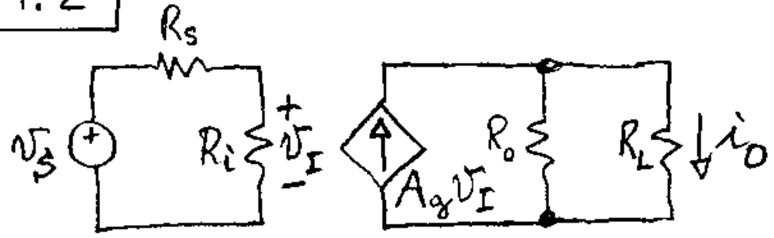
(1.1)

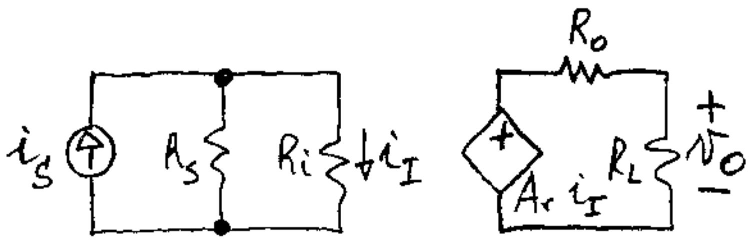
1.1 $75\ mV = (100\ mV) R_i / (100\ k\Omega + R_i) \Rightarrow$ $R_i = 300\ k\Omega$. $2 = (A_{oc} \times 75\ mV)\, 10/(R_o + 10)$, and $1.8 = (A_{oc} \times 75\ mV)(30 \| 10)/[R_o + (30\|10)]$; Solving gives $A_{oc} = 40\ V/V$, $R_o = 5\ \Omega$.

1.2



Xconductance amp

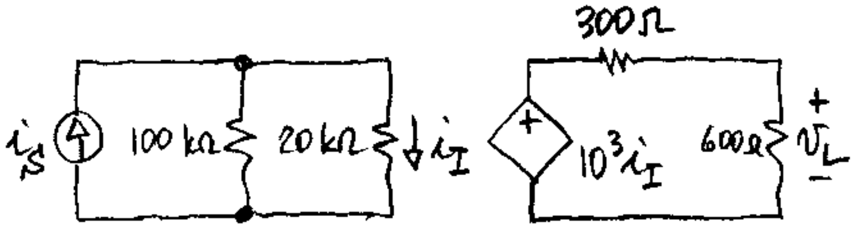
$$i_O = \frac{R_i}{R_S + R_i} A_g \frac{R_o}{R_o + R_L} v_S$$



Xresistance amp

$$v_O = \frac{R_s}{R_s + R_i} A_r \frac{R_L}{R_o + R_L} i_S$$

1.3 (a)



$$v_L / i_S = \frac{100}{100+20} 10^3 \frac{600}{300+600} = \frac{5}{6} 10^3 \frac{2}{3} = 0.\bar{5}\ V/mA$$

$p_S = [(100 \| 20)\ k\Omega]\, i_S^2 = 16.\bar{6} \times 10^3 i_S^2$; $p_L = v_L^2/600$;

$p_L/p_S = (v_L/i_S)^2 / (16.\bar{6} \times 10^3 \times 600) = 30.86\ mW/W$.

(b) $A_r = 1.8\ V/mA$; $0.1\ W/W$.

1.4 $25\text{ mV} = (30\text{ mV})R_i/(100\text{ k}\Omega + R_i) \Rightarrow$ $R_i = 500\text{ k}\Omega$. $0.9 = (A_{oc} \times 25\text{ mV})R_o/(R_o + 20)$, and $0.8 = (A_{oc} \times 25\text{ mV})R_o/(R_o + 30)$; solving gives $A_{oc} = 48\text{ A/V}$, $R_o = 60\ \Omega$. We now have $v_I = (33\text{ mV})500/(100+500) = 27.5\text{ mV}$, $v_O = (48 \times 27.5\text{ mV})60/(60+40) = 0.792\text{ V}$.

1.5 (a) $v_O = 10^4(750.25 - 751.50)10^{-3} = -12.5\text{ V}$; (b) $v_N = 0 - (-5)/10^4 = 0.5\text{ mV}$; (c) $v_P = 5 + 5/10^4 = 5.0005\text{ V}$; (d) $v_N = 1 - (-1/10^4) = 1.0001\text{ V}$.

1.6 $i_{r_o} = 5/1 = 5\text{ mA}$; $v_{r_o} = 75 \times 5 \times 10^{-3} = 0.375\text{ V}$; $v_{r_d} = v_O/a = 5/(200 \times 10^3) = 25\ \mu\text{V}$; $i_{r_d} = (25\ \mu\text{V})/(2\text{ M}\Omega) = 12.5\text{ pA}$.

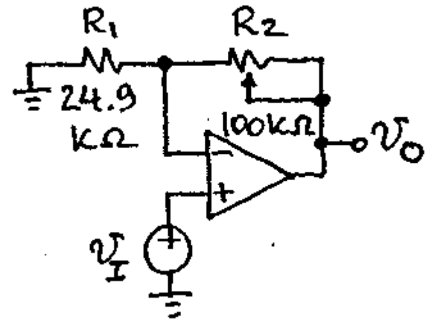
1.7 (a) $A = 1 + 200/100 = 3\text{ V/V}$; $A = 1 + 200/(100+100) = 2\text{ V/V}$; $A = 1 + 200/(100 \| 100) = 5\text{ V/V}$; $A = 1 + (200+100)/100 = 4\text{ V/V}$; $A = 1 + (200 \| 100)/100 = 5/3\text{ V/V}$. (b) $A = 2\text{ V/V}$, -1 V/V, -4 V/V, -3 V/V, $-2/3\text{ V/V}$.

1.8 (a) $1 + R_2/R_1 = 1 + 100/R_1 = 5 \Rightarrow R_1 = 25\text{ k}\Omega$ (use $24.9\text{ k}\Omega$).

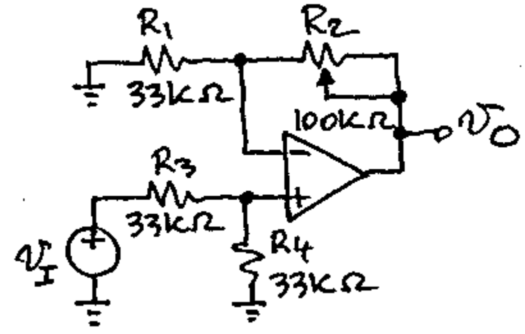
(b) $$v_O = (1 + R_2/R_1)v_P = \left(1 + \frac{R_2}{R_1}\right)\frac{R_4}{R_3 + R_4}v_I.$$

$R_2 = 0 \Rightarrow R_4/(R_3 + R_4) = 0.5 \Rightarrow R_3 = R_4$.
$R_2 = 100\text{ k}\Omega \Rightarrow (1 + 100/R_1) \times 0.5 = 2 \Rightarrow R_1 = \frac{100}{3}$.
Use $R_1 = R_3 = R_4 = 33\text{ k}\Omega$.

1.3



(a)



(b)

1.9 (a) $A_{min} = 1 + 9.5/10.5 \cong 1.9$ V/V, $A_{max} = 1 + 10.5/9.5 \cong 2.1$ V/V. For the exact calibration, implement R_2 with a 9.1-kΩ resistor in series with a 2-kΩ potentiometer connected as a variable resistor from 0 to 2kΩ.

(b) -1.1 V/V $< A < -0.9$ V/V. Implement R_2 as in part (a).

1.10 $v_O = [-10/(1 + 11/a)]v_I$, $v_N = -v_O/a$.

(a) $v_O = -0.9479$ V, $v_N \cong 10$ mV.

(b) $v_O = -0.9989$ V, $v_N \cong 0.1$ mV.

(c) $v_O = -0.999989$ V, $v_N \cong 1$ μV.

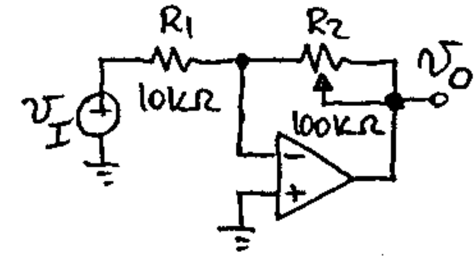
A gain a is increased, v_O approaches -1 V and v_N approaches 0.

1.11 (a) $R_2/R_1 = 100/R_1 = 10 \Rightarrow R_1 = 10$ kΩ.

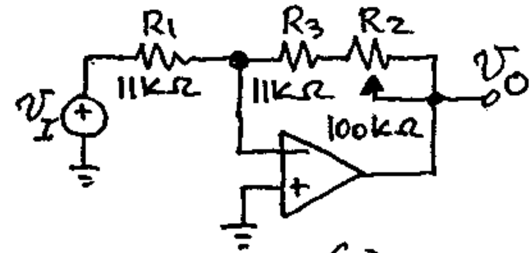
(b) $v_O = -[(R_2+R_3)/R_1]v_I$.

$R_2 = 0 \Rightarrow R_3/R_1 = 1$; $R_2 = 100$ kΩ $\Rightarrow$ $(R_3+100)/R_1 = 10 \Rightarrow 1 + 100/R_1 = 10 \Rightarrow R_1 = 100/9 = 11$ kΩ. Use $R_1 = R_3 = 11$ kΩ.

1.4



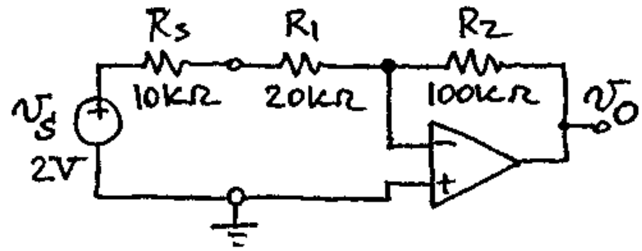
(a)



(b)

1.12

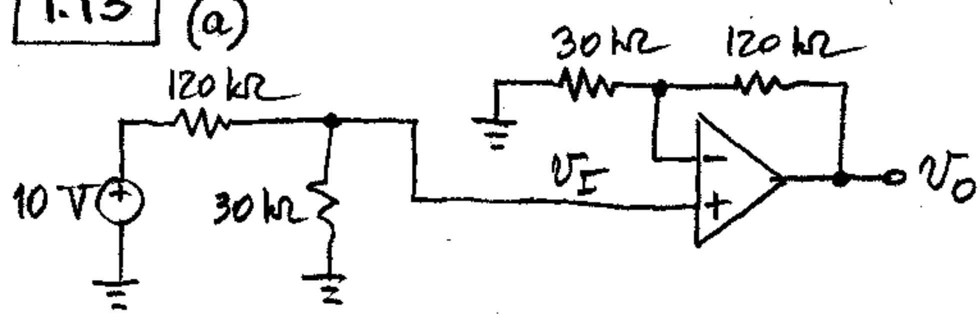
$v_O = -[100/(10+20)]\times 2 = -3.33\times 2 = -6.67$ V.



$$10 = \frac{R_2}{10+20}\times 2 \Rightarrow$$

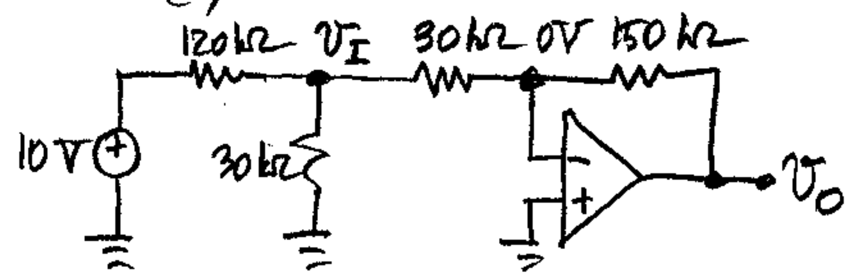
$R_2 = 150$ kΩ.

1.13 (a)



$$v_I = \frac{30}{120+30}10 = 2 \text{ V}; \quad v_O = \left(1+\frac{120}{30}\right)2 = 10 \text{ V}.$$

(b)

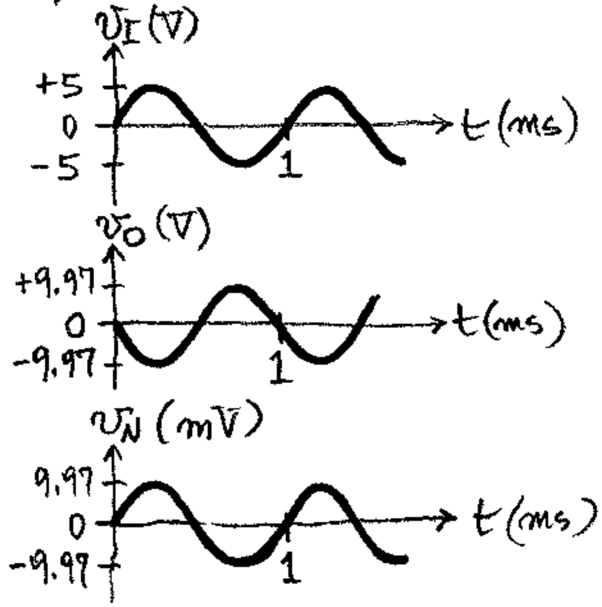


$$v_I = \frac{30\|30}{120+(30\|30)}10 = 1.\bar{1} \text{ V}; \quad v_O = -\frac{150}{30}1.\bar{1}$$

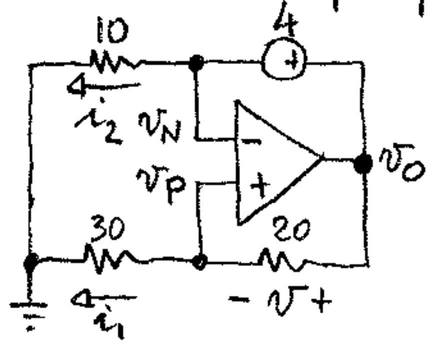
$= -5.\bar{5}$ V.

In (a) there is no loading by the amplifier; in (b) there is loading.

1.14 $v_O = Av_I$, $A = (-20/10)/(1+3/10^3) = -1.994$ V/V; $v_N = -v_O/10^3$.



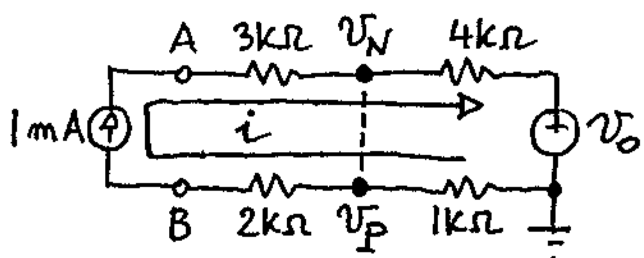
1.15 Since op amp keeps $v_N = v_P$, we have



$v = 4$ V. Then, $i_1 = 4/20 = 0.2$ mA; $v_N = v_P = 30 i_1 = 6$ V; $v_O = v_N + 4 = 10$ V; $i_2 = v_N/10 = 0.6$ mA; $P_{4V} = 4 i_2 = 2.4$ mW.

To check, recompute v_N and v_P and verify that $v_N = v_P$. KVL: $v_N = v_o - 4 = 6$ V; voltage divider: $v_P = v_O 30/(30+20) = 6$ V; so, $v_N = v_P$.

1.16 (a) Virtual short keeps $v_N = v_P$;



however, no current flows through it. Using Ohm's

(1.6)

law and KVL, $v_P = -1 \times I = -1V$; $v_N = v_P = -1V$, $v_O = v_N - 4 \times i = -1-4 = -5V$. Moreover, $v_A = v_N + 3 \times i = -1+3 = +2V$; $v_B = v_P - 2 \times i = -1-2 = -3V$.

(b) Now source sees $5\,k\Omega$ in parallel with $(3\,k\Omega + R_{VS} + 2\,k\Omega) = 5\,k\Omega$. By the current divider formula we now have $i = (1\,mA) \times 5/(5+5) = 0.5\,mA$. Then, $v_P = -0.5V$, $v_N = -0.5V$, $v_O = -2.5V$, $v_A = +1V$, $v_B = -1.5V$.

$\boxed{1.17}$ (a) $v_N = v_P = [10/(10+40)]v_O = 0.2\,v_O$. $(v_S - v_N)/50 = (v_N - v_O)/20 \Rightarrow (9 - 0.2v_O)/50 = (0.2v_O - v_O)/20 \Rightarrow v_O = -5\,V$, $v_N = v_P = -1\,V$.

(b) $v_O = -10\,V \Rightarrow v_N = v_P = -2V$; $[9-(-2)]/50 = -2/R + [-2-(-10)]/20 \Rightarrow R = 100/9\,k\Omega$.

```
Problem 1.17(b)
Vs 1 0 dc 9
R1 1 2 50k ;node 2 is vN
R2 2 3 20k ;node 3 is vO
R3 0 4 10k ;node 4 is vP
R4 4 3 40k
R 2 0 11.11k
eOA 3 0 4 2 1Meg
.end
```

NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE
(1)	9.0000	(2)	-2.0002	(3)	-10.0010

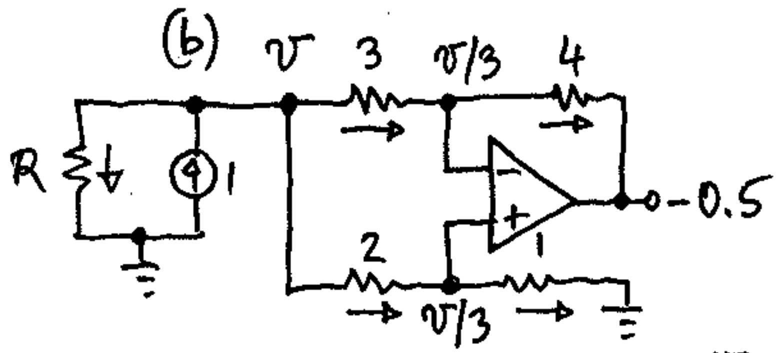
NODE	VOLTAGE
(4)	-2.0002

1.18 (a) $v_N = v_P = [20/(20+30)]v_O = 0.4 v_O$;
$v_O = v_N - 10 \times 0.3 = 0.4 v_O - 3 \Rightarrow v_O = -5$ V,
$v_N = v_P = -2$ V.

(b) KCL: $0.3 + (0 - v_N)/40 = (v_N - v_O)/10$
$\Rightarrow 0.3 - 0.4 v_O/40 = (0.4 v_O - v_O)/10 \Rightarrow v_O = -6$ V,
$v_N = v_P = -2.4$ V. To check, verify that KCL is satisfied at node v_N. Current into node is $0.3 + 2.4/40 = 0.36$ mA; current out of node is $[-2.4 - (-6)]/10 = 0.36$ mA

1.19 (a) Since $v_N = v_P$, the 3-kΩ and 2-kΩ resistances appear in parallel. Hence, $i_{3k\Omega} = [2/(2+3)]i_S = 0.4$ mA, and $i_{2k\Omega} = 0.6$ mA.
$v_N = v_P = 1 \times 0.6 = 0.6$ V; $v_O = v_N - 4 \times 0.4 = -1$ V.

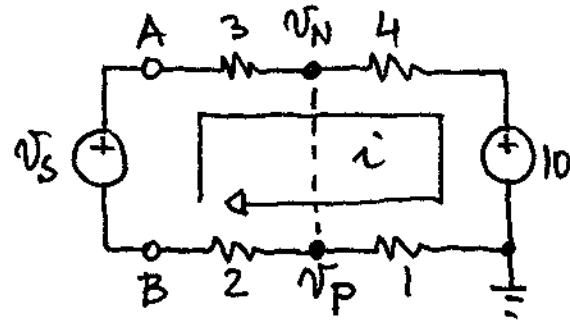
(b)



$v_N = v_P = \frac{1}{2+1} v = v/3$. KCL: $\frac{v - v/3}{3} = \frac{v/3 - (-0.5)}{4} \Rightarrow v = 0.9$ V. KCL again:

$$1 = \frac{0.9}{R} + \frac{0.9}{2+1} + \frac{0.9 - 0.9/3}{3} \Rightarrow R = 1.8\ \text{k}\Omega.$$

1.20 (a) Because of virtual short between v_N and v_P, we have



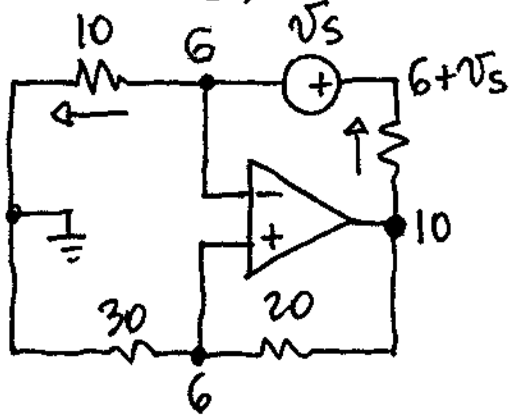
$$i = \frac{v_S}{3+2} = \frac{-10}{4+1}$$

$\Rightarrow v_S = -10\ \mathrm{V}$

(v_S positive @ B).

(b)

$$v_N = v_P = \frac{30}{30+20}10 = 6\ \mathrm{V}$$



Applying KCL:

$$\frac{6}{10} = \frac{10-(6+v_S)}{5}$$

$\Rightarrow v_S = 1\ \mathrm{V}.$

1.21 (a) Switch open $\Rightarrow i_{R_3} = 0$; thus, $v_P = v_I$, $v_N = v_I$, $i_{R_1} = i_{R_2} = 0$, $v_O = v_I$, $A = +1$ V/V. Switch closed $\Rightarrow v_P = 0 \Rightarrow v_O = (-R_2/R_1)v_I$.

(b) Switch closed $\Rightarrow v_N = v_P = 0$, so R_4 has no effect, and $A = -R_2/R_1$ as before. Switch = open $\Rightarrow v_N = v_P = v_I$, $i_{R_1} = 0$, and $A = 1 + R_2/R_4$.

(c) Impose $R_2/R_1 = 2$, and $1 + R_2/R_4 = 2$. A possible set is $R_1 = R_3 = 10\ \mathrm{k\Omega}$, $R_2 = R_4 = 20\ \mathrm{k\Omega}$.

$\boxed{1.22}$ (a) $v_P = k v_I$, $0 \le k \le 1$. Superposition: $v_O = (-R_2/R_1)v_I + (1+R_2/R_1)k v_I \Rightarrow A = k + (k-1)R_2/R_1$; as k is varied from 0 to 1, A varies from $-R_2/R_1$ to $+1$ V/V.

(b) KCL: $(v_I - v_N)/R_1 + (v_O - v_N)/R_2 = v_N/R_4$; Substituting $v_N = v_P = k v_I$ gives $A = v_O/v_I = k(1 + R_2/R_1 + R_2/R_4) - R_2/R_1$. As k is varied from 0 to 1, A varies from $-R_2/R_1$ to $1 + R_2/R_4$.

(c) Impose $R_2/R_1 = 5$, and $1 + R_2/R_4 = 5$. A possible set is $R_1 = 4.02$ kΩ, $R_2 = 20.0$ kΩ, $R_4 = 4.99$ kΩ, all 1%. For R_3, use a 10-kΩ pot.

$\boxed{1.23}$ Statement (a) is correct ($R_i = \infty$). Statements (b) and (c) are wrong because it is v_N that follows v_P, not the other way around.

$\boxed{1.24}$ (a) $v_{P1} = v_{O2} \times R_4/(R_3 + R_4)$, $v_{O2} = -(R_2/R_1)v_O$. Eliminating v_{O2} and letting $v_{P1} = v_{N1} = v_I$ because of the virtual short at the input of OA_1, we get $A = v_O/v_I = -(1 + R_3/R_4)R_1/R_2$.

(b) Make $R_3 = 0$ and $R_4 = \infty$ to save components, and choose $R_2 = 1$ kΩ, $R_1 = 100$ kΩ.

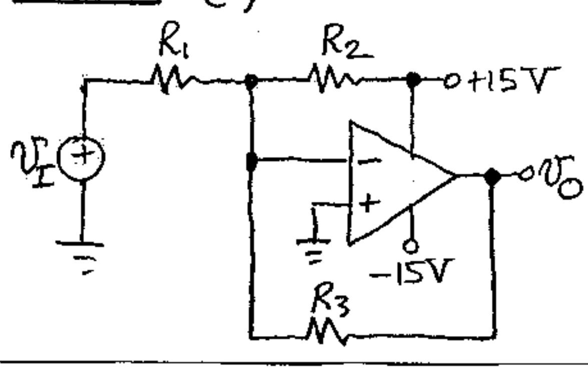
1.25 (a) Wiper down $\Rightarrow v_R = 0$ and $v_L = -\frac{R_2}{10}\frac{10\|10}{R_1 + 10\|10}v_I = \frac{-0.5R_2}{R_1+5}v_I$; wiper up $\Rightarrow v_L = 0$ and $v_R = \frac{-0.5R_2}{R_1+5}v_I$; wiper in the middle $\Rightarrow v_L = v_R = -\frac{R_2}{10}\frac{5\|10}{R_1+5\|10} = -\frac{R_2}{3R_1+10}$

(b) For a gain of -1 V/V at the wiper extremes, impose $0.5R_2 = R_1 + 5$. For a gain of $-1/\sqrt{2}$ with the wiper in the middle, impose $R_2/(3R_1+10) = 1/\sqrt{2}$. Solving gives $R_1 = 24.14$ kΩ (use 24.3 kΩ), and $R_2 = 58.28$ kΩ (use 59.0 kΩ).

1.26 (a) Let $R_F = 330$ kΩ; then, $R_1 = 330/400 = 825$ Ω (use 820 Ω); $R_2 = 330/300 = 1.1$ kΩ; $R_3 = 1.65$ kΩ (use 1.6 kΩ); $R_4 = 330/100 = 3.3$ kΩ.

(b) We now have $0 = -330(0.02/0.82 + -0.05/1.1 + v_3/1.6 + 0.1/3.3)$, which gives $v_3 = -14.78$ mV.

1.27 (a)

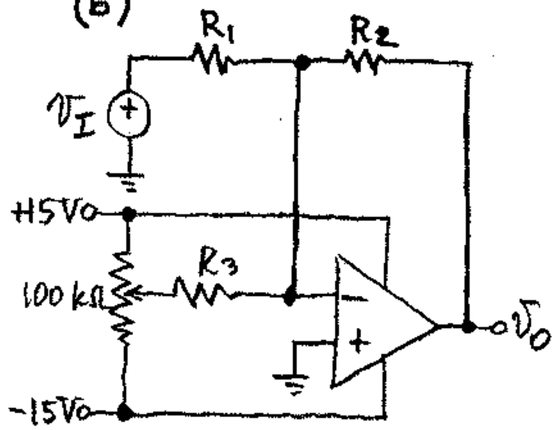


$$v_O = -\frac{R_3}{R_1}v_I - \frac{R_3}{R_2}15$$
$$= -\frac{R_3}{R_1}\left(v_I + \frac{R_1}{R_2}15\right)$$
$$\Rightarrow R_3/R_1 = 10,$$
$$15R_1/R_2 = 1.$$

1.11

Use $R_1 = 10\,k\Omega$, $R_2 = 150\,k\Omega$, $R_3 = 100\,k\Omega$.

(b)



Let $R_3 = 300\,k\Omega$. With the wiper all the way up, we want $V_{offset} = -5\,V$, so $-5 = (-R_2/R_3)15$, or $R_3 = 3R_2$; moreover, we want $R_2/R_1 = 1$. Use $R_1 = R_2 = 100\,k\Omega$.

1.28

$v_O = 2v_2 - 3v_1$.

(a) $10 = 2v_2 - 3\times 3 \Rightarrow v_2 = 9.5\,V$;

(b) $0 = 2\times 6 - 3v_1 \Rightarrow v_1 = 4\,V$;

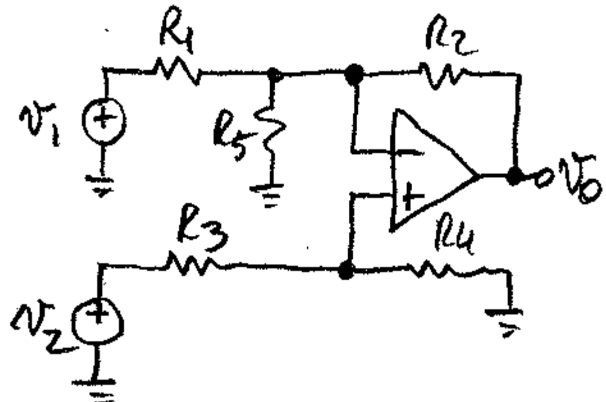
(c) $10 = 2v_2 - 3\times 1 \Rightarrow v_2 = 6.5\,V$

$-10 = 2v_2 - 3\times 1 \Rightarrow v_2 = -3.5\,V$

Thus, $-3.5\,V \le v_2 \le 6.5\,V \Rightarrow -10\,V \le v_O \le +10\,V$.

1.29

(a)

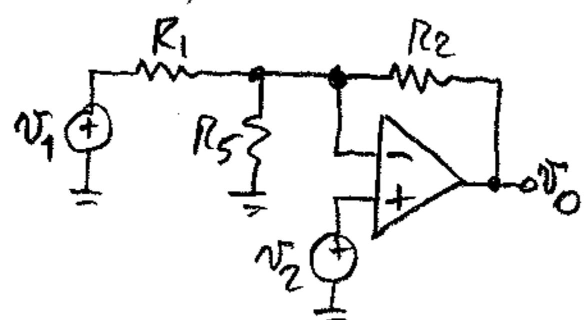


Superposition:

$$A_2 = \left(1 + \frac{R_2}{R_1 /\!/ R_5}\right)\frac{R_4}{R_3 + R_4}$$

$$A_1 = -R_2/R_1.$$

(b)



$A_1 = -5 \Rightarrow R_2/R_1 = 5$

$A_2 = 10 \Rightarrow 1 + \frac{R_2}{R_1 /\!/ R_5} = 10$

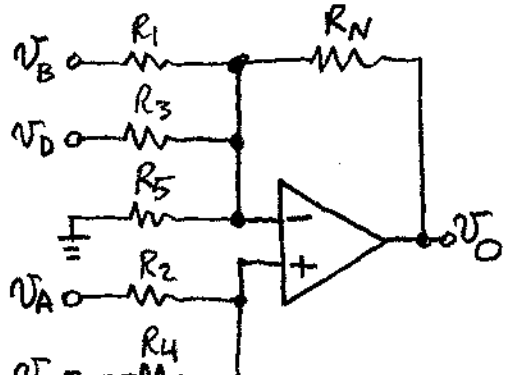
Pick $R_1 = 20\,k\Omega$.

Then, $R_2 = 100\,k\Omega$, and $R_5 = 25\,k\Omega$.

1.30 (a) $v_O = 10(v_2 - v_1) = 10 \cos 2\pi 10^3 t$ V.
(b) $v_O = -10v_1 + 11[101/(10+101)]v_2 = 10.009v_2 - 10v_1 \simeq 0.09 \cos 2\pi 60t + 10 \cos 2\pi 10^3 t$ V. In (a) we have a true difference amplifier, so the output comprises only the 1-kHz component; the 60-Hz component is completely suppressed. In (b), because of the mismatch in the resistance ratios, the 60-Hz component is not completely suppressed.

1.31 Grounding all inputs except v_1 gives $v_O/v_1 = -R_N/R_1 = -1$ V/V. Grounding all inputs except v_2 gives $v_O/v_2 = [1 + R_N/(R_1 \| R_3 \| R_5)] \times (R_P \| R_4 \| R_6)/[R_2 + (R_P \| R_4 \| R_6)] = [1 + R/(R/3)] \times (R/3)/(R + R/3) = 4 \times 1/4 = 1$ V/V. By symmetry, $v_O = v_2 + v_4 + v_6 - v_1 - v_3 - v_5$.

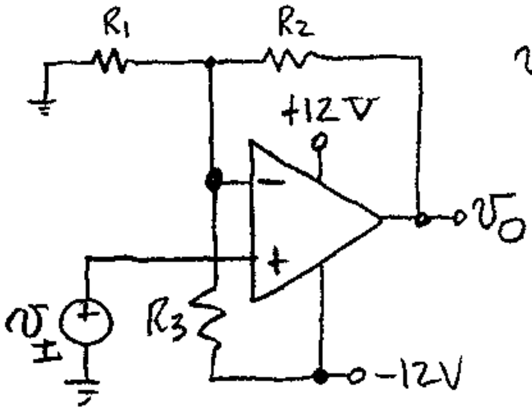
1.32



$$v_O = -\frac{R_N}{R_1}v_B - \frac{R_N}{R_3}v_D + \left(1 + \frac{R_N}{R_1 \| R_3 \| R_5}\right) \times \left(\frac{R_4}{R_2+R_4}v_A + \frac{R_2}{R_2+R_4}v_C\right).$$

Let $R_1 = 10\,k\Omega$. Then, $R_N = 30\,k\Omega$, and $R_3 = 30\,k\Omega$.
We must have $R_4/(R_2+R_4) = 2R_2/(R_2+R_4)$, or $R_4 = 2R_2$. Let $R_2 = 10\,k\Omega$, $R_4 = 20\,k\Omega$. Imposing $[1 + 30/(10 \| 30 \| R_5)]\, 20/(10+20) = 4$ gives $R_5 = 30\,k\Omega$.

1.33 (a)



Superposition:

$$v_O = \left(1 + \frac{R_2}{R_1 \| R_3}\right) v_I - \frac{R_2}{R_3}(-12)$$

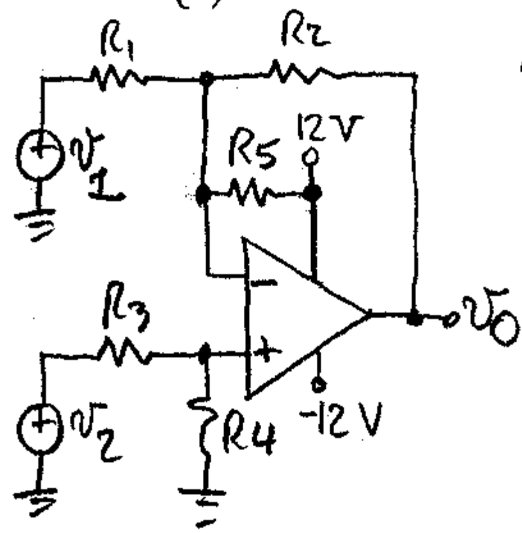
$$= 10\, v_I + 5\ \text{V}.$$

Imposing $\frac{R_2}{R_3} 12 = 5$ gives $R_3 = 2.4 R_2$.

Use $R_2 = 10\ \text{k}\Omega$, $R_3 = 24\ \text{k}\Omega$.

Imposing $1 + \frac{10}{R_1} + \frac{10}{24} = 10$ gives $R_1 = 1.165\ \text{k}\Omega$.

(b)



Superposition:

$$v_O = -\frac{R_2}{R_1} v_1 - \frac{R_2}{R_5} 12 + \left(1 + \frac{R_2}{R_1 \| R_5}\right) \frac{R_4}{R_3 + R_4} v_2$$

$$= 10 v_2 - 10 v_1 - 5\ \text{V}.$$

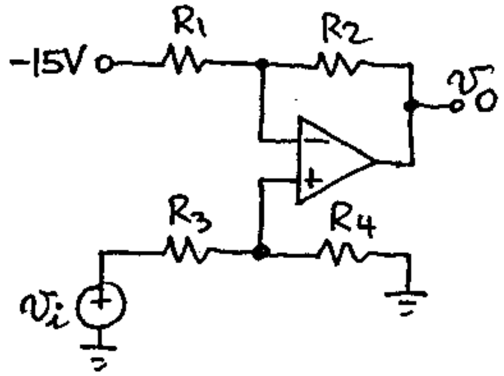
Equating coefficients pairwise gives

$R_2 = 10 R_1$, $R_5 = 2.4 R_2$. Use $R_1 = 10\ \text{k}\Omega$, $R_2 = 100\ \text{k}\Omega$, $R_5 = 240\ \text{k}\Omega$. Finally, imposing

$$\left(1 + \frac{100}{10} + \frac{100}{240}\right) \frac{R_4}{R_3 + R_4} = 10 \text{ gives } R_4 = \frac{120}{17} R_3.$$

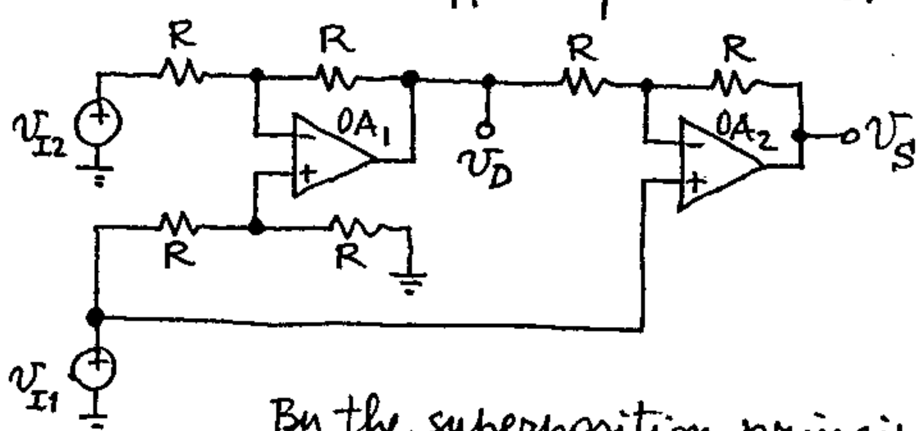
Use $R_3 = 13\ \text{k}\Omega$, $R_4 = 91\ \text{k}\Omega$.

1.34 $-(R_2/R_1)(-15) = 5 \Rightarrow R_1 = 3R_2$. Also,



$\left(1+\frac{R_2}{R_1}\right)\frac{R_4}{R_3+R_4} = 1 \Rightarrow$ $R_4 = 3R_3$. Use $R_1 = R_4 = 300\,k\Omega$, $R_2 = R_3 = 100\,k\Omega$. The resistance seen by v_i is $R_3 + R_4 > 100\,k\Omega$.

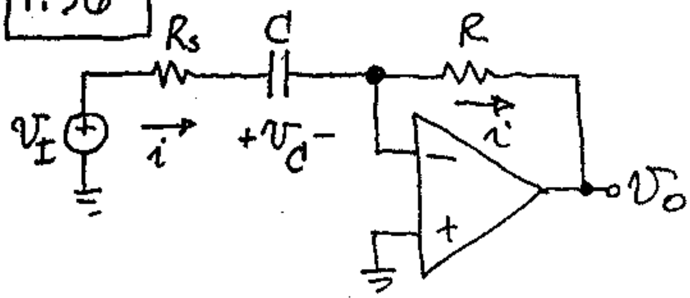
1.35 OA_1 is a diff-amp : $v_D = v_{I1} - v_{I2}$



By the superposition principle, $v_S = 2v_{I1} - v_D = v_{I1} + v_{I2}$. Use $R = 100\ k\Omega$.

(1.15)

1.36



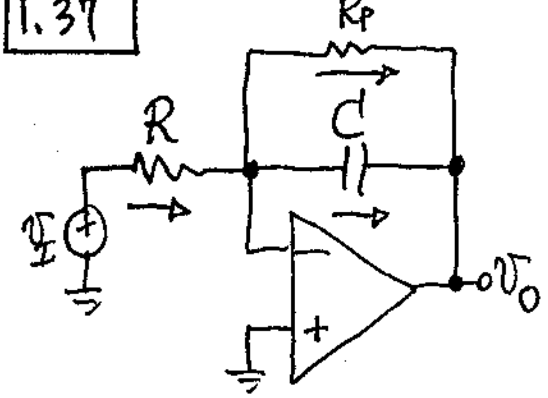
$$v_O = -Ri = -RC\frac{dv_C}{dt} = -RC\frac{d(v_I - R_s i)}{dt}$$

$$v_O = -RC\frac{dv_I}{dt} - R_s C\frac{dv_O}{dt}.$$

If v_I changes slowly, so does i, indicating that $v_C \cong v_I$. So, $v_O \cong -RC \times dv_I/dt$, indicating differentiator behavior.

If v_I changes rapidly, then the derivatives will be much greater than v_O, so we can approximate $\Delta v_O \cong -\frac{R}{R_s}\Delta v_I$, indicating amplifier behavior.

1.37



KCL:

$$\frac{v_I}{R} = C\frac{d(-v_O)}{dt} + \frac{-v_O}{R_P} \Rightarrow$$

$$dv_O = \frac{-v_I\,dt}{RC} - \frac{-v_O\,dt}{R_P C}$$

Changing t to dummy integration variable,

$$v_O(t) = v_O(0) - \frac{1}{RC}\int_0^t v_I(\xi)\,d\xi - \frac{1}{R_P C}\int_0^t v_O(\xi)\,d\xi.$$

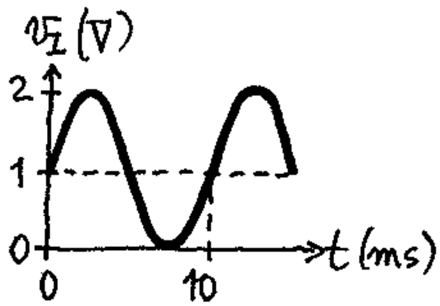
Rapidly changing v_I implies $|i_{R_P}| \ll |i_C|$, so

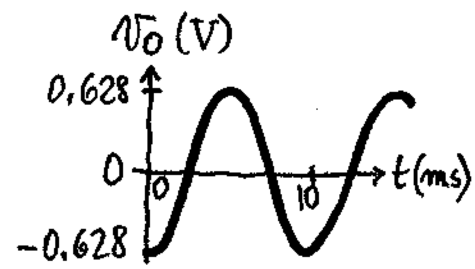
$$\frac{v_I}{R} \cong C\frac{d(-v_O)}{dt} \Rightarrow v_O(t) = v_O(0) - \frac{1}{RC}\int_0^t v_I(\xi)\,d\xi,$$

indicating integrator behavior.
Slowly changing v_I implies $|i_C| << |i_{R_p}|$, so $\frac{v_I}{R} \cong -\frac{v_O}{R_p}$, or $v_O \cong \left(-\frac{R_p}{R}\right)v_I$, indicating amplifier behavior.

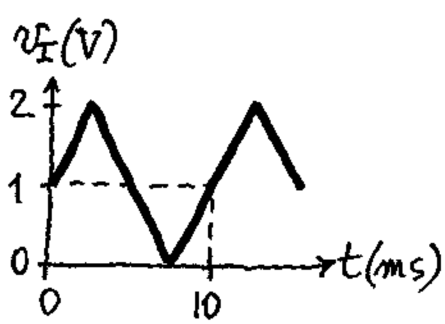
$\boxed{1.38}$ $\tau = RC = 10^{-3}$ s; $T = 1/100 = 10$ ms.

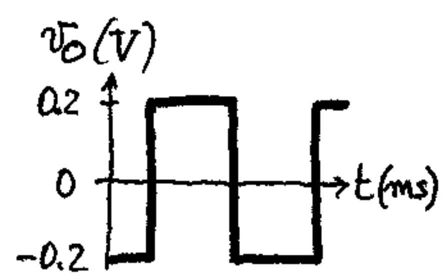
(a) $v_I = 1 + 1 \sin 2\pi 10^2 t$ V; $dv_I/dt = 2\pi 10^2 \cos 2\pi 10^2 t$ V/s; $v_O = -10^{-3} \times 2\pi 10^2 \times \cos 2\pi 10^2 t = -0.628 \cos 2\pi t/0.01$ V.





(b) $dv_I/dt = \pm 2/10^{-2}$ V/s $\Rightarrow v_O = \mp 10^{-3} \times 2/10^{-2} = \mp 0.2$ V.

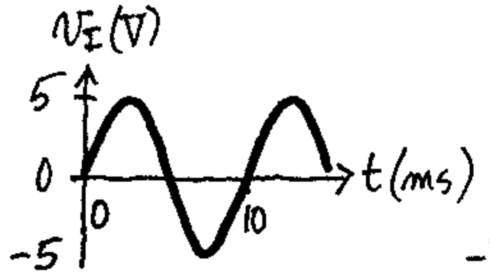


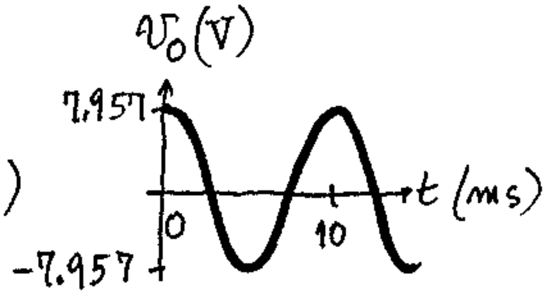


1.39 $\tau = RC = 10^{-3}\,\text{s}$; $v_O(t) = v_O(0) - 10^3 \int_0^t v_I(\xi)\,d\xi$.

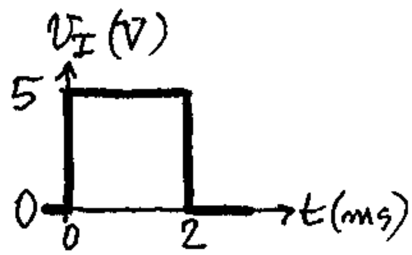
(a) $v_O = -10^3 \int_0^t 5 \sin 2\pi 100 \xi \, d\xi =$

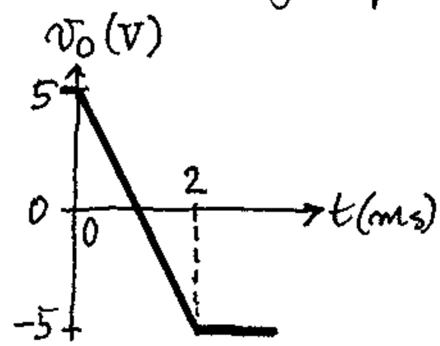
$-\frac{5\times10^3}{2\pi 100}\left(-\cos 2\pi 100 t\right) = 7.957 \cos 2\pi 100 t$ V.



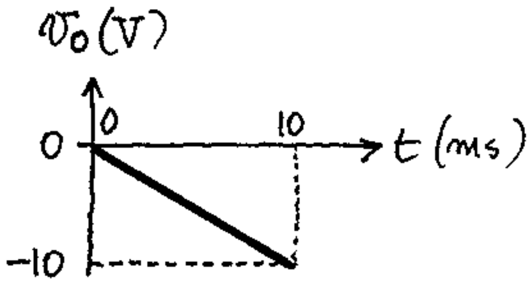


(b) $v_O(t) = v_O(0) - 10^3 5t$ during the pulse.



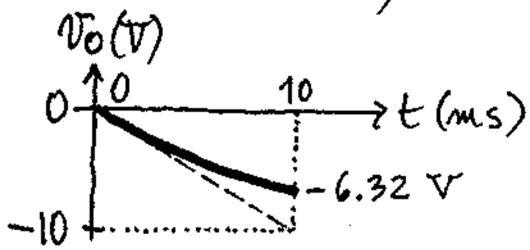


1.40 (a) $v_O = -t/(10^4\times10^{-7}) = -10^3 t$ V.



(b) $v_O(0) = 0$; $v_O(\infty) = -(100/10)1 = -10$ V;

$\tau = R_2 C = 10$ ms; $v_O = -10\left(1 - e^{-t/(10\,\text{ms})}\right)$ V.

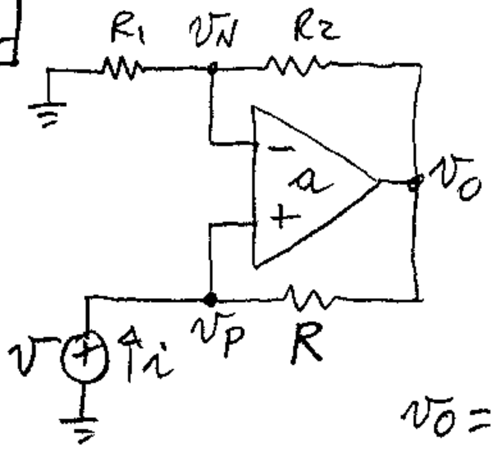


1.18

1.41 (a) $i_1+i_2+i_3=i_C \Rightarrow v_1/R_1+v_2/R_2+v_3/R_3=C\,d(0-v_O)/dt \Rightarrow v_O(t)=v_O(0)-\left(\frac{1}{R_1C}\int_0^t v_1\,d\xi+\frac{1}{R_2C}\int_0^t v_2\,d\xi+\frac{1}{R_3C}\int_0^t v_3\,d\xi\right)$.

(b) $1/(R_1\times10^{-8})=10^3 \Rightarrow R_1=100\text{ k}\Omega$; likewise, $R_2=50\text{ k}\Omega$ and $R_3=200\text{ k}\Omega$.

1.42



$v_O=a(v_P-v_N)$,

$v_P=v$

$v_N=\frac{R_1}{R_1+R_2}v_O$.

Substituting gives

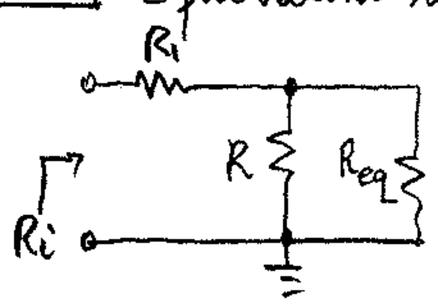
$$v_O=\frac{(R_1+R_2)a}{R_1+R_2+R_1a}v.$$

$$i=\frac{v_P-v_O}{R}=\frac{1}{R}\left[v-\frac{(R_1+R_2)a}{R_1+R_2+R_1a}v\right]$$

$$=\frac{1}{R}\,\frac{R_1+R_2-aR_2}{R_1+R_2+aR_1}v=-\frac{1}{R}\frac{R_2}{R_1}\,\frac{a-1-R_1/R_2}{a+1+R_2/R_1}v$$

$$R_{eq}=\frac{v}{i}=-R\frac{R_1}{R_2}\,\frac{1+(1+R_2/R_1)/a}{1-(1+R_1/R_2)/a}.$$

1.43 Equivalent circuit:



$R_{eq}=-R_2\frac{R_1}{R_2}=-R_1$;

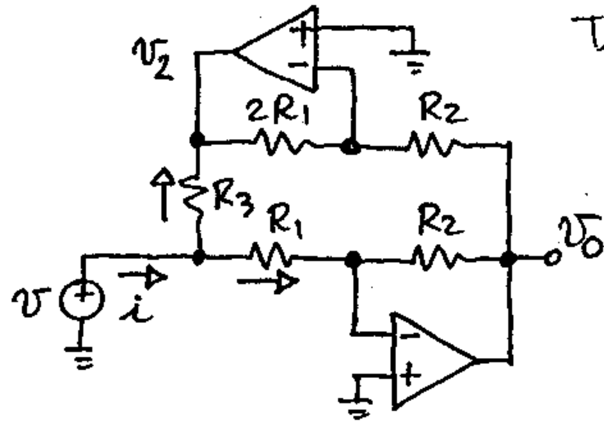
$R_i=R_1+(R\|-R_1)$

$R_i=R_1-\frac{RR_1}{R-R_1}=\frac{R_1}{1-R/R_1}$.

$R_i>0$ for $R<R_1$; $R_i<0$ for $R>R_1$; $R_i=\infty$ for $R=R_1$.

(1.19)

1.44 (a) $v_O = -(R_2/R_1)v$, $v_2 = -(2R_1/R_2)v_O$



Thus, $v_2 = 2v$.

$$i = \frac{v}{R_1} + \frac{v - v_2}{R_3}$$

$$= v\left(\frac{1}{R_1} - \frac{1}{R_3}\right).$$

$R_{eq} = v/i =$ $R_1R_3/(R_3 - R_1)$.

(b) $R_1 = R_3 = 10.0\ k\Omega$, $2R_1 = 20.0\ k\Omega$, $R_2 = |A|R_1 = 100\ k\Omega$.

1.45 (a) $\beta = 10^{-3}$ V/V; $T = a\beta = 100$; $A = (1/\beta) \times 1/(1 + 1/T) = 10^3/(1 + 1/100) = 990$ V/V; deviation is -1%; $v_O = Av_I = 9.9$ V; $v_d = v_o/a = 99\ \mu$V; $v_f = \beta v_o = 9.9$ mV.

(b) $\beta = 10^{-2}$ V/V; $T = 10^3$; $A = 99.9$ V/V; deviation $= -0.1\%$; $v_o = 0.999$ V; $v_d = 9.99\ \mu$V; $v_f = 9.99$ mV.

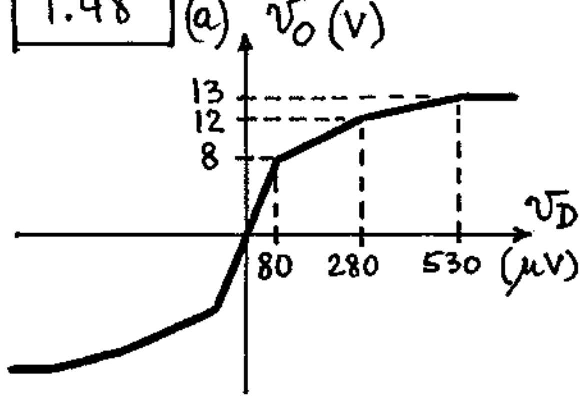
(c) $\beta = 10^{-1}$ V/V; $T = 10^4$; $A = 9.999$ V/V; deviation $= -0.01\%$; $v_o = 99.99$ mV; $v_d = 999.9$ nV, $v_f = 9.999$ mV.

(d) $\beta = 1$ V/V; $T = 10^5$; $A = 0.99999$ V/V; deviation $= -10$ ppm; $v_o = 9.9999$ mV; $v_d = 99.999$ nV; $v_f = 9.9999$ mV.

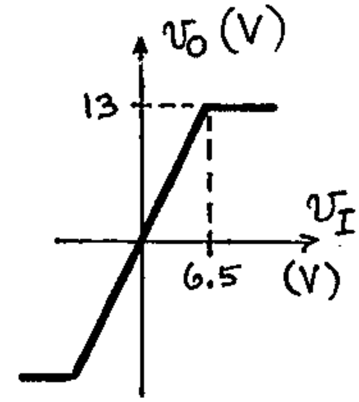
1.46 (a) $1+a\beta = a/A = 10$; $\beta = (10-1)/a = 0.009$. (b) $a = 900 \Rightarrow A = 900/(1+900\times 0.009) = 98.90$ (exactly); $\Delta A/A \cong (\Delta a/a)/(1+a\beta) = -0.1/10 = -0.01 \Rightarrow A = 10^2(1-0.01) = 99$ (appx). (c) $a = 500 \Rightarrow A = 500/(1+500\times 0.009) = 90.91$ (exactly); $\Delta A/A \cong -0.5/10 = -0.05 \Rightarrow A = 10^2(1-0.05) = 95.00$ (appx). Observations: A dramatic drop in a of 50% affects A by less than 10%; approximated calculations give results a bit more optimistic than exact calculations.

1.47 $A = 100$ V/V $\pm 0.1\%$; $a = 10^4$ V/V $\pm 25\%$. We need to desensitize the $\pm 25\%$ variation to 0.1%, or $1+a\beta = 250$. With a single stage we would have $1+a\beta = a/A = 10^4/10^2 = 100 < 250$. Try a cascade of two stages with individual gains $A_1 = A_2 = 10$ V/V. Then, $1+a\beta_1 = a/A_1 = 10^4/10 = 10^3 > 250$. $\beta_1 = \beta_2 = (10^3-1)/a = 0.0999$ V/V. Using $A = A_1 \times A_2 = A_1^2 = [a/(1+a\beta_1)]^2$, we find that as gain a varies over the range 7,500 V/V to 12,500 V/V, gain A varies over the range 99.93 V/V to 100.04 V/V, i.e. within $\pm 0.1\%$.

1.48 (a)



Open-loop VTC

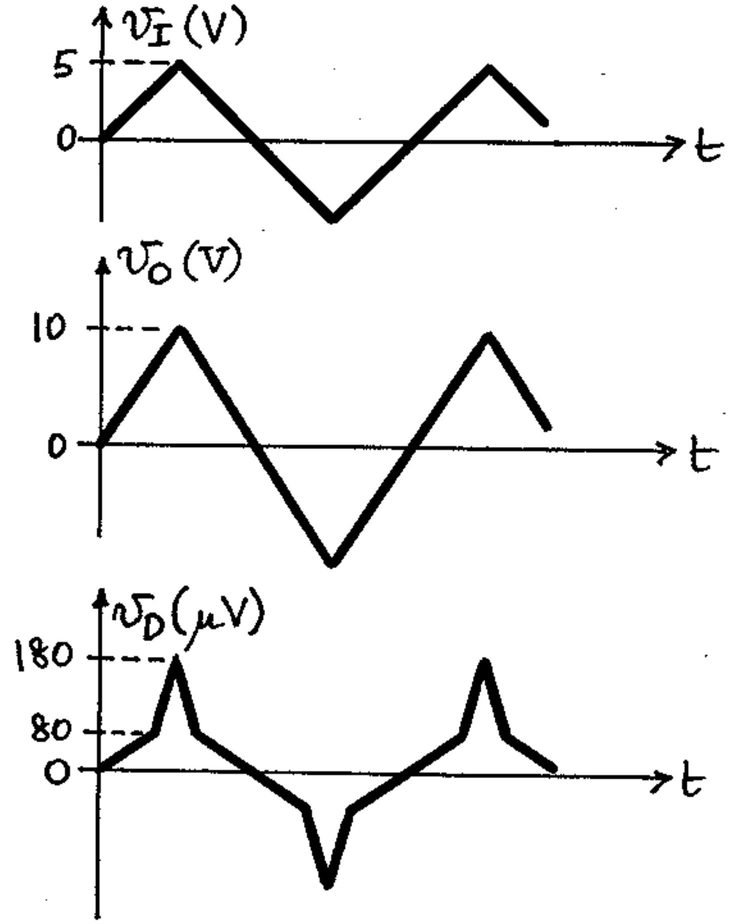


Closed-loop VTC

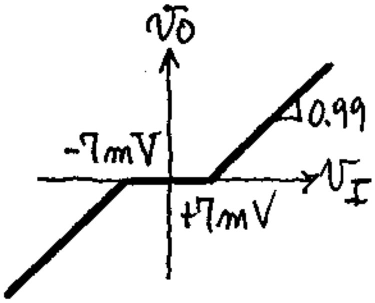
Slope of open-loop VTC is 100,000 for $|v_O| < 8\text{V}$, 20,000 for $8\text{V} < |v_O| < 12\text{V}$, and 4,000 for $12\text{V} < |v_O| < 13\text{V}$. Using $A = 2/(1+2/a)$, the corresponding slopes of the closed-loop VTC are 1.99996, 1.9998, and 1.999, respectively. These values are virtually indistinguishable from 2.

(b) Since $v_O \cong 2v_I$, v_O is essentially an undistorted $\pm 10\text{V}$ triangular wave. $v_D(t)$ is obtained from $v_O(t)$ using the open-loop VTC in reverse. We see that thanks to the high loop gain, the amplifier provides an undistorted output while reflecting the effect of nonlinear open-loop VTC back to the error input.

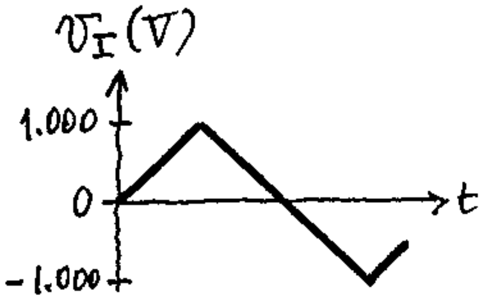
1.22

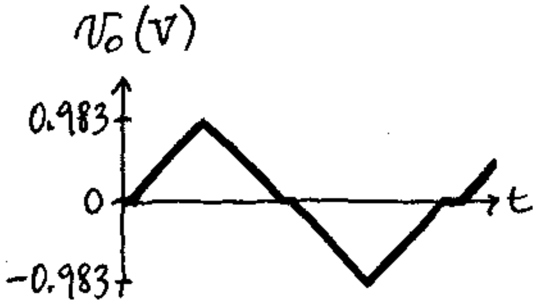


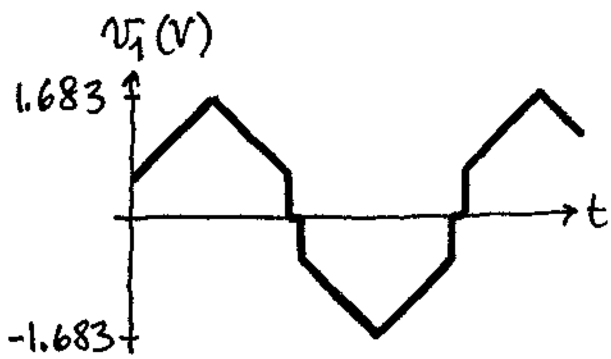
1.49 (a) The deadband is reduced by the amount of feedback, and is $(\pm 0.7\text{V})/(1+100) \cong \pm 7$ mV. The slope is $A = 100/(1+100) \cong 0.99$ V/V.



(b) The output waveform has a small crossover distortion, and peaks at $\pm(0.99 \times 1\text{ V} - 7\text{mV}) = \pm 0.983$ V. Moreover, $v_1 = v_O + 0.7\text{ V}$ for $v_O > 0$, and $v_1 = v_O - 0.7$ V for $v_O < 0$.







1.50 $a_1 = 2/(1\times10^{-3}) = 2{,}000$ V/V.

$1 + a_1\beta = a_1/A \Rightarrow 1 + 2{,}000\beta = 2{,}000/10$

$\Rightarrow \beta = 0.0995$ V/V.

1.51 (a) $A \cong \frac{a}{1+a} = \frac{10^3}{1+10^3} = 0.999$ V/V;

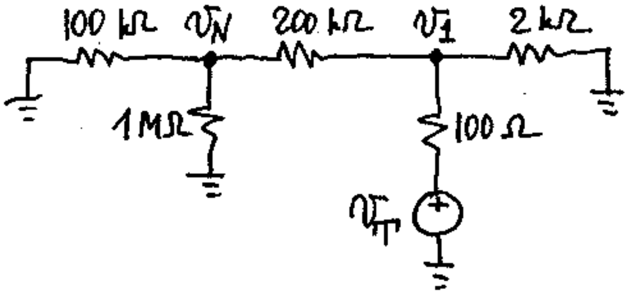
$R_i \cong r_d(1+a) \cong 1$ GΩ; $R_o \cong \frac{r_o}{1+a} = 1$ Ω.

$v_O = \frac{R_i}{R_s + R_i} A \frac{R_L}{R_o + R_L} v_I = 9.970$ V.

(b)

$v_O = 9.970 \frac{10^3}{1+10^3} = 9.960$ V.

1.52



$v_N = \frac{100 // 1000}{200 + (100 // 1000)} v_1 = \frac{1}{3.2} v_1$

$v_1 = \frac{2 \| [200 + (100 \| 1000)]}{0.1 + 2 \| [200 + (100 \| 1000)]} v_O = \frac{v_O}{1.05}$

$\beta = 1/(3.2 \times 1.05) = 0.2975$ V/V.

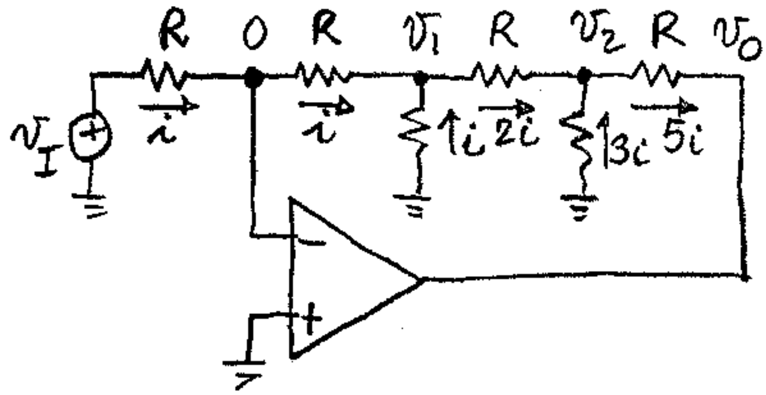
(a) $1 + a\beta \geq 100 \Rightarrow a \geq 333$ V/V

(b) $1 + a\beta \geq 10^5 \Rightarrow a \geq 336$ V/mV.

1.53 $\beta = 1 \Rightarrow a\beta = 10^6$. $A = 1/(1+10^{-6}) = 0.999999$; $R_i \cong 10^3(1+10^6) = 1$ GΩ; $R_o \cong 20 \times 10^3/(1+10^6) = 20$ mΩ. Thanks to the large loop gain, the closed-loop parameters are very close to ideal!

1.54

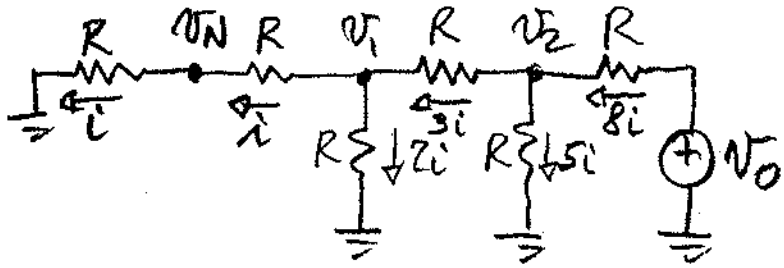
(a)



$i = v_I/R$; $v_1 = -v_I$; $v_2 = v_1 - R \times 2i = -3v_I$;

$v_O = v_2 - R \times 5i = -8v_I$; $A_{ideal} = -8$ V/V.

(b)



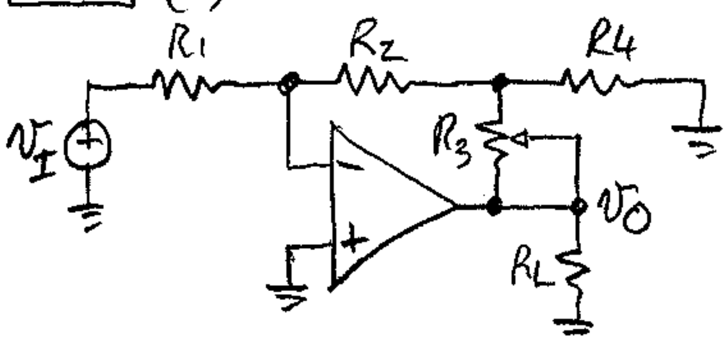
$i = v_N/R$; $v_1 = 2v_N$; $v_2 = v_1 + R \times 3i = 5v_N$;

$v_O = v_2 + R \times 8i = 13v_N$; $\beta = 1/13$ V/V;

$100/a\beta \le 0.1 \Rightarrow a \geq 100/0.1\beta = 13{,}000$ V/V.

1.55

(a)



Wiper up $\Rightarrow |A| = |A_{min}| = R_2/R_1 = 0.5$ V/V $\Rightarrow$

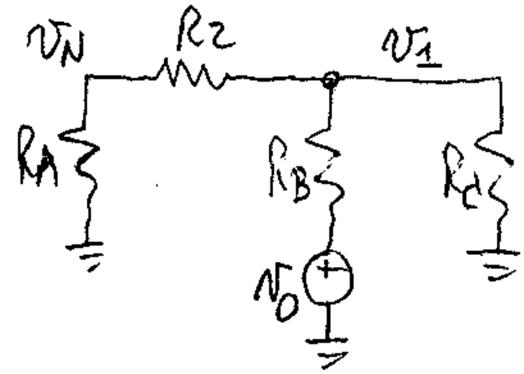
$R_1 = 500$ kΩ, $R_2 = 250$ kΩ. Wiper down $\Rightarrow$

(1.26)

$|A| = |A_{max}| = (R_2/R_1)[1 + R_3/(R_2 \| R_4)] = 10^3$ V/V.

$0.5(1 + 10^3/250 + 10^3/R_4) = 10^3$ gives $R_4 = 0.501$ kΩ.

(b) Equivalent circuit to find β:



$R_A = R_1 \| r_d = 333$ kΩ;
$R_2 = 250$ kΩ;
$R_B = R_3 + r_o = R_3 + 0.1$;
$R_C = R_L \| R_4 = 0.401$ kΩ;

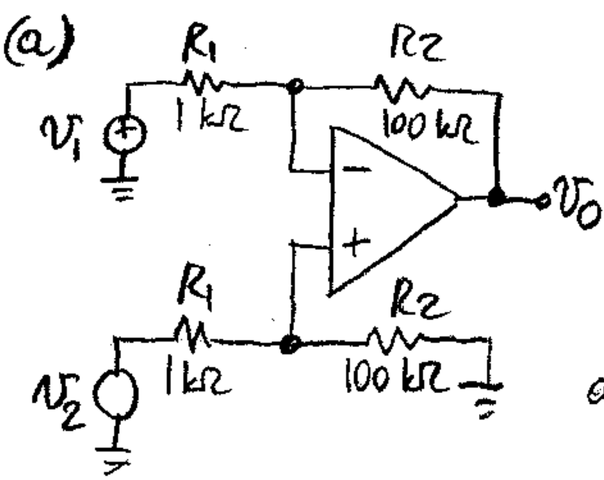
$v_N = \dfrac{R_A}{R_A + R_2} v_1 = \dfrac{v_1}{1.75}$. Since $R_A + R_2 \gg R_C$, we can write $v_1 \cong \dfrac{R_C}{R_B + R_C} v_O = \dfrac{v_O}{1 + (R_3 + 0.1)/0.401}$;

Thus, $\beta \cong \dfrac{1}{1.75\,[1 + (R_3 + 0.1)/0.401]}$

Wiper up $\Rightarrow R_3 = 0 \Rightarrow \beta = 0.4574$ V/V; $T = a\beta \cong 45{,}737$; gain departure from ideal is $-100/T = -0.002\%$.

Wiper down $\Rightarrow R_3 = 1$ MΩ $\Rightarrow \beta = 2.29 \times 10^{-4}$ V/V; $T \cong 23$; gain departure from ideal is about $-100/23 = -4.3\%$.

$\boxed{1.56}$ (a)



(b) $\beta = \dfrac{1}{101}$;

$T \geq 10^3$;

$a \geq \dfrac{10^3}{1/101} \Rightarrow$

$a \geq 10^5$ V/V.

1.57 Fig. P1.15: suppressing the 4-V source gives $v_D = v_P - v_N = (3/5-1)v_O = -(2/5)v_O$; $\beta = -v_D/v_O = 2/5 = 0.4$ V/V.

Fig. P1.16: Suppressing the source gives $v_P = 0$ and $v_N = v_O$, so $\beta = 1$ V/V.

Fig. P1.17: Suppressing the source gives $v_D = (1/5 - 5/7)v_O = -(18/35)v_O$, so $\beta = 18/35$ V/V.

Fig. P1.18: suppressing the source gives $v_D = (2/5)v_O - v_O = -(3/5)v_O \Rightarrow \beta = 0.6$ V/V.

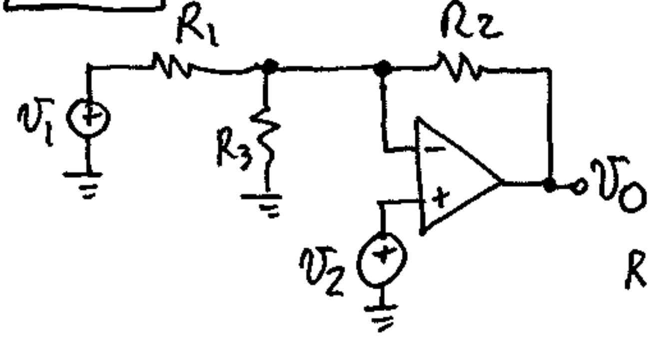
Fig. P1.19: Suppressing the source gives $v_D = v_P - v_N = \frac{1}{1+2+3+4}v_O - \frac{1+2+3}{1+2+3+4}v_O = -0.5v_O \Rightarrow \beta = 0.5$ V/V.

1.58 Suppressing the sources gives

$$\beta = \frac{v_N}{v_O} = \frac{10\|30}{(10\|30)+100} = \frac{3}{34} \text{ V/V.}$$

$1 + a\beta \geq 100 \Rightarrow a \geq 1122$ V/V.

1.59



$v_O = 100(3v_2 - 2v_1) = 300v_2 - 200v_1$. $R_2/R_1 = 200 \Rightarrow R_1 = 1\text{k}\Omega,\ R_2 = 200\text{k}\Omega$.

1.28

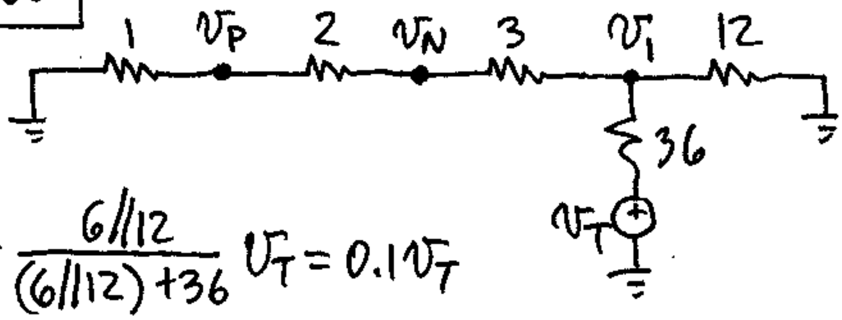
$1 + R_2/(R_1 \| R_3) = 1 + R_2/R_1 + R_2/R_3 = 300 \Rightarrow$

$1 + 200 + 200\,\text{k}\Omega/R_3 = 300 \Rightarrow R_3 = 2.02\ \text{k}\Omega.$

$\beta = (R_1 \| R_3)/[(R_1 \| R_3) + R_2] = 1/300.$ We want

$T = a\beta \geq 1000 \Rightarrow a \geq 10^3 \times 300 = 300\ \text{V/mV}.$

1.60



$v_1 = \dfrac{6 \| 12}{(6 \| 12) + 36} v_T = 0.1 v_T$

$v_N = \frac{1}{2} v_1 = \frac{1}{20} v_T \Rightarrow \beta_N = 1/20$

$v_P = \frac{1}{3} v_N = \frac{1}{60} v_T \Rightarrow \beta_P = 1/60$

$\beta = \beta_N - \beta_P = 1/30;\ T = a\beta = \frac{3000}{30} = 100.$

1.61 (a) Turn the current source into an open circuit; then, $\beta_P = 0$, $\beta_N = 1$, $\beta = 1$.

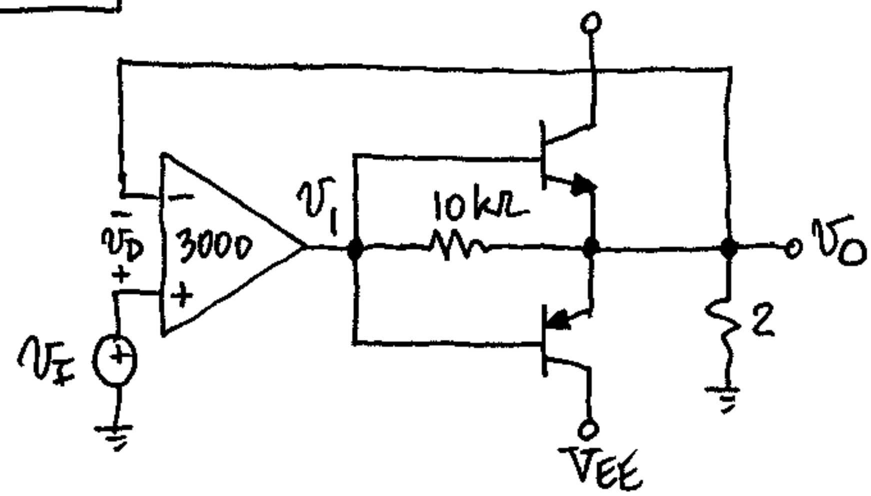
(b) Turn the voltage source into a short circuit; then, $v_P = \dfrac{1}{1+2+3} v_N \Rightarrow$ $\beta_P = \frac{1}{6}\beta_N$; $\beta_N = \dfrac{6}{6+4} = 0.6$; $\beta = 0.6 - \frac{1}{6}0.6 = 0.5.$

1.62 (a) Turning i_S into an open circuit gives $v_P = \dfrac{1}{1+2+3} v_N \Rightarrow \beta_P = \frac{1}{6}\beta_N$; $\beta_N = \dfrac{6}{6+4} =$ 0.6; $\beta = 0.6 - 0.6/6 = 0.5.$

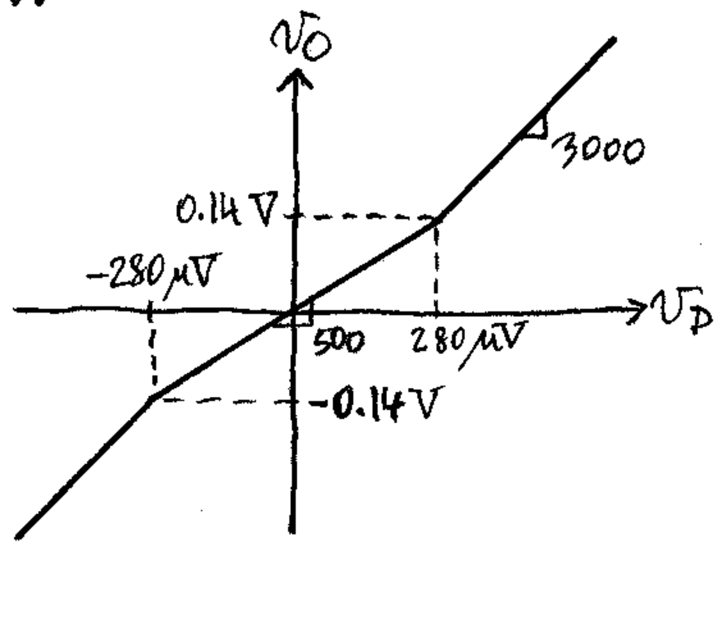
(b) Turning v_S into a short circuit gives $\beta_P = 0$; $\beta_N = 3/(3+4) = 3/7 = \beta.$

1.29

1.63

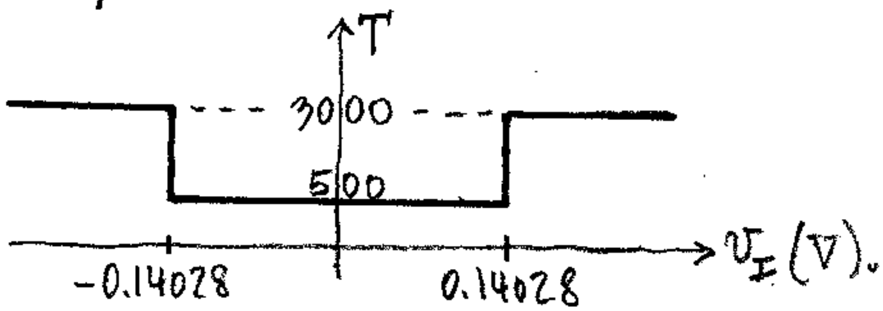


(a) Both BJTs are off for $|v_O| \leq 2 \times \frac{0.7}{10} = 0.14V$. Over this range we have $v_O = \frac{2}{10+2} 3000 v_D = 500 v_D$, indicating that the open-loop VTC will have a slope of 500 V/V over the range $|v_D| \leq \frac{0.14}{500} = 280 \mu V$. For $|v_D| \geq 280\ \mu V$, one of the BJTs conducts, and the slope of the open-loop VTC becomes 3000 V/V.

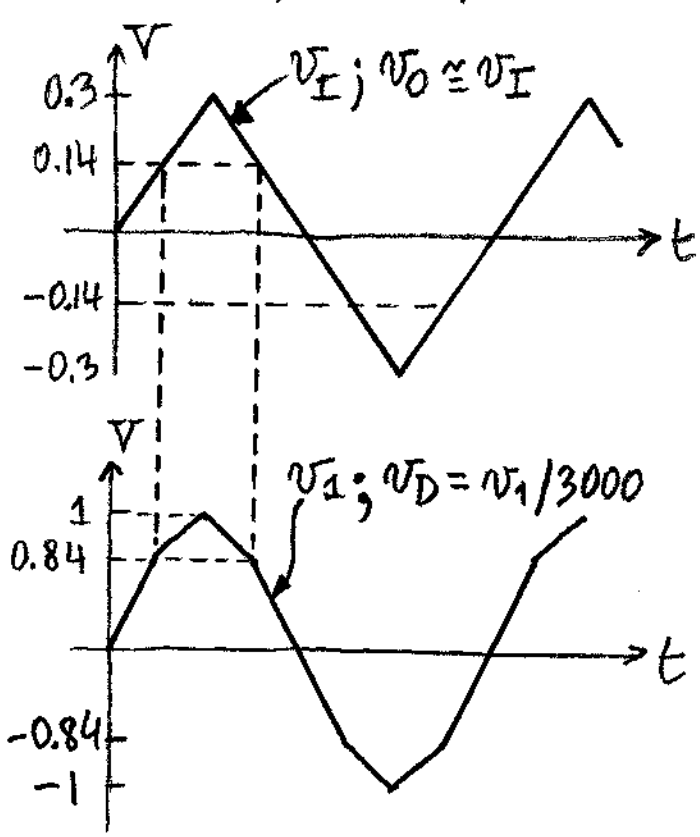


(1.30)

(b) Since $\beta = 1$, we have $T = 500$ for $|v_O| \le 0.14$ V, and $T = 3000$ for $|v_O| \ge 0.14$ V. Thus, the closed-loop gain is $A = \frac{1}{1+1/500} = 0.998$ V/V for $|v_I| \le 0.14/0.0998 = 0.14028$ V, and $A = \frac{1}{1+1/3000} = 0.999\overline{6}$ V/V for $|v_I| \ge 0.14028$ V.



(c) Due to the closeness of A to unity, we have $v_O \cong v_I$. Moreover, $v_1 = (1+10/2)v_O = 6v_O$ for $|v_O| \le 0.14$ V, and $v_1 = v_O + 0.7$ V for $|v_O| \ge 0.14$ V; $v_D = v_1/3000$ throughout.



1.64 (a) $v_O = -2(-5) = 10\text{ V}$; $i_L = 5\text{ mA}$; $i_{R_2} = i_{R_1} = 0.5\text{ mA}$; $i_O = 5.5\text{ mA}$; $i_{CC} = 0.5 + 5.5 = 6\text{ mA}$; $i_{EE} = 0.5\text{ mA}$

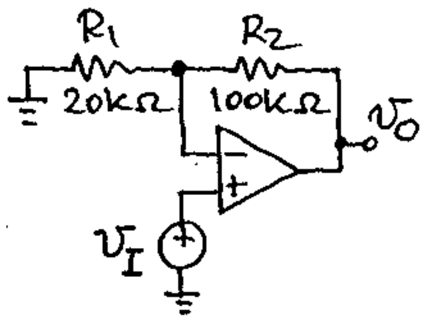
(b) $P_{OA} = 30 \times 0.5 + (15-10)5.5 = 42.5\text{ mW}.$

1.65 $v_N = v_P = -1\text{ V}$; $v_O = -\frac{30}{10}v_I + \left(1+\frac{30}{10}\right)(-1) = -3v_I - 4\text{ V}.$

(a) $v_I = +2\text{V} \Rightarrow v_O = -10\text{ V}$, $i_{10\text{k}\Omega} = i_{30\text{k}\Omega} = 0.3\text{ mA}\ (\rightarrow)$, $i_{2\text{k}\Omega} = 5\text{ mA}\ (\uparrow)$, $i_O = 5.3\text{ mA}\ (\leftarrow)$, $P_{OA} = 30 \times 1.5 + [-10-(-15)] \times 5.3 = 71.5\text{ mW}.$

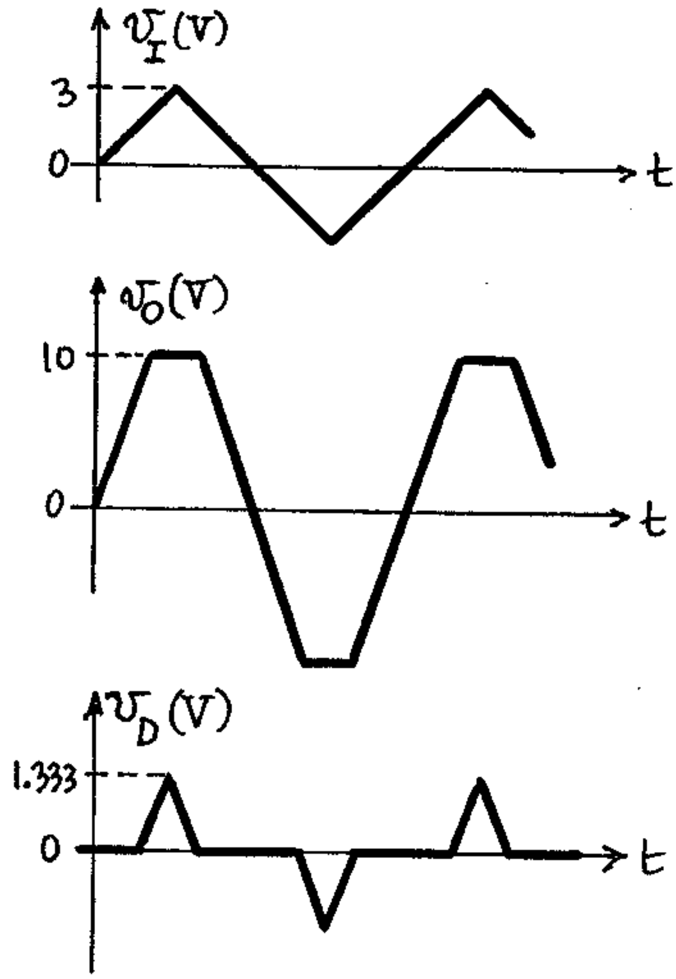
(b) $v_I = -2\text{V} \Rightarrow v_O = +2\text{V}$, $i_{10\text{k}\Omega} = i_{30\text{k}\Omega} = 0.1\text{ mA}\ (\leftarrow)$, $i_{2\text{k}\Omega} = 1\text{ mA}\ (\downarrow)$, $i_O = 1.1\text{ mA}\ (\rightarrow)$, $P_{OA} = 45 + (15-2)1.1 = 59.3\text{ mW}.$

1.66 $\pm V_{sat} \cong \pm 10\text{ V}$; v_O will clip for $|v_I| \geq 10/6 = 1.667\text{ V}.$ During this time, $|v_P| > |v_N|$, that is, $v_D \neq 0$. By KVL, $v_{D(max)} = 3 - 1.667 = 1.333\text{ V}.$

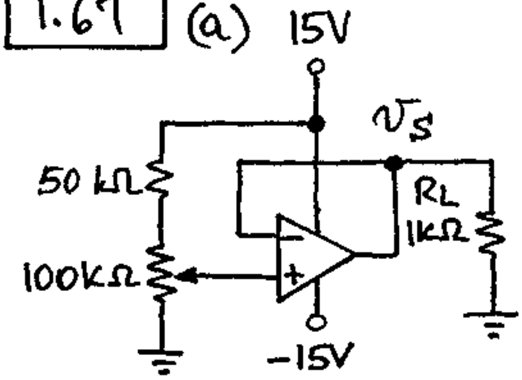


The waveforms are shown next:

1.32



1.67 (a)



(b) $P_{OA} = 30 \times 1.5 + (15 - v_S)\frac{v_S}{R_L}$

$= 45 + 15v_S - v_S^2$ mW.

$dP_{OA}/dv_S = 15 - 2v_S$

$dP_{OA}/dv_S = 0$ for

$v_S = 7.5$ V; $P_{OA(max)} = 45 + (15 - 7.5)7.5 = 101.25$ mW.

1.68 Within the linear region we have $v_O = 5V - 10v_I$, and $v_N \cong v_P = 0$.

(a) v_O is within the linear region, so $v_I = 0$ and $v_N \cong 0$.

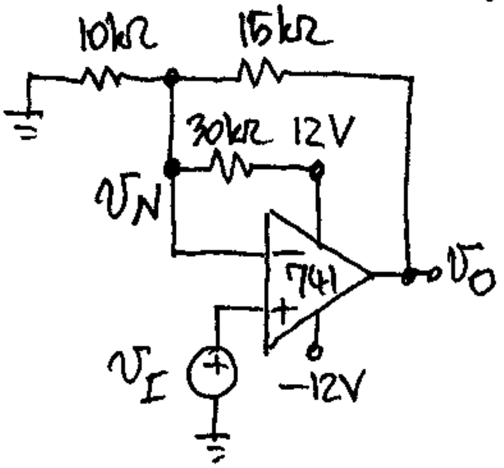
(1.33)

$v_I = (7.5-5)(-10) = -0.25$ V. For $v_O < 0$, i_O flows into the op amp, and P_{OA} is maximized for $v_O = -7.5$V, which is achieved when $v_I = (-7.5-5)/(-10) = 1.25$ V; $P_{OA} = 2.625$ mW.

(b) With $v_I = 3$V the opamp would try to give $v_O = 5 - 30 = -25$ V $\Rightarrow v_O = -V_{sat} = -13$V. Find v_N via KCL as

$$\frac{3 - v_N}{10} = \frac{v_N - (-15)}{300} + \frac{v_N - (-13)}{100} \Rightarrow v_N = \frac{18}{17}\text{ V.}$$

1.69



$$v_O = \left(1 + \frac{15}{10 \| 30}\right) v_I - \frac{15}{30} 12$$

$$= 3v_I - 6\text{V}.$$

$\pm V_{sat} \cong \pm 10$ V

(a) Try $v_O = 3 \times 4 - 6 = 6$V. Since v_O is within the linear region, we get $v_N = v_I = 4$V.

(b) Now $v_O = 3(-2) - 6 = -12$V $\Rightarrow$ Saturation $\Rightarrow v_O = -10$V. By KCL @ v_N

$$\frac{12 - v_N}{30} = \frac{v_N}{10} + \frac{v_N - (-10)}{15} \Rightarrow v_N = -\frac{4}{3}\text{ V.}$$

1.70 (a) $v_O = -10v_I + 5$ V. The output drives a 100-kΩ load to ground, and a 100-kΩ feedback resistor to virtual ground, so $i_O = \frac{v_O}{100\,k\Omega} + \frac{v_O}{100\,k\Omega} = \frac{v_O}{50\,k\Omega}$. For $v_O > 0$, i_O flows out of the op amp, so $P_{OA} = 30 \times 0.05 + (15 - v_O)v_O/50$. This is maximized for $v_O =$ 7.5V, at which point $P_{OA} = 2.625$ mW, and $v_I = (7.5-5)(-10) = -0.25$ V. For $v_O < 0$, i_O flows into the op amp, and P_{OA} is maximized when $v_O = -7.5$V, or $v_I = (-7.5-5)/(-10) =$ 1.25V. Then, $P_{OA} = 2.625$ mW.

(b) Imposing $-13\text{ V} \le (-10v_I + 5\text{V}) \le +13$ V gives $-0.8\text{ V} \le v_I \le +1.8\text{ V}$.

$\boxed{1.71}$ $v_O = -\frac{120}{30}v_1 + \left(1 + \frac{120}{30}\right)\frac{30}{20+30}v_2 = 3v_2 - 4v_1$.

(a) $v_O = 6 \sin \omega t - 4v_1$. $|v_1|_{max} = \frac{13-6}{4}$ = 1.75V, so the allowed range is $-1.75\text{ V} \le v_1$ +1.75V.

(b) $v_O = -3 - 4V_m \sin \omega t$.

$$\left.\begin{array}{l} -13 = -3 - 4V_m \Rightarrow V_m = 2.5\text{ V} \\ +13 = -3 - 4(-V_m) \Rightarrow V_m = 4\text{ V} \end{array}\right\} \Rightarrow V_m \le 2.5\text{V}.$$

(c) We now have $\pm V_{sat} \cong \pm 9$ V, so we get for (a) $-0.75\text{ V} \le v_1 \le +0.75$V, and for (b) $V_m \le 1.5$ V.

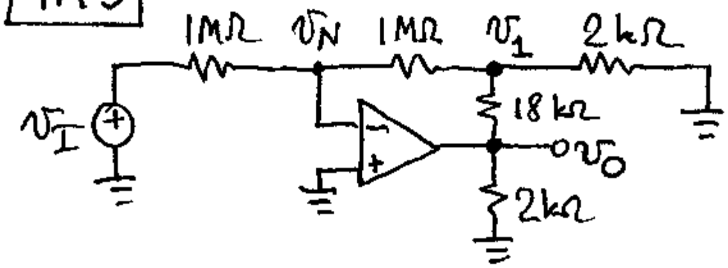
$\boxed{1.72}$ Fig. P1.17: $v_O = (-20/50)v_S + (1 + 20/50) \times [10/(10+40)]v_O \Rightarrow v_O = (-5/9)v_S$

$|v_O| \le 10\text{V} \Rightarrow |v_S| \le 18$ V.

(1.35)

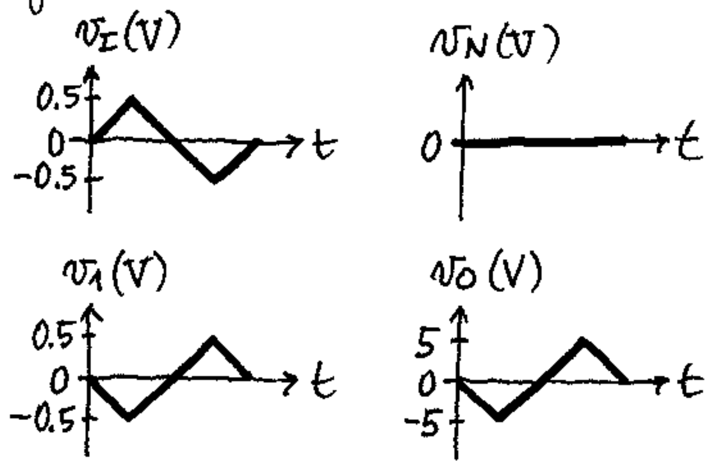
Fig. P1.19: $i_{2k\Omega} = [3/(2+3)]i_S = 0.6 i_S$; $i_{3k\Omega} = 0.4 i_S$; $v_P = 1 \times i_{2k\Omega} = 0.6 i_S$; $v_O = v_N - 4 i_{3k\Omega} = 0.6 i_S - 4 \times 0.4 i_S = (-1\ k\Omega) i_S$. $|v_O| \le 10\ V \Rightarrow |i_S| \le 10\ mA$.

1.73



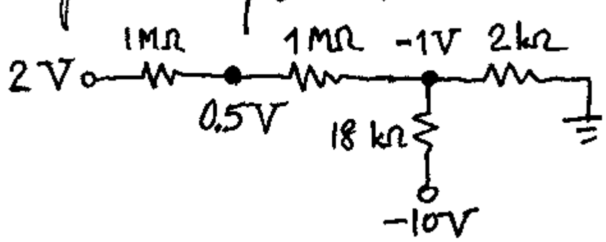
Ideally, $v_N = 0$, $v_1 = -v_I$, $v_O = [1 + 8/(1000 \| 2)] v_1 = 10.018 v_1 \cong -10 v_I$.

(a) $V_{im} = 0.5V \Rightarrow V_{om} = 10 \times 0.5 = 5V \Rightarrow$ linear region.

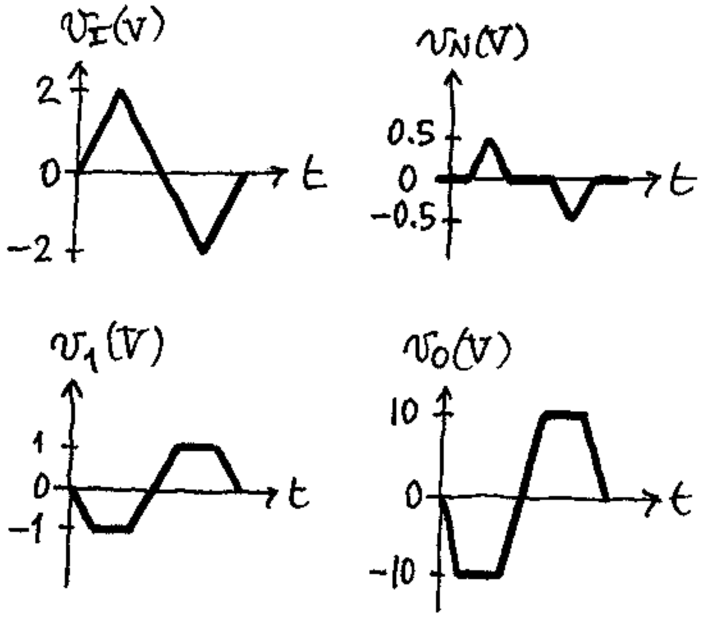


(b) $V_{im} = 2V \Rightarrow V_{om} = 10 \times 2 = 20V \Rightarrow$ saturation

Shown below is the situation when v_I reaches its positive peak:



1.36

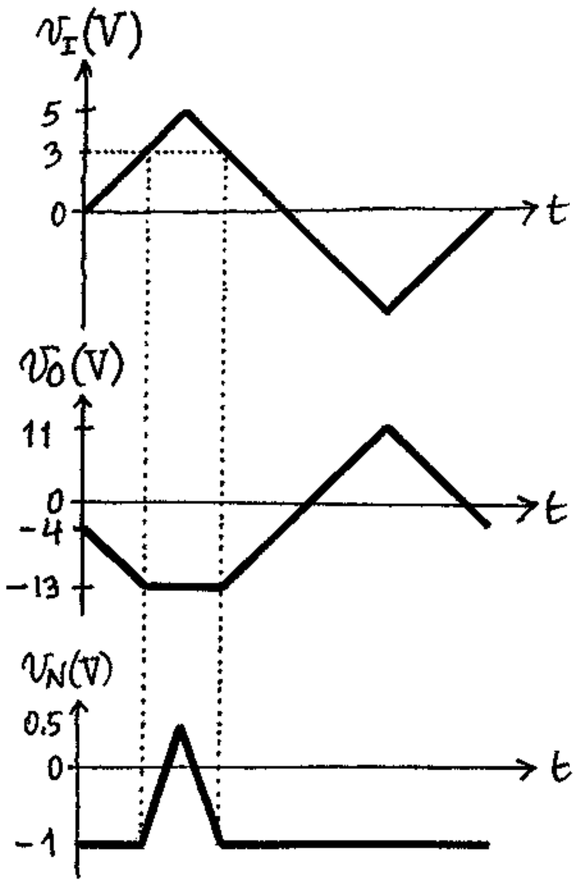


1.74

(a) $v_O = v_{O1} - v_{O2} = [1 + (A-1)R/R]v_I - [-(AR/R)v_I] = 2Av_I$.

(b) $-13V \le v_{O1} \le 13V$; $-13V \le v_{O2} \le 13V$; $-26V \le v_O \le 26V$, $v_{O(max)} = 52\ V_{pk\text{-}pk}$.

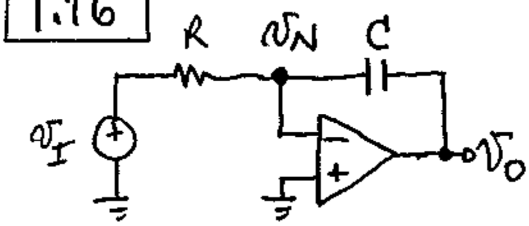
1.75



(1.37)

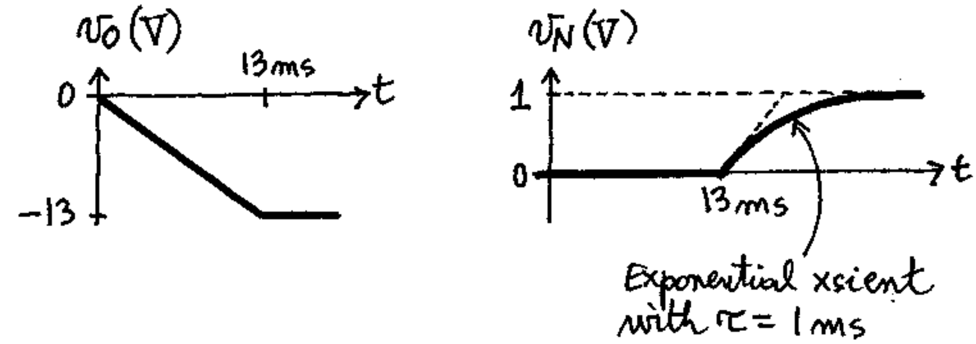
$v_P = -1\text{V}$. When in the linear region, the op amp gives $v_N = -1\text{V}$ and $v_O = -3v_I - 4\text{V}$.
$v_I = -5\text{V} \Rightarrow v_O = 11\text{ V} \Rightarrow$ linear region.
$v_I = +5\text{V} \Rightarrow v_O = -19\text{V} \Rightarrow$ saturation. The op amp saturates for $v_I \geq (-13+4)/(-3) = 3\text{V}$.
$v_N(\text{peak}) = [30\times5 + 10(-13)]/(10+30) = 0.5\text{V}$.

1.76



In the linear region,
$v_O = -10^3 t$

(a)



(b) Same as above, except that the ramp now lasts 13 s, and the asymptotic value of v_N is 1 mV.

(c) Same as in (b), except that the voltages now have opposite polarities (v_O saturates at +13 V, and v_N tends to −1 mV).