1}} + R_{P1}\overline{I_{OS1}})$, where the overbar indicates max value.

$\boxed{5.35}$ (a) $V_1 = (1+R/R_1)V_{OS1}$. Superposition:



$$E_o = -\frac{R_2}{R}V_1 + \left(1+\frac{R_2}{R_1/\!/R}\right)V_{OS2}$$

Eliminating V_1 and manipulating,

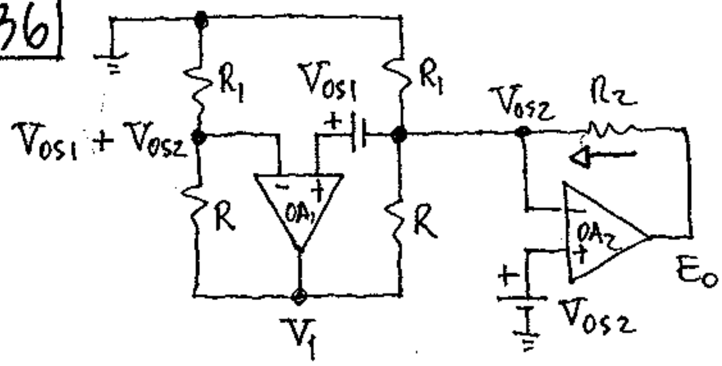
$$E_o = V_{OS2} + \frac{R_2}{R_1/\!/R}\left(V_{OS2} - V_{OS1}\right).$$

(b) Lift OA_2's noninverting input and return it to a variable voltage V_x, $-V_2 \le V_x \le V_2$, $V_2 = E_{o(max)}/[1 + R_2/(R_1\|R)]$.

(5.20)

$\boxed{5.36}$

(a)

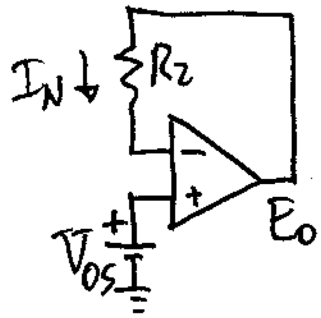


KCL: $(E_o - V_{OS2})/R_2 = V_{OS2}/R_1 + (V_{OS2} - V_1)/R$, where $V_1 = (1 + R/R_1)(V_{OS1} + V_{OS2})$. Eliminating V_1, $E_o = V_{OS2} - [R_2/(R_1 /\!/ R)]V_{OS1}$.

(b) Lift OA_2's noninverting input and return it to a variable voltage V_X, $-V_2 \le V_X \le V_2$, $V_2 \gtrsim V_{OS2(max)} + [R_2/(R_1 + R)]V_{OS1(max)}$.

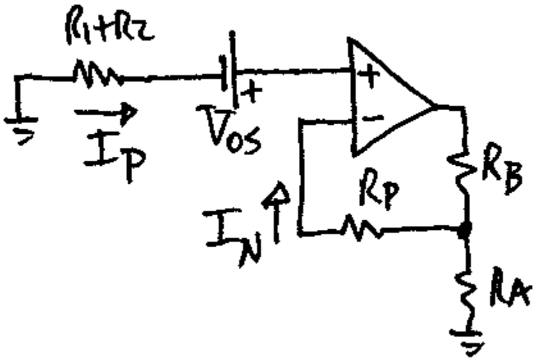
$\boxed{5.37}$ Fig. 2.1 : $E_o = V_{OS} - RI_{OS}$. $E_{o(max)} = 10^{-3} + 10^6 \times 2 \times 10^{-9} = 3$ mV. Fig. 2.2 : using the superposition principle, $E_o = R_{eq} I_N + (1 + R_2/R_1)(V_{OS} - R_P I_P)$, where $R_{eq} = (1 + 20/100 + 20/2.26)100 = 1\,\text{M}\Omega$, $1 + R_2/R_1 = 9.8$, $(1 + R_2/R_1)R_P = 1\,\text{M}\Omega$. Thus, $E_o = (1 + R_2/R_1)V_{OS} - R_{eq} I_{OS}$, and $E_{o(max)} = 9.8 \times 10^{-3} + 10^6 \times 2 \times 10^{-9} = 9.8 + 2 = 11.8$ mV. While the contribution from I_{OS} is the same, that from V_{OS} is much larger in the second circuit due to the fact that the noise gain is unity in the first circuit, but $1 + R_2/R_1$ in the second.

5.38 Dc equivalent is as shown:



$E_O = V_{OS} + R_2 I_N \cong V_{OS} + R_2 I_B$
$\cong 10^{-3} + 316\times10^{3} \times 50\times10^{-9}$
$= 16.8$ mV. To minimize the output error, return the noninverting input to ground via a dummy resistance $R_p = R_2 = 316$ kΩ. Then, $E_O = V_{OS} - R_2 I_{OS}$, and $|E_O|_{max} =$ $10^{-3} + 316\times10^{3}\times 5\times10^{-9} = 2.58$ mV. To null this residual error, return R_p to a variable voltage V_x, $-3\,\text{mV} \le V_x \le 3\,\text{mV}$.

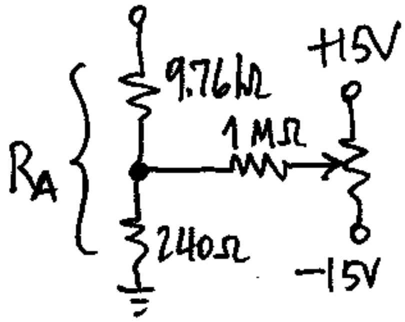
5.39 Since noninverting input sees a dc



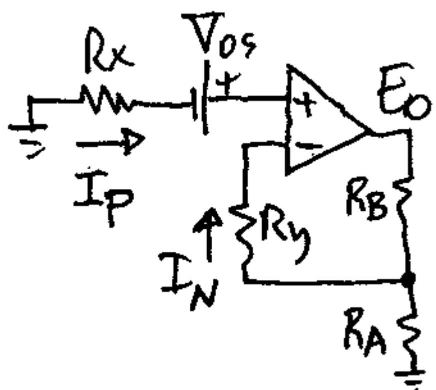
resistance of $R_1+R_2 = 31.6$ kΩ, and the inverting input sees a dc resistance of $R_A \| R_B = 6.40$ kΩ, we either scale R_A and R_B to achieve $R_A \| R_B = R_1+R_2$ while retaining the same ratio in order to leave Q unchanged, or we leave them as they are, but insert a dummy resistance $R_p = R_1+R_2 - R_A // R_B =$ 25.2 kΩ, as shown. In either case we have:

5.22

$E_O = \left(1+\frac{R_B}{R_A}\right)\left[V_{OS} - (R_1+R_2)I_{OS}\right]$, $|E_O|_{max} =$
$2.8\,(10^{-3} + 31.6\times10^{3}\times 5\times10^{-9}) = 3.24$ mV. To null it, return R_A to a variable voltage V_x, $-3.5\,\text{mV} \le V_x \le 3.5\,\text{mV}$ as shown



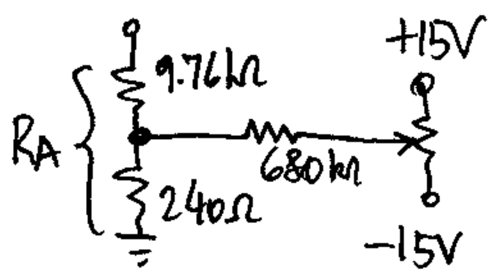
5.40 Both circuits have a dc equiv- To minimize the error, insert a dummy resistor $R_y = R_x - (R_A \| R_B)$. Then, the output



error is $E_O = (1+R_B/R_A)(V_{OS} - R_x I_{OS})$.

<u>Example 3.13</u>: $R_x = R_2 = 22.5\,\text{k}\Omega$, $R_y = 22.5 - (10\|28.7) = 15\,\text{k}\Omega$. $|E_O|_{max} = 3.86 \times (1 + 22.5\times10^{3}\times 5\times10^{-9}) = 4.3$ mV

<u>Example 3.14</u>: $R_x = 2R = 53.1\,\text{k}\Omega$; $R_y = 53.1 - 0.870 = 52\,\text{k}\Omega$. $|E_O|_{max} = (47/12)\times (10^{-3} + 53.1\times10^{3}\times 5\times10^{-9}) = 4.94$ mV.

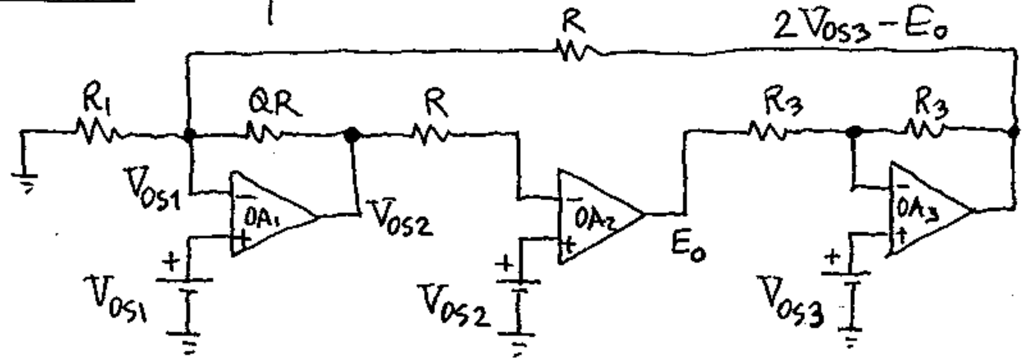


To null the error, split R_A and use external nulling as shown.

(5.23)

5.41

Dc equivalent:



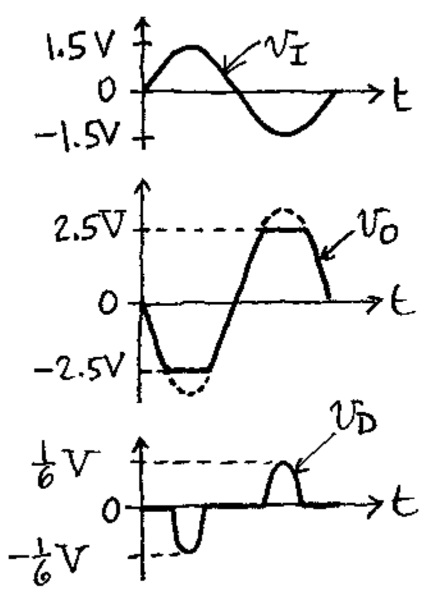
KCL: $\frac{V_{OS2}-V_{OS1}}{QR}+\frac{0-V_{OS1}}{R_1}+\frac{(2V_{OS3}-E_O)-V_{OS1}}{R}=0$

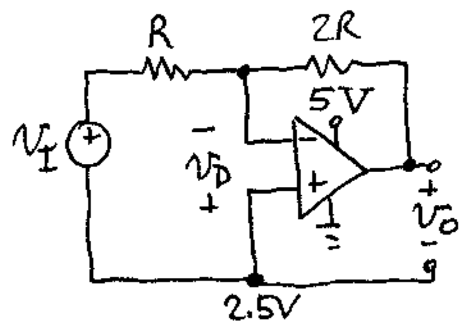
$\Rightarrow E_o = 2V_{OS3}-\left(1+\frac{1}{Q}+\frac{R}{R_1}\right)V_{OS1}+\frac{V_{OS2}}{Q}$

$E_{o(max)} = \left[2+\left(1+\frac{1}{40}+\frac{20}{78.7}\right)+\frac{1}{40}\right]5\times10^{-3} = 16.3\text{ mV}.$

To null E_o, return OA_3's noninverting input to an adjustable voltage V_x such that $2(V_{OS3}+V_x)-1.28V_{OS1}+0.025V_{OS2}=0 \Rightarrow |V_x|_{max}=$ 8.2 mV. For safety, make $-10\text{ mV} \le V_x \le 10\text{ mV}$.

5.42





(a) As v_O tries to swing to ± 3V, it clips at ± 2.5V; also, v_D peaks at $\pm\left(\frac{2}{3}1.5-\frac{1}{3}2.5\right)=\pm\frac{1}{6}$V.

(b) $v_I = 1.25\sin\omega t$ V.

5.24

$\boxed{5.43}$ (a) $i_O = 10/2 = 5$ mA; $v_{R_6} = 0.027 \times 5 = 0.135$ V; Q_{15} = off; $i_{C15} = 0$; $i_{C14} = i_O = 5$ mA; $P_{Q4} = [15 - (10 + 0.135)]5 = 24.3$ mW; $v_{B22} = 10 + 0.135 + 0.7 - 3 \times 0.7 = 8.735$ V.

(b) $10/0.2 = 50$ mA $> 0.7/27 \cong 26$ mA $\Rightarrow$ $i_O \cong 26$ mA; $v_O \cong 0.2 \times 26 = 5.2$ V; $i_{C14} \cong i_O \cong 26$ mA; $i_{C15} = 0.18 - 26/250 = 76$ μA; $P_{Q14} \cong (15 - 5.2)26 = 255$ mW; v_{B22} close to V_{CC}.