CH. 1 – PROBLEM SOLUTIONS (UPDATED NOVEMBER 12, 2013)

1.1 [V, kΩ, mA]. By the superposition principle,

$$v_{OC} = \frac{R_2}{R_1+R_2} v_S - R_3 i_S = \frac{3}{2+3} v_S - 1 i_S = 0.6 v_S - i_S.$$

By inspection, $R_{eq} = (R_1 /\!/ R_2) + R_3 = (2/\!/3) + 1 = 2.2\ \text{k}\Omega$.

(a) $v_{OC} = 0.6 \times 25 - 4 = 11\ \text{V} > 0 \Rightarrow$ Diode is on with $v = 0$ and $i = 11/2.2 = 5\ \text{mA}$

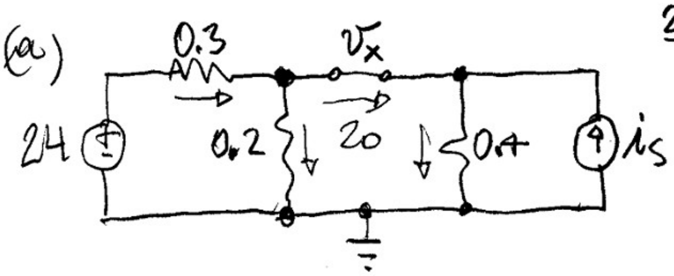
(b) $v_{OC} = 0.6 \times 10 - 10 = -4\ \text{V} \Rightarrow$ Diode is off; $i = 0$, $v = -4\ \text{V}$.

(c) $v_{OC} = 0 \Rightarrow$ Diode is off; $i = 0$, $v = 0$

(d) No difference in (a) and (c), as $v = 0$ in both cases. In (b) the diode voltage changes from $v = -4\ \text{V}$ to $v = \frac{1.8}{2.2+1.8}(-4) = -1.8\ \text{V} < 0 \Rightarrow i = 0$ still.

1.2 [V, mA, kΩ].

(a)

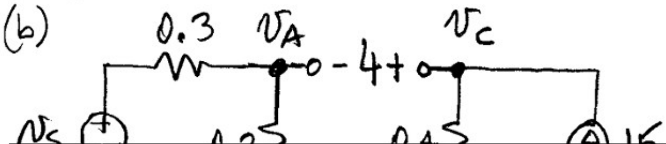


$$\frac{24-v_x}{0.3}=\frac{v_x}{0.2}+20 \Rightarrow v_x=7.2\,V;$$

$$20+i_s=\frac{7.2}{0.4} \Rightarrow i_s=-2\,mA,$$

or $i_s = 2\,mA\ (\downarrow)$.

(b)

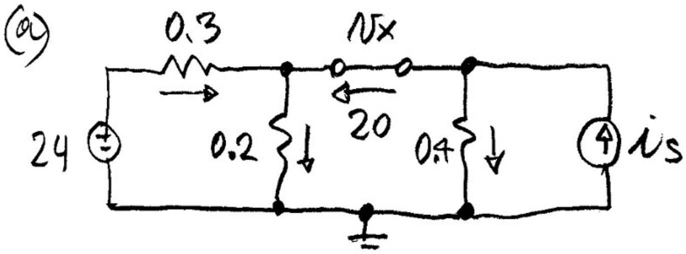


$v_C = 0.4\times15 = 6\,V;$

$v_A = v_C - 4 = 6-4 = 2\,V;$

1.3 [V, mA, kΩ].

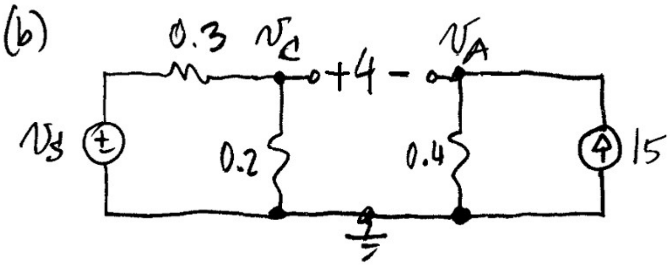
(a)



$$\frac{24-v_x}{0.3}+20=\frac{v_x}{0.2} \Rightarrow v_x=12\,V;$$

$$i_s = 20+\frac{12}{0.4}=50\,mA.$$

(b)



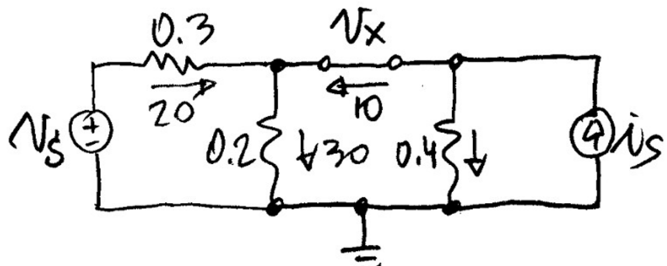
$v_A = 0.4\times15 = 6\,V;$

$v_C = v_A + 4 = 10\,V;$

$$10=\frac{0.2}{0.3+0.2}v_s \Rightarrow v_s=25\,V.$$

(c) $v_A = 10\times0.4 = 4\,V = v_C = \dfrac{0.2}{0.3+0.2}v_s \Rightarrow v_s = 10\,V.$

(d) Solution is not unique, depending on the choice of the directions for i_{300} and i_{200}. One possibility:



$v_x = 0.2\times30 = 6\,V;$

$$\frac{v_s-v_x}{0.3}=20 \Rightarrow v_s=12\,V$$

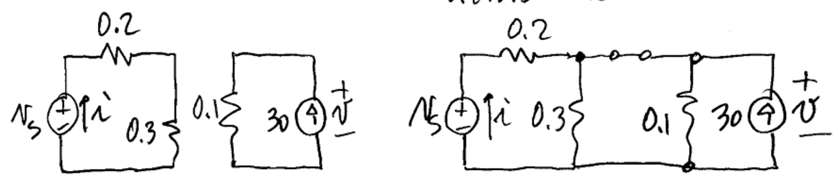
$$i_s = 10+\frac{v_x}{0.4}=10+\frac{6}{0.4}=25\,V.$$

If i_{300} is assumed to flow to the left, then we need $v_s = 0$ and $i_s = 65\,mA$.

1.4 [V, mA, kΩ]. (a) The open-circuit voltage seen by the diode is

$$v_{OC}=\frac{R_2}{R_1+R_2}v_S-R_3 i_S=\frac{0.3}{0.2+0.3}v_S-0.1\times 30=0.6v_S-3\text{ V}.$$

$v_S<5\text{V}\Rightarrow \text{diode}=\text{off}\Rightarrow i=\dfrac{v_S}{0.2+0.3}=\dfrac{v_S}{0.5\text{ k}\Omega}=2v_S;\ v=3\text{V}.$

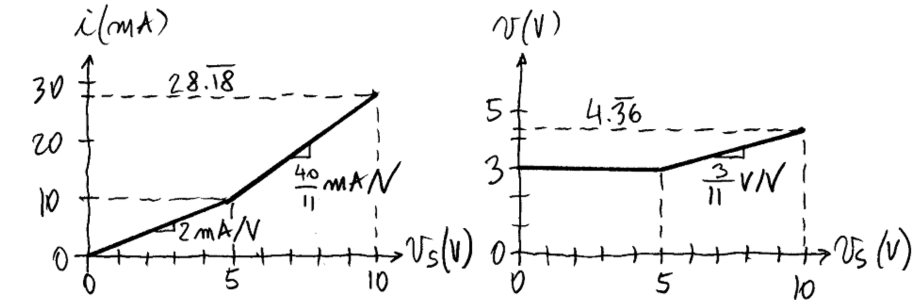


$v_S<5\text{V}$ $\qquad\qquad$ $v_S>5\text{V}$

$v_S>5\text{V}\Rightarrow \text{diode}=\text{on}\Rightarrow i=\dfrac{v_S}{0.2+(0.3/\!/0.1)}-\dfrac{v}{0.2};$

$$v=\frac{0.3/\!/0.1}{0.2+(0.3/\!/0.1)}v_S+(0.2/\!/0.3/\!/0.1)30=\frac{3v_S+18}{11}\text{ V}.$$

Substituting, $i=\dfrac{40v_S-90}{11}$ V.

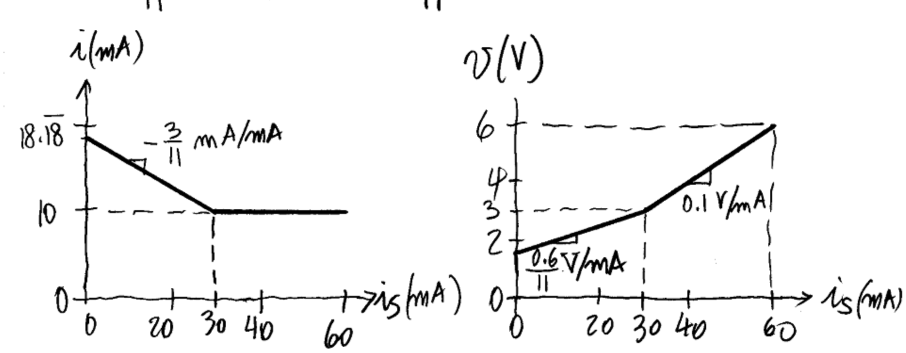


(b) $v_{OC}=0.6\times 5-0.1i_S=3-0.1i_S.$

$i_S>30\text{mA}\Rightarrow\text{diode}=\text{off}\Rightarrow i=\dfrac{5}{0.2+0.3}=10\text{mA},\ v=0.1i_S.$

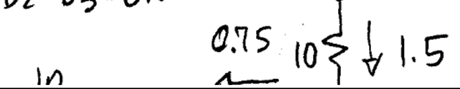
$i_S<30\text{mA}\Rightarrow\text{diode}=\text{on}\Rightarrow$

$v=\dfrac{15+0.6i_S}{11},\ i=\dfrac{200-3i_S}{11}.$

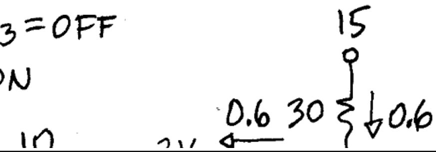


1.5 [V, kΩ, mA]. By the superposition principle, D_1's anode sees $v_{OC} = \frac{15}{30+15}15 + \frac{30}{30+15}(-15) = -5\text{V}$ and $R_{eq} = 15 // 30 = 10\ \text{k}\Omega$. Redraw the circuit in simplified form:

(a) $D_1 = \text{OFF}$
$D_2 = D_3 = \text{ON}$

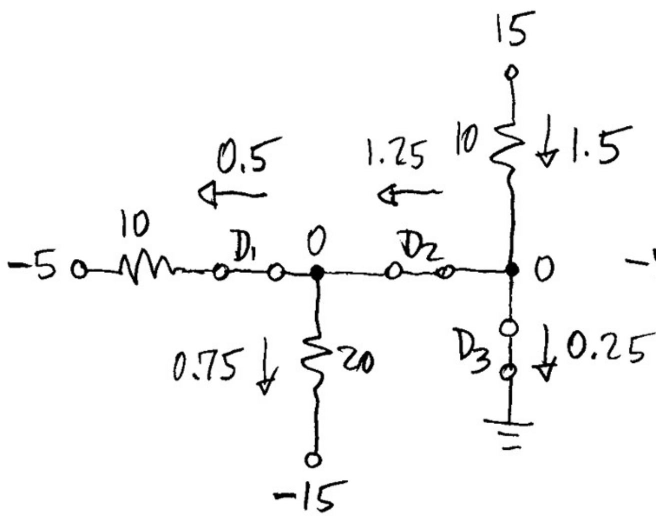


(b) $D_1 = D_3 = \text{OFF}$
$D_2 = \text{ON}$



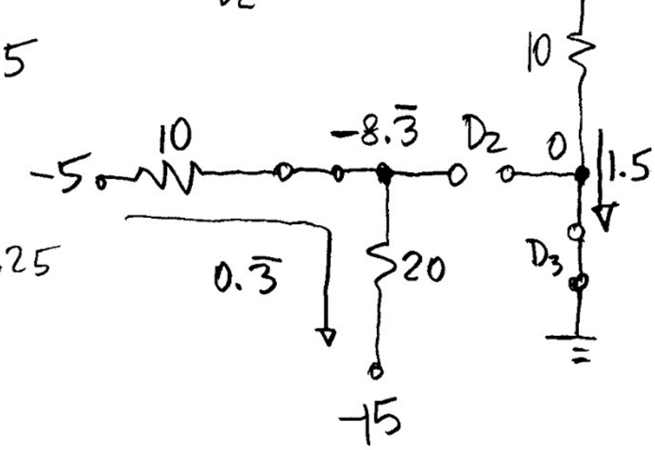
1.6 [V, mA, kΩ]. The network seen by D_1's anode admits a Thévenin equivalent with $R_{eq} = 30 // 15 = 10\ \text{k}\Omega$ and $v_{OC} = 15 \times [15/(30+15)] - 15 \times [30/(30+15)] = -5\text{V}$.

(a) $D_1 = D_2 = D_3 = \text{ON}$



(b) $D_1 = D_3 = \text{ON}$, $D_2 = \text{OFF}$

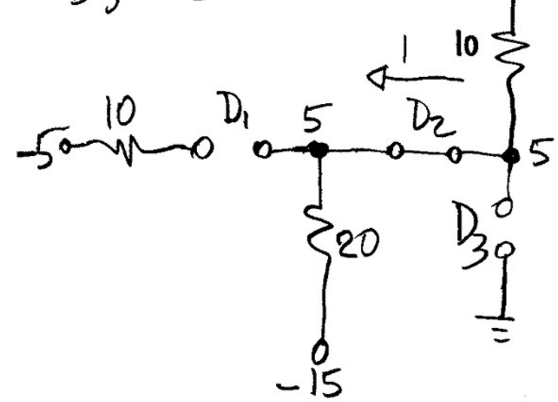
$v_{D_2} = -8.\overline{3}\ \text{V}$.



(c) $D_2 = \text{ON}$, $D_1 = D_3 = \text{OFF}$

$v_{D_1} = -10\text{V}$

$v_{D_3} = -5\text{V}$

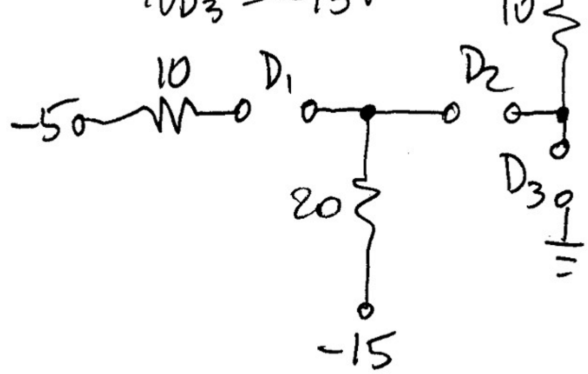


(d) $D_1 = D_2 = D_3 = \text{OFF}$

$v_{D_1} = -10\ \text{V}$

$v_{D_2} = -30\text{V}$

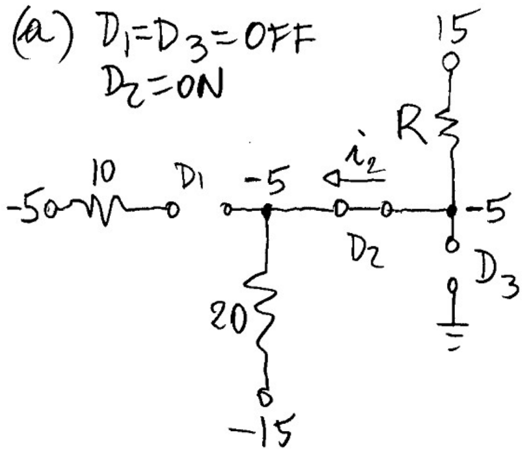
$v_{D_3} = -15\text{V}$



1.7

[V, mA, kΩ]. D_1's anode sees a Thévenin equivalent consisting of $R_{eq} = 30 // 15 = 10\,k\Omega$ and $v_{OC} = 15\left[\frac{15-30}{30+15}\right] = -5\,V$.

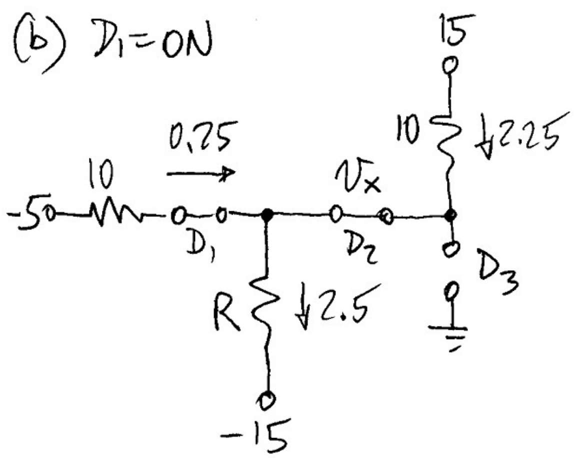
(a) $D_1 = D_3 = OFF$
$D_2 = ON$



$$i_2 = \frac{-5-(-15)}{20} = 0.5\,mA;$$

$$R = \frac{15-(-5)}{0.5} = 40\,k\Omega$$

(b) $D_1 = ON$



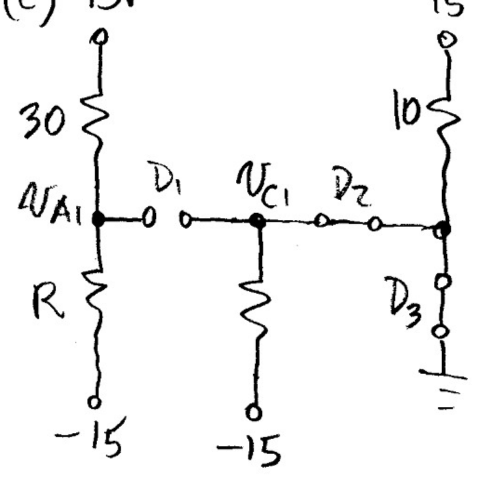
$$\frac{-5-v_X}{10} = 0.25 \Rightarrow v_X = -7.5\,V;$$

$\Rightarrow D_2 = ON \Rightarrow D_3 = OFF;$

$$0.25 + \frac{15-v_X}{10} = \frac{v_X-(-15)}{R}$$

$\Rightarrow R = 3\,k\Omega.$

(c)



$i_{D1} = 0 \Rightarrow D_2 = D_3 = ON,\ D_1 = OFF$

$\Rightarrow v_{C1} = 0\,V$

$v_{D1} = 0 \Rightarrow v_{A1} = 0.$

$i_{D1} = 0 \Rightarrow i_{30} = i_R \Rightarrow$

$$\frac{15-0}{30} = \frac{0-(-15)}{R} \Rightarrow R = 30\,k\Omega.$$

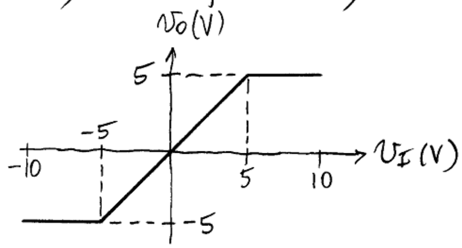
1.8 (a) For $v_I = 0$ all diodes are on, so $v_O = v_I = 0$. Ditto for $v_I = \pm 3$ V, when we also have $v_O = \pm 3$ V. For $v_I = 6$V, D_1 and D_4 are off, D_2 and D_3 are on. So, $v_O = [10/(10+10)]10 = 5$ V. By symmetry, when $v_I = -6$ V, $v_O = -5$V.

(b) With $R_3 = 30$ kΩ, v_I would have to exceed $\pm \frac{30}{10+30} 10 = \pm 7.5$ V for any diode to go off. Consequently all diodes are on, and $v_O = 0, \pm 3$V, ± 6V.

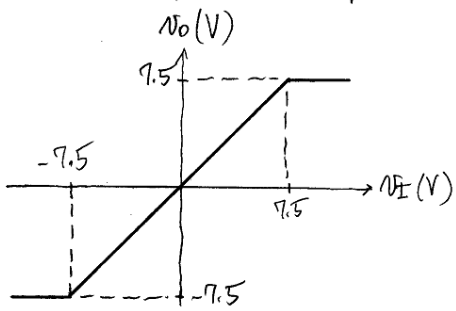
(c) With $R_1 = 30$ kΩ, it takes $v_I > \frac{10}{30+10} 10 = 2.5$V to turn D_1 off. Consequently, $v_I = 0, +3, +6$ V yields $v_O = 0, +2.5, +2.5$ V. For $v_I \le 0$, the situation remains as in (a), so $v_I = 0, -3, -6$ V gives $v_O = 0, -3, -5$ V.

(d) $D_3 = D_4 =$ OFF. For $v_I \ge 0$, the situation is as in (a), so $v_I = 0, +3, +6$V gives $v_O = 0, +3, +5$V. For $v_I \le 0$, $D_2 =$ OFF and $v_O = 0$ regardless of v_I. So, $v_I = 0, -3, -6$ V gives $v_O = 0, 0, 0$ V.

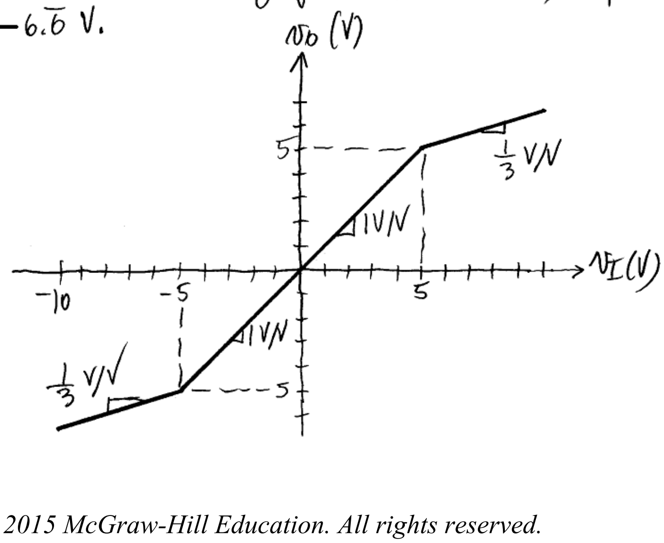
1.9 (a) For $v_I = 0$ V, all diodes are on, in effect shorting v_O to v_I to give $v_O = v_I$. If we raise v_I above 0 V, the diodes will continue to remain on till v_I reaches $\frac{R_3}{R_1+R_3}10 = \frac{10}{10+10}10 = 5$ V. Raising v_I above 5 V will cause D_1 and D_4 to go off, thus giving $v_O = 5$ V. By symmetry, lowering v_I below -5 V will cause D_2 and D_3 to go off, thus giving $v_O = -5$ V. In summary, $v_O = v_I$ for $|v_I| < 5$ V, $v_O = +5$ V for $v_I > 5$ V, $v_O = -5$ V for $v_I < -5$ V.



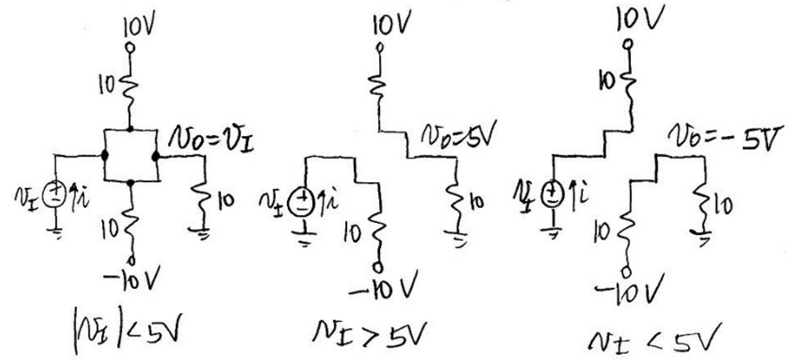
(b) Now the breakpoints occur for $v_I = \pm \frac{30}{10+30}10 = \pm 7.5$ V.



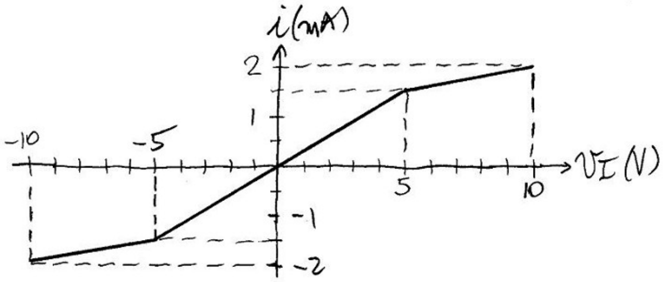
(c) No change for $|v_I| < 5$. For $v_I > 5$ V, D_1 and D_4 go off, D_3 and D_2 are on, and $(v_I - v_O)/10 + (10 - v_O)/10 = v_O/10$, or $v_O = (v_I + 10)/3$. Slope is now (1/3) V/V, and v_O peaks at $v_O = 20/3 = 6.\bar{6}$ V. By symmetry, for $v_I < 0$, v_O peaks at $-6.\bar{6}$ V.



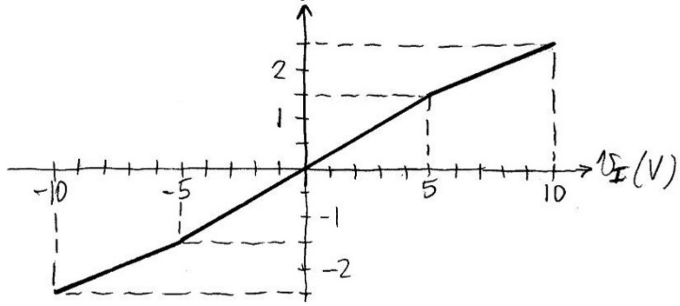
1.10 (a) Shown below are three significant cases:



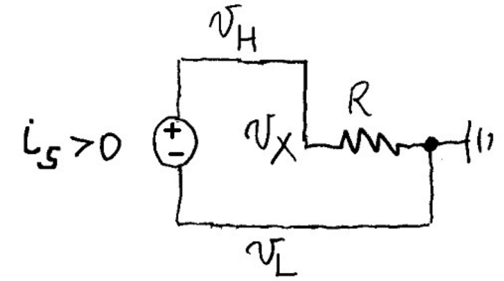
For $|v_I| < 5V$ all diodes are on. Applying KCL to the diode supernode gives $i + \frac{10 - v_I}{10} = \frac{v_I}{10} + \frac{v_I - (-10)}{10}$, or $i = 0.3 v_I$.
At the extremes, $i = 0.3(\pm 5) = \pm 1.5$ mA.
For $v_I > 5V$, D_1 and D_4 go off, and $i = \frac{v_I - (-10)}{10} = 0.1 v_I + 1$.
At the extreme, $i = 0.1(10) + 1 = 2$ mA.
For $v_I < 5V$, D_2 and D_3 go off, and $i = -\frac{10 - v_I}{10} = 0.1 v_I - 1$.
At the extreme, $i = 0.1(-10) - 1 = -2$ mA.



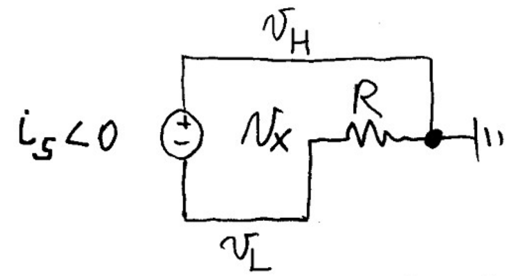
(b) As long as $|v_I| < 5V$, R_4 has no effect as it is shorted out by the diodes, so $i = 0.3 v_I$. For $|v_I| > 5V$, the source v_I sees a resistance $R_{eq} = 10 // [5 + (10//10)] = 5$ kΩ, so the slope of i versus v_I is now $1/R_{eq} = 1/5 = 0.2$ mA/V.
At the extremes, we have $i = \pm(1.5 + 0.2 \times 5) = \pm 2.5$ mA.



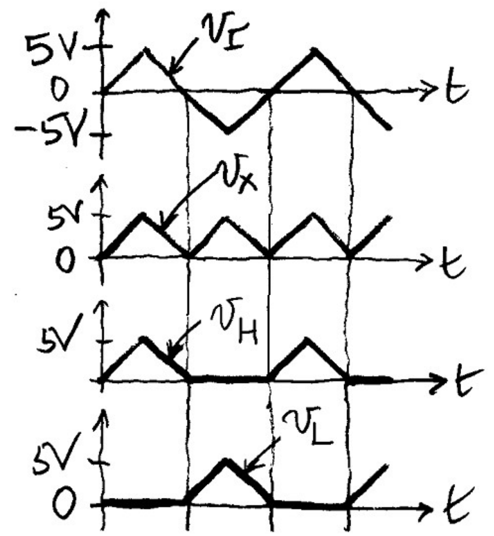
1.11 (a) Y grounded:



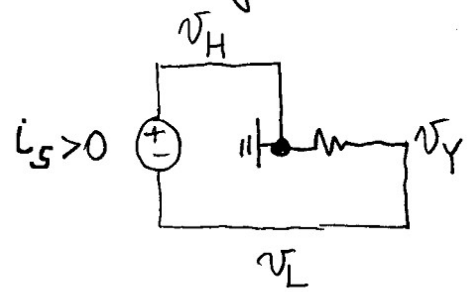
$v_L = 0,\ v_X = v_H = v_I$



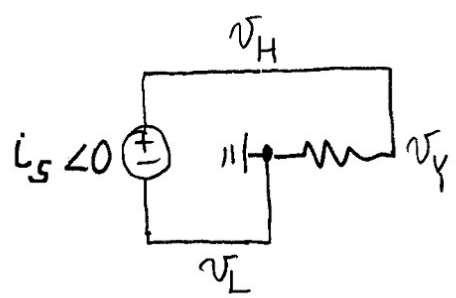
$v_H = 0,\ v_X = v_L = v_H - v_I = -v_I$



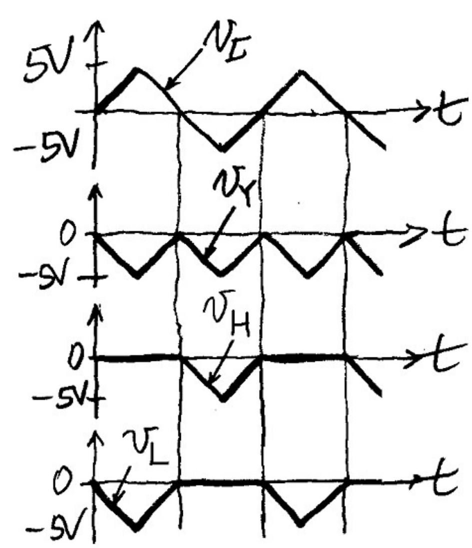
(b) X grounded:



$v_H = 0,\ v_Y = v_L = v_H - v_I = -v_I$

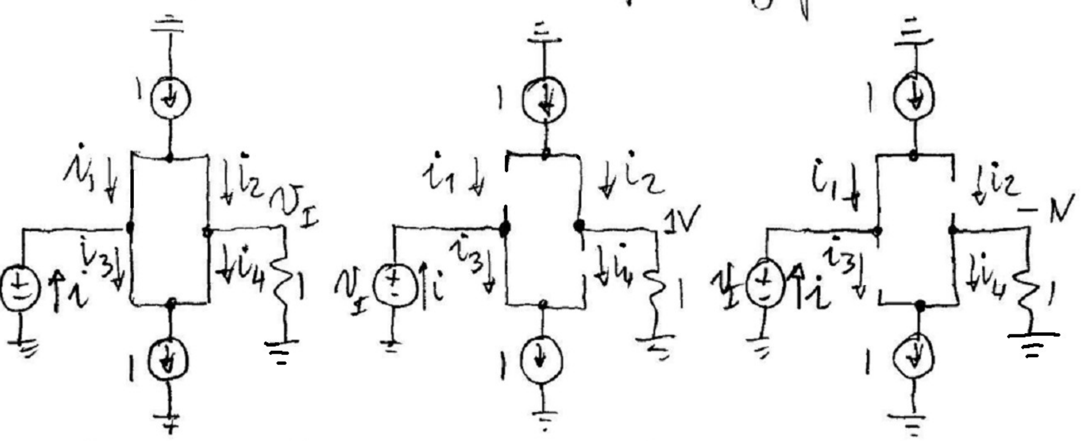


$v_L = 0,\ v_Y = v_H = v_I$



1.12 (a) As long as $-R_L I_S < v_I < +R_L I_S$, all diodes are on, in effect shorting the output node to the input node, and giving $v_O = v_I$. If v_I is raised above $+R_L I_S$, D_1 and D_4 go off, giving $v_O = +R_L I_S$. Conversely, lowering v_I below $-R_L I_S$ causes D_3 and

1.13 [V, kΩ, mA]. We have the following possibilities:

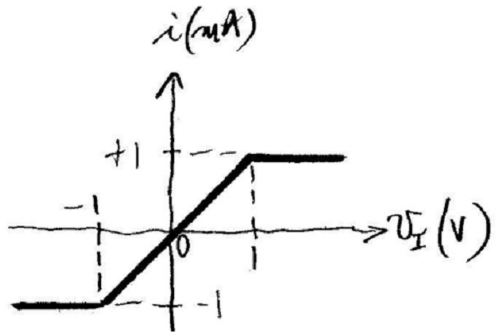


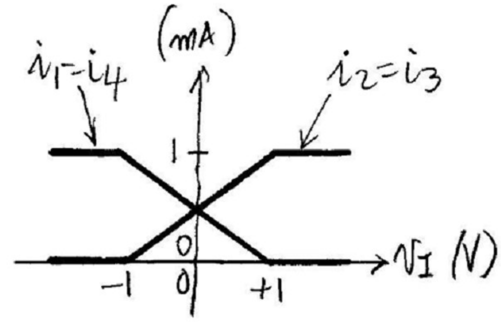
$-1\text{V} \le v_I \le 1\text{V}$ $\qquad$ $v_I > 1\text{V}$ $\qquad$ $v_I < 1\text{V}$

(a) For $-1\text{V} \le v_I \le +1\text{V}$, we apply KCL at the supernode, $i + 1 = 1 + \frac{v_I}{1}$, or $i = v_I$. Applying KCL further, $i_1 + i_2 = 1$, $i_3 + i_4 = 1$, $i_3 = i_1 - i = i_1 - v_I$; $i_4 = i_2 - \frac{v_I}{1} = i_2 - v_I$. Combining, $i_1 + i_4 = 1 - v_I$, and $i_2 + i_3 = 1 + v_I$. But, by symmetry, $i_1 = i_4 = (1 - v_I)/2$, and $i_2 = i_3 = (1 + v_I)/2$.

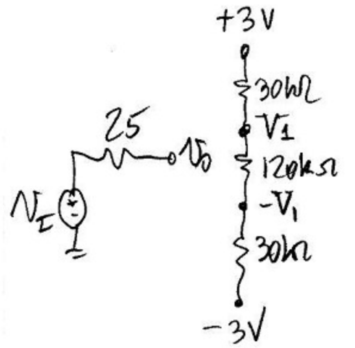
(b) For $v_I > 1\text{ V}$, $i = 1$, $i_1 = i_4 = 0$, $i_2 = i_3 = 1$.

(c) For $v_I < 1\text{ V}$, $i = -1$, $i_1 = i_4 = 1$, $i_2 = i_3 = 0$.



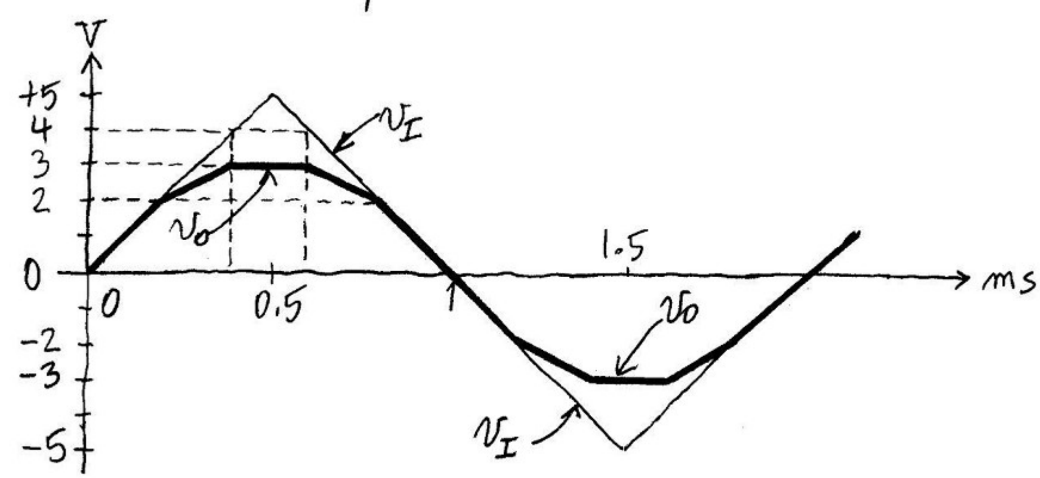


1.14 (a) For $v_I = 0$ all diodes are off and we have $v_O = v_I$. The voltages at the extremes of R_3 are $\pm V_1$, where V_1 is such that



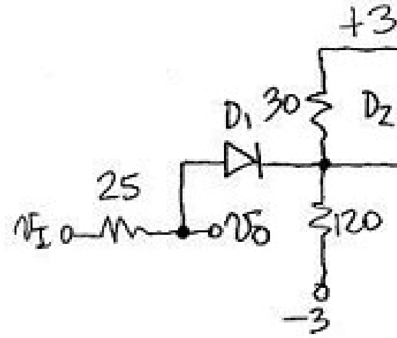
$$\frac{3-V_1}{30} = \frac{V_1-(-3)}{120+30}, \text{ or } V_1 = 2\text{ V}.$$

As v_I increases to 2 V, D_1 goes on, in effect shorting v_O to node V_1. We now have $(v_I - v_O)/25 + (3 - v_O)/30 = [v_O - (-3)]/(120+30)$, or $v_O = 0.5v_I + 1\text{V}$. Once v_I is raised to the point of making $v_O = 3\text{V}$, D_2 goes on, shorting v_O to the +3V source. This occurs when $0.5v_I + 1 = 3$, or $v_I = 4\text{V}$. The case $v_I \geq 0$ can be summarized by saying that $v_O = 0.5v_I$ for $0 < v_I < 2\text{V}$, $v_O = 0.5v_I + 1\text{V}$ for $2\text{V} < v_I < 4\text{V}$, and $v_O = 3\text{V}$ for $v_I > 4\text{V}$. Circuit behavior for $v_I < 0$ is symmetric to that for $v_I > 0$. This circuit can be used as a waveshaper.



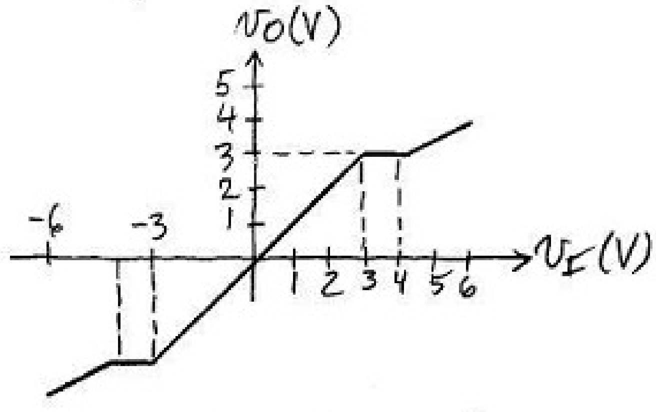
(b) Removing D_2 and D_4 will eliminate the flat segments at the top and bottom; v_O will peak out at $\pm(0.5 \times 5 + 1) = \pm 3.5\text{ V}$.

1.15 [V, mA, kΩ]. (a) Since circuit is symmetric, consider only the case $v_I > 0$. As long as

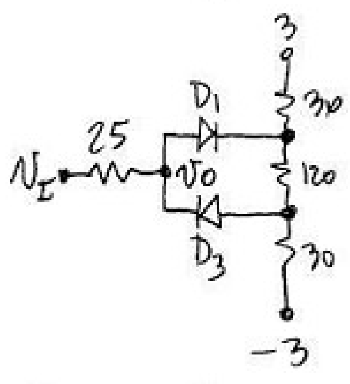


$0 < v_I < 3$ V, D_1 = OFF and D_2 = ON, so $v_O = v_I$. D_1 turns on when v_I reaches 3V, and stays on for $v_I > 3$V. As long as it still on, D_2 clamps v_O at 3V. D_2 goes off when v_I is raised to a value such that

$\frac{v_I - 3}{25} = \frac{3-(-3)}{120}$, or $v_I = 4.25$ V. For $v_I > 4.25$V, the slope of the VTC becomes $\frac{30 /\!/ 120}{25+(30/\!/120)} = \frac{24}{49}$ ($\simeq 0.5$) V/V. The case $v_I < 0$ is symmetric to the case $v_I > 0$.



(b) We now have the situation below. For $v_I = 0$, both diodes are off. The voltage at D_1's

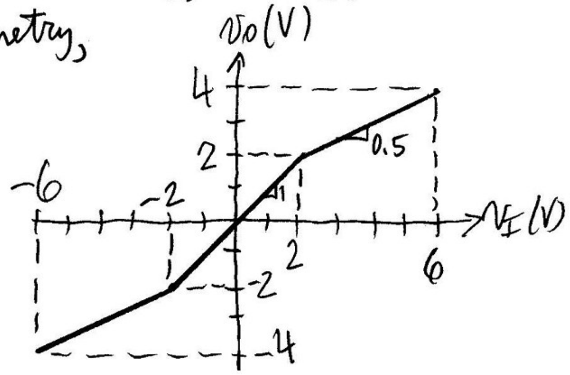


cathode is $3 - 30\frac{3-(-3)}{30+120+30} = 2$ V, and that at D_3's anode is −2V. So, for $0 \le v_I \le 2$V we have $v_O = v_I$, and for $v_I > 2$V we have

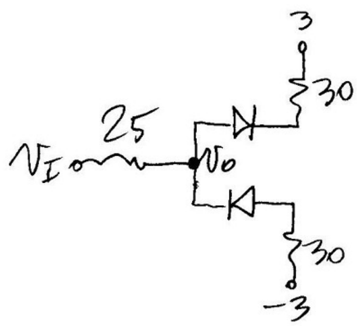
(Continued)

(1.15 continued) $\frac{v_I - v_O}{25} + \frac{3 - v_O}{30} = \frac{v_O - (-3)}{150} \Rightarrow v_O = 0.5 v_I + 1\,V.$

By symmetry,



(c) The circuit is now as shown:

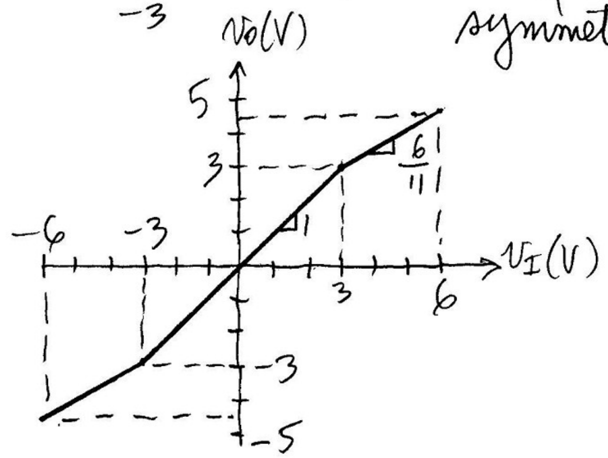


$0 \le v_I \le 3V \Rightarrow v_O = v_I$

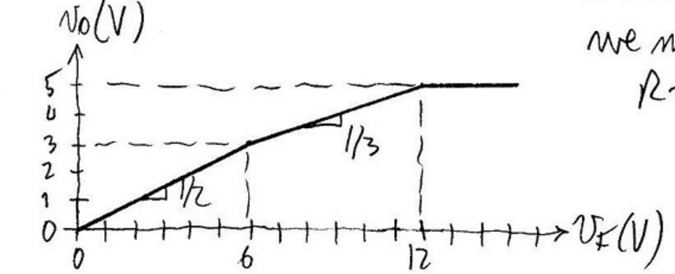
$v_I > 3V \Rightarrow$

$v_O = \frac{30 v_I + 25 \times 3}{25 + 30} = \frac{6 v_I + 15}{11}.$

The curve for $v_I < 0$ is symmetric of that for $v_I > 0$.

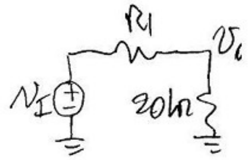


1.16 (a) [V, mA, kΩ].



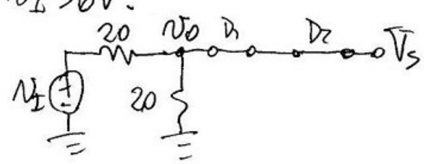
To ensure symmetry, we must have $R_3 = R_2$.

$0 < v_I < 6\,V$:



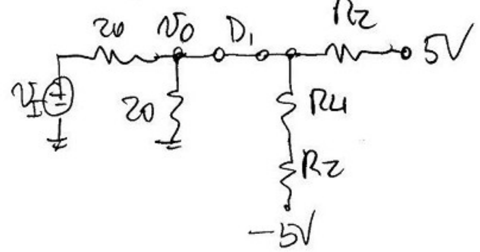
$v_O = 0.5 v_I \Rightarrow R_1 = 20\,k\Omega$

$v_I > 6V$:



$v_O = 5V \Rightarrow V_S = 5V$

$6V < v_I < 12V$



D_1 goes on for $v_I = 6V$, or $v_O = 3V$. So,

$$\frac{5-3}{R_2} = \frac{3-(-5)}{R_4 + R_2}$$

$$\Rightarrow R_4 = 3R_2$$

To ensure a slope of 1/3 V/V, we need

$$\frac{1}{3} = \frac{[20 // R_2 // (R_4 + R_2)]}{20 + [20 // R_2 // (R_4 + R_2)]} = \frac{20 // R_2 // 3R_2}{20 + [20 // R_2 // 4R_2]}$$

$$\Rightarrow 3 = \frac{20}{20 // R_2 // 4R_2} + 1 \Rightarrow 2 = 20\left(\frac{1}{20} + \frac{1}{R_2} + \frac{1}{4R_2}\right) \Rightarrow R_2 = 25\,k\Omega.$$

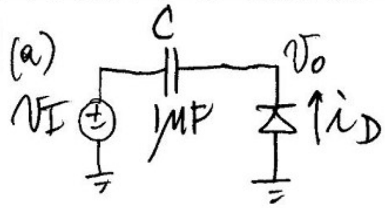
$\therefore R_1 = 20\,k\Omega$, $R_2 = R_3 = 25\,k\Omega$, $R_4 = 75\,k\Omega$, $V_S = 5\,V$.

(b) If D_2 and D_4 are omitted, slope will be 1/3 V/V also for $|v_I| > 12\,V$.

(c) If V_S is doubled, the coordinates of the breakpoints will double, while the slopes will remain the same.

1.17

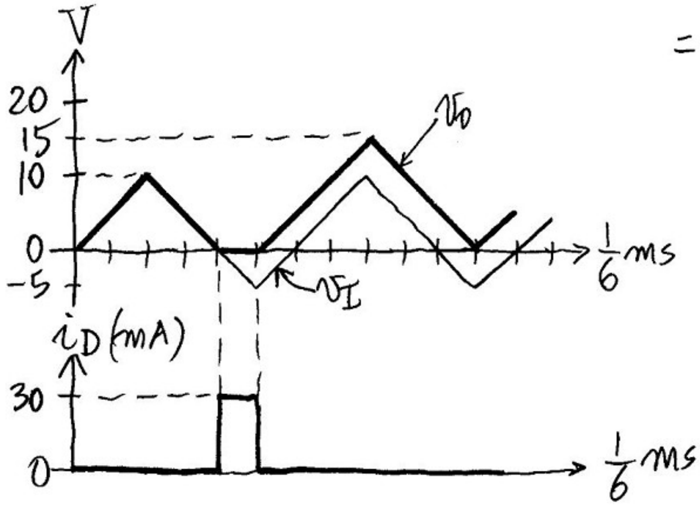
(a)



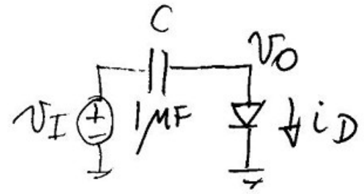
During conduction,

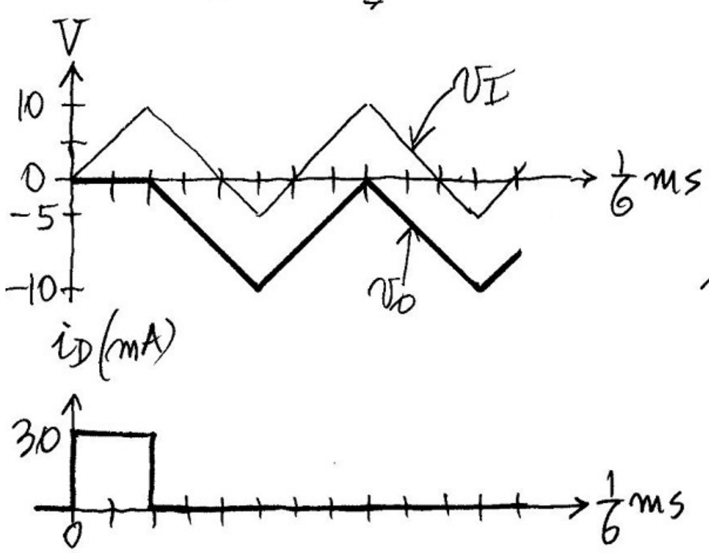
$$i_D = C\frac{d(v_O - v_I)}{dt}$$

$$= 10^{-6}\frac{5}{(1/6)10^{-3}} = 30\,mA$$



(b)





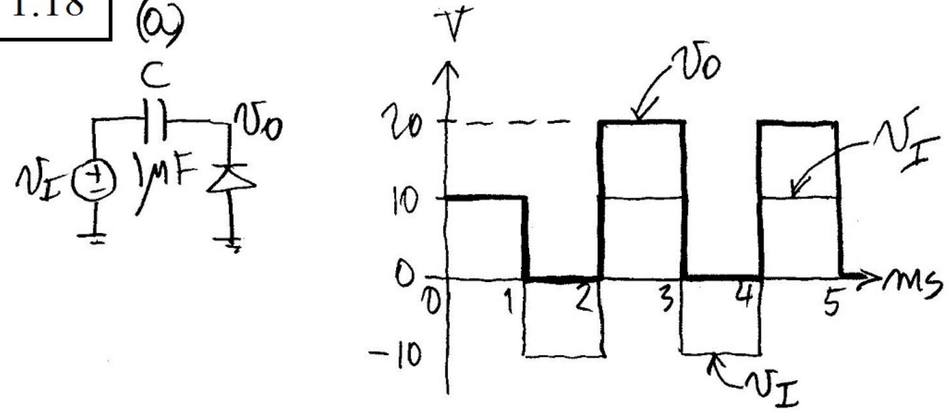
$$i_D = C\,\frac{\Delta V}{\Delta t}$$

$$= 10^{-6}\frac{10}{(2/6)10^{-3}} = 30\,mA.$$

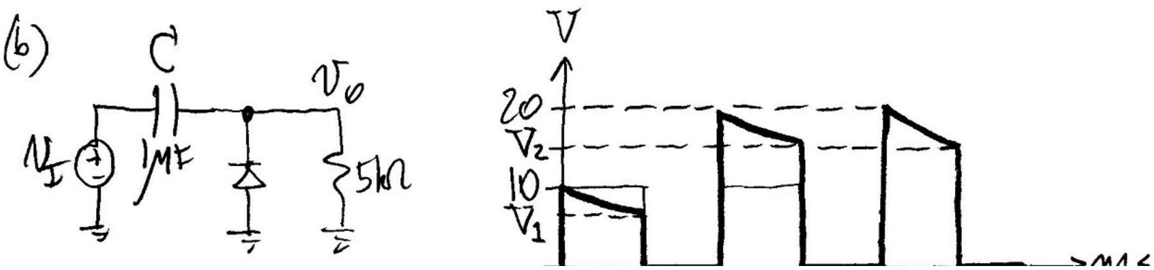
(c) Doubling (halving) the frequency will yield similar waveforms, but with half (twice) the period, and i_D twice (half) as large, or 60mA (15mA).

1.18

(a)

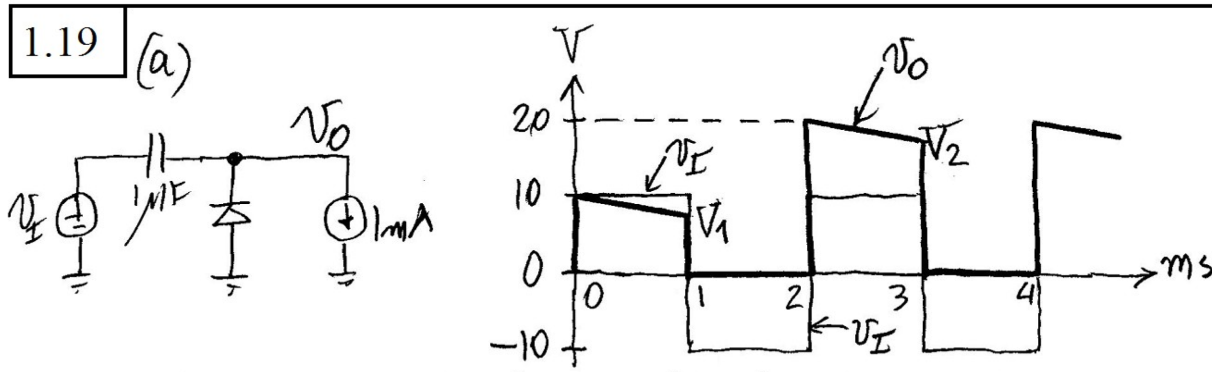


(b)



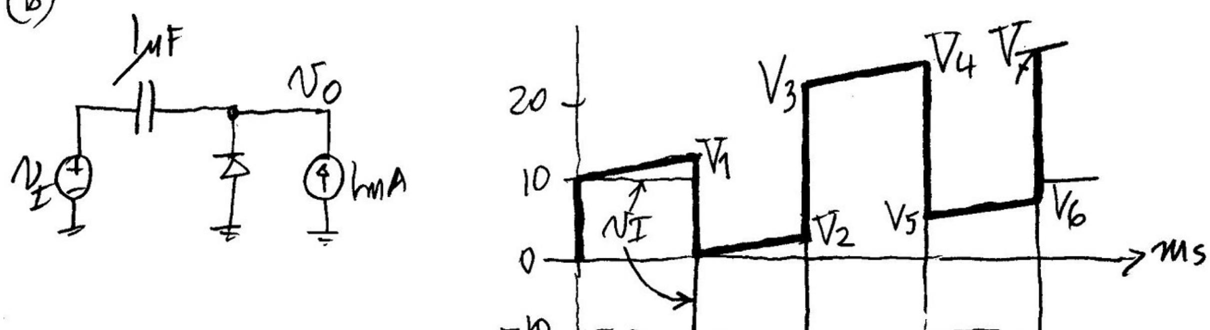
1.19

(a)



$C\Delta V = I\Delta t \Rightarrow \Delta V = I\Delta t/C = (10^{-3} \times 10^{-3})/10^{-6} = 1$ V. So, $V_1 = 9$ V, and $V_2 = 19$ V.

(b)



$V_1 = 10+1 = 11$ V; $V_2 = 0+1 = 1$ V; $V_3 = V_2 + 20 = 21$ V; $V_4 = V_3 + 1 = 22$ V; $V_5 = 22 - 10 = 2$ V; $V_6 = V_5 + 1 = 3$ V; $V_7 = V_6 + 20 = 23$ V, and so on.

1.20 Op amp rule $\Rightarrow v_N = V_P = 0$ V (virtual ground).

(a) $v_I > 0 \Rightarrow i_{R1}$ flows to the right $\Rightarrow D_1 = ON$ & $D_2 = OFF$, so $v_O = v_N = 0$. $v_I < 0 \Rightarrow i_{R1}$ flows to the left $\Rightarrow D_1 = OFF \Rightarrow D_2 = ON \Rightarrow$ $v_O = -(R_2/R_1)v_I = -v_I$; $v_I < 0 \Rightarrow v_O > 0$.

(b) $v_O = 0$ for $v_I > 0$, $v_O = -2v_I$ for $v_I < 0$.

(c) $v_O = -4v_I$ for $v_I > 0$, $v_O = 0$ for $v_I < 0$.

1.21 Op amp rule: $v_N = V_P = 1.0$ V.

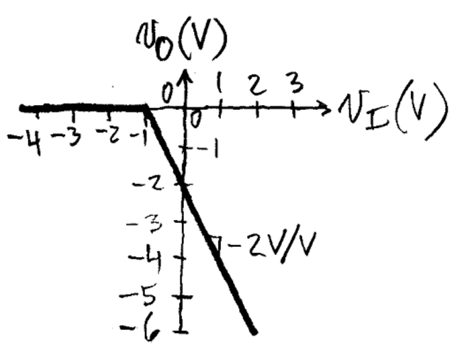
(a) $v_I > 1.0\text{V} \Rightarrow i_{R_1}$ flows to the right $\Rightarrow D_1 = ON \Rightarrow D_2 = OFF \Rightarrow$ $i_{R_2} = 0 \Rightarrow v_O = v_N = 1.0$ V. $v_I < 1.0\text{V} \Rightarrow i_{R_1}$ flows to the left $\Rightarrow$ $D_1 = OFF$ & $D_2 = ON$. KCL $\Rightarrow (v_O - v_N)/R_2 = (v_N - v_I)/R_1 \Rightarrow v_O - 1 = 2(1 - v_I)$ $\Rightarrow v_O = 3 - 2v_I$. Summarizing, $v_O = 1$V for $v_I > 1$V, $v_O = 3 - 2v_I$ for $v_I < 1$V.

(b) $v_I > 1\text{V} \Rightarrow D_1 = OFF$ and $D_2 = ON$, so $(v_I - 1)/R_1 = (1 - v_O)/R_2$ $\Rightarrow v_O = 4 - 3v_I$. $v_I < 1\text{V} \Rightarrow D_1 = ON$ & $D_2 = OFF$, $v_O = 1.0$ V

1.22 $v_N = 0$ (virtual ground); $i_{R_3} = 3/R_3 = 0.1$ mA ($\rightarrow$). The onset of conduction for D_1 occurs when $i_{R_1} = i_{R_3}$, or $(v_N - v_I)R_1 = 0.1$ mA $\Rightarrow (0 - v_I)/10 = 0.1 \Rightarrow v_I = -1$ V. Two cases:

$v_I < -1\text{ V} \Rightarrow D_1 = ON$ and $D_2 = OFF \Rightarrow i_{R_2} = 0 \Rightarrow v_O = v_N = 0$.

$v_I > -1\text{ V} \Rightarrow D_1 = OFF$ and $D_2 = ON \Rightarrow i_{R_1} + i_{R_3} = i_{R_3} \Rightarrow v_I/R_1 + 0.1 =$ $(0 - v_O)/R_2 \Rightarrow v_I/10 + 0.1 = -v_O/20 \Rightarrow v_O = -2 - 2v_I$.



1.23

Consider the case $v_I > 0$ first. This results in $v_O < 0$, so D_2's anode is negative and we can ignore the

tual
$/R_4$,
hes
, on,
cts
2.5V.
for

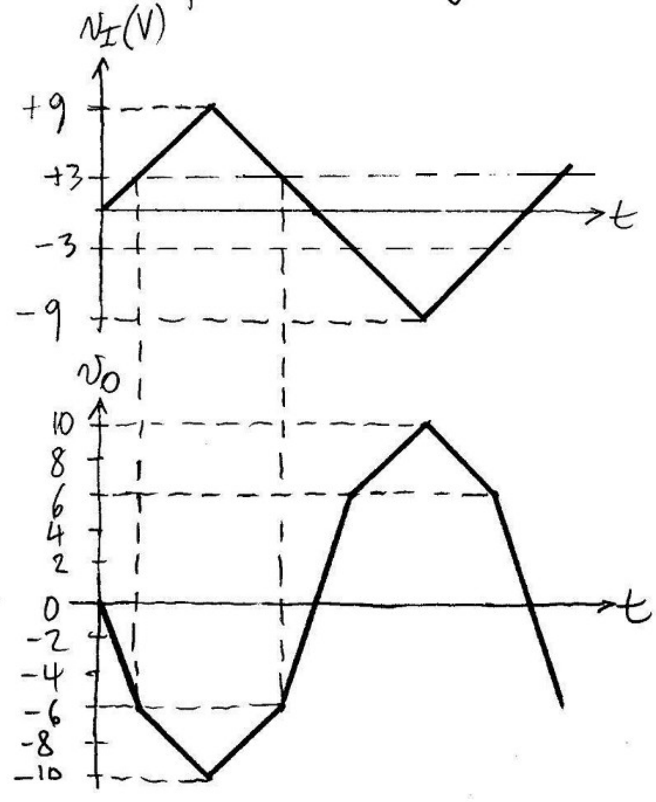
1.24

Consider first the case $v_I > 0$. This implies $v_O < 0$, indicating that D_2 will be off, and the entire circuit made up of D_2, R_5, and R_6 can be ignored. Now, D_1's anode is at virtual ground, and D_1 will go on when v_O is sufficiently negative to result in $(V_S - 0)/R_3 = (0 - v_O)/R_4$, or when v_O reaches $-(R_4/R_3)V_S = -(10/20)12 = -6$ V. Given that with D_1 still off we have $v_O = -(R_2/R_1)v_I = -2v_I$, D_1 will start conducting when $v_I = -(-6)/2 = +3$ V.

So, for $v_I > 3$ V, D_1 goes on, placing R_4 in parallel with R_2, and causing the op amp to act as a summing amp,

$$v_O = -\left(\frac{R_4 /\!/ R_2}{R_1} v_I - \frac{R_4 /\!/ R_2}{R_3} V_S\right) = -\left(\frac{10/\!/20}{10} v_I - \frac{10/\!/20}{20} 12\right) = -\frac{2}{3} v_I - 4\text{ V}.$$

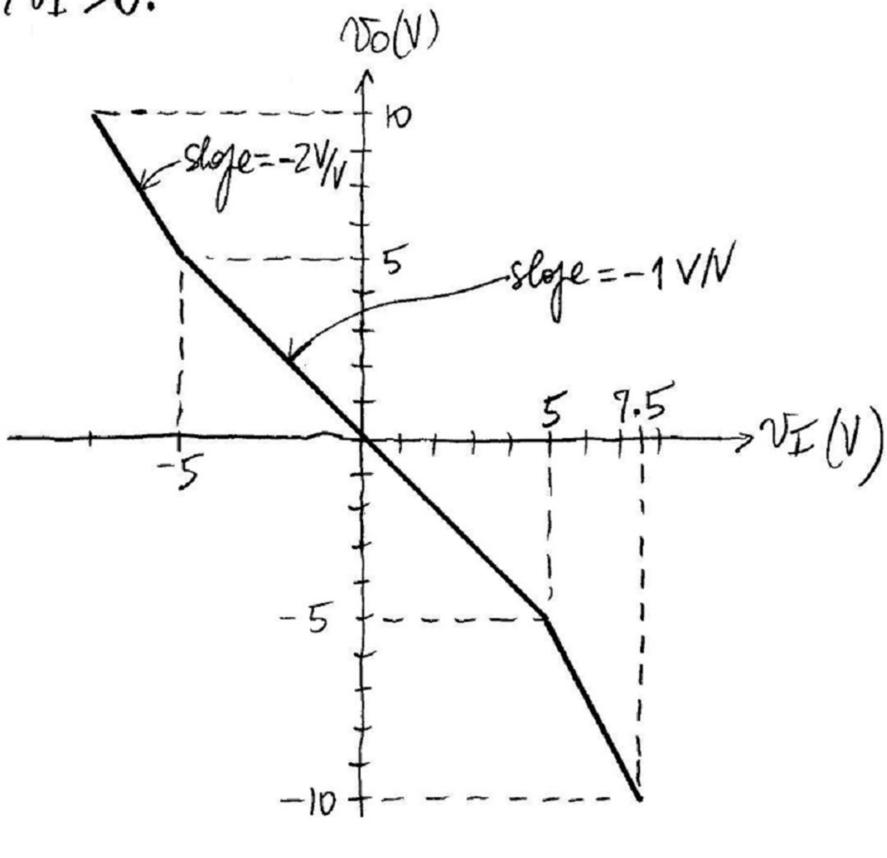
Circuit behavior for $v_I < 0$ is symmetric to that for $v_I > 0$.



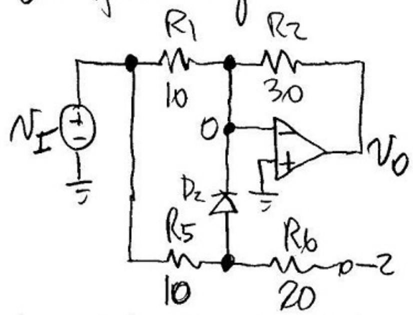
1.25 Consider first the case $v_I > 0$. Since D_1's anode is at virtual ground and D_1's cathode is positive, D_1 will be off, and we can ignore the circuit made up of D_1, R_3, and R_4. As long as D_2 is also off, we have $v_O = -(R_2/R_1)v_I = -v_I$. D_2 will go on when v_I is sufficiently positive to yield $(v_I - 0)/R_5 = [0-(-V_S)]/R_6$, or $v_I/10 = 10/20$, or $v_I = +5$ V. For $v_I > 5$V, D_2 is on, in effect placing R_5 in parallel with R_1, and causing the op amp to work as a summing amplifier,

$$v_O = -\left(\frac{R_2}{R_1 /\!/ R_5} v_I - \frac{R_2}{R_4}(-V_S)\right) = -\left(\frac{10}{10/\!/10} v_I - \frac{10}{20}(-10)\right) = -2v_I + 5\text{V}.$$

Circuit behavior for $v_I < 0$ is symmetric to that for $v_I > 0$.

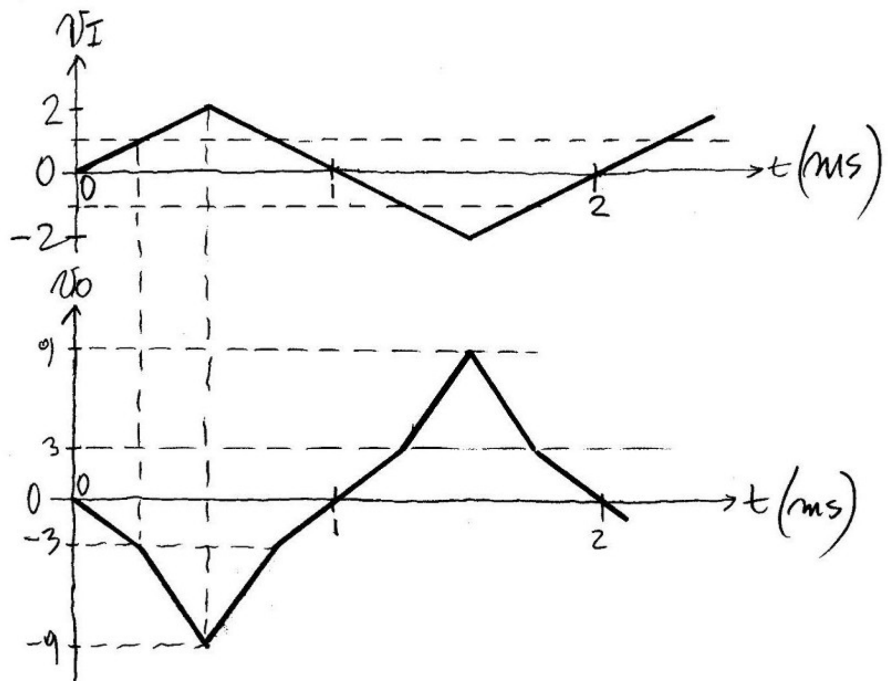


1.26 For $v_I > 0$ we have $v_O < 0$, indicating that the op amp output will sink current out of the inverting-input node. This node is at virtual ground, so D_1 will be off for $v_I > 0$, and we only need to examine the following subcircuit:



For $v_I > 0$ & v_I sufficiently small, $D_2 = \text{OFF}$, and $v_O = -(30/10)v_I = -3v_I$. D_2 goes on when v_I is such that

$(v_I - 0)/10 = [0-(-2)]/20$, or $v_I = +1$ V. Once on, D_2 in effect places R_5 in parallel with R_1, giving a slope of $-30/(10/\!/10) = -6$ V/V. In fact, using the superposition principle, we have $v_O = -6v_I - (30/20)(-2) = 3 - 6v_I$. Circuit behavior for $v_I < 0$ is symmetric to that for $v_I > 0$.



1.27 (a) n-type slab, with $n \cong N_D - N_A = 10^{15} - 4\times10^{14} = 6\times10^{14}/cm^3$; $p = (2\times10^{20})/(6\times10^{14}) = 0.33\times10^5/cm^3$.

(b) $n_i^2(400K) = 1.5\times10^{33} \times 400 \exp(-14028/400) = 5.6\times10^{25}/cm^6$. So, $n \cong 6\times10^{14}/cm^3$, $p = (5.6\times10)^{25}/(6\times10^{14}) = 0.93\times10^{10}/cm^3$.

(c) $p \cong N_A - N_D \Rightarrow N_A \cong p + N_D = 5\times10^{15} + 10^{16} = 1.5\times10^{16}/cm^3$.

(d) $$\mu_n = 68 + \frac{1346}{1+\left(\frac{1.5\times10^{16}+10^{16}}{9.2\times10^{16}}\right)^{0.71}} = 1031\ cm^2/Vs$$

$$\mu_p = 45 + \frac{427}{1+\left(\frac{2.5\times10^{16}}{2.2\times10^{17}}\right)^{0.72}} = 398\ cm^2/Vs$$

1.28 $$R = \rho\frac{L}{A} = \rho\frac{10\times10^{-4}}{1\times10^{-4}\times2\times10^{-4}} = 5\times10^4\rho$$

(a) $$\rho = \frac{1}{qn_i(\mu_p+\mu_n)} = \frac{1}{1.6\times10^{-19}\times1.4\times10^{10}(45+427+68+1346)}$$
$= 2.4\times10^5\ \Omega\,cm \Rightarrow R = 5\times10^4\times2.4\times10^5 = 12\ G\Omega$.

(b) $$n \gg p \Rightarrow \rho \cong \frac{1}{qN_D\mu_n} = \frac{1}{1.6\times10^{-19}\times10^{16}\times1183} = 0.53\ \Omega\,cm$$
$\Rightarrow R = 26\ k\Omega$

(c) $$\rho \cong \frac{1}{qN_A\mu_p} = \frac{1}{1.6\times10^{-19}\times10^{18}\times152} = 41\ m\Omega\,cm \Rightarrow R = 2\,k\Omega$$

(d) $$\rho \cong \frac{1}{1.6\times10^{-19}\times10^{20}\times77} = 811\ \mu\Omega\,cm \Rightarrow R = 41\ \Omega$$

(e) $$\rho \cong \frac{1}{1.6\times10^{-19}\times10^{20}\times50} = 41.4\ \mu\Omega\,cm \Rightarrow R = 62.5\,\Omega$$

(f) $R = 5\times10^4 \times 2.7\times10^{-6} = 0.14\ \Omega$.

1.29 (a) $E = v/L = (1\,V)/(20\,\mu m) = 1/(20\times10^{-4}) = 500$ V/cm

(b) $n \cong 10^{14}/cm^3$, $p \cong 2\times10^{20}/10^{14} = 2\times10^{6}/cm^3$.

$\mu_n \cong 1400\ cm^2/Vs$; $\mu_p \cong 470\ cm^2/Vs$.

$v_n = \mu_n E = 1400\times500 = 700\times10^3$ cm/s

$v_p = \mu_p E = 235\times10^3$ cm/s

(c) $|J_n| = q n v_n = 1.602\times10^{-19}\times10^{14}\times700\times10^3 = 11.2\ A/cm^2$

$|J_p| = q p v_p = 1.602\times10^{-19}\times2\times10^{6}\times235\times10^3 = 75\,nA/cm^2$

$\Rightarrow |J_p| \ll |J_n| \Rightarrow$ can ignore drift minority current.

(e) $R = v/i = v/[(J_p+J_n)A] \cong v/(J_nA) = \dfrac{1}{11.2\times2\times5\times(10^{-4})^2}$

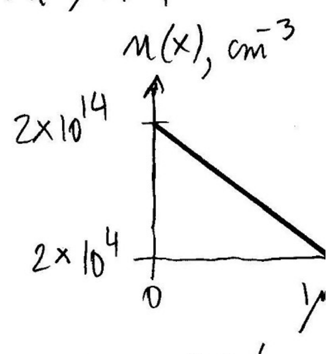
$= 893\ k\Omega$.

(d) $t_n = \dfrac{L}{v_n} = \dfrac{20\times10^{-4}}{700\times10^3} = 2.86\,ns$; $t_p = 8.5\,ns$.

1.30 $n(L) = 2\times1($

$\mu_n = 68 + \dfrac{}{1+[10^{16}/}$

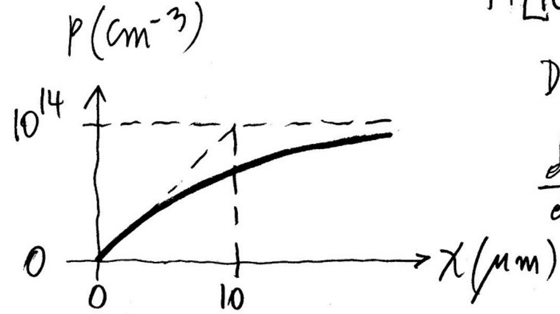
$D_n = \mu_n V_T = 1183\times1$



$i = JA = -9.9\,(20\times1$

(or 98.6 μA flow

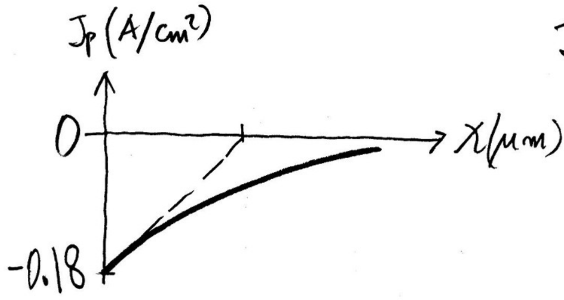
1.32 (a) $\mu_p = 45 + \dfrac{427}{1+[10^{16}/(2.2\times10^{17})]^{0.72}} \cong 430\ cm^2/Vs$



$D_p = 430\times0.026 \cong 11.2\ cm^2/s$

$\dfrac{dp}{dx} = -10^{14} e^{-x/(10\mu m)} \dfrac{-1}{10\mu m}$

$= +10^{17} e^{-x/(10\mu m)}\ cm^{-4}$



$J_p = -qD_p \dfrac{dp}{dx} = -1.6\times10^{-19}\times11.2\times$

$\times10^{17} e^{-x/(10\mu m)}$

$\cong 0.18 e^{-x/(10\mu m)}\ A/cm^2$

(b) J_p depends on dp/dx, regardless of whether p is large or small. In our example, slope is highest where p is small, and vice-versa.

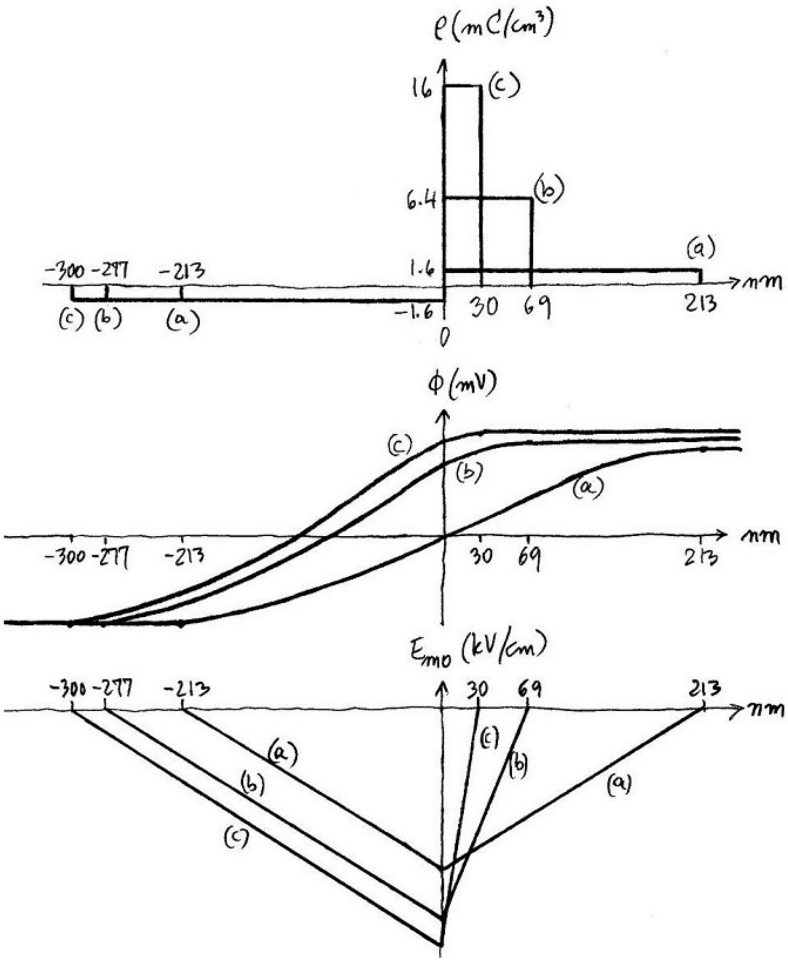
1.33

$\phi_p = 26 \ln \frac{1.4\times10^{10}}{10^{16}} = -350\,\text{mV}$; $\phi_n = 26\,\text{mV} \ln \frac{N_D}{1.4\times10^{10}}$;

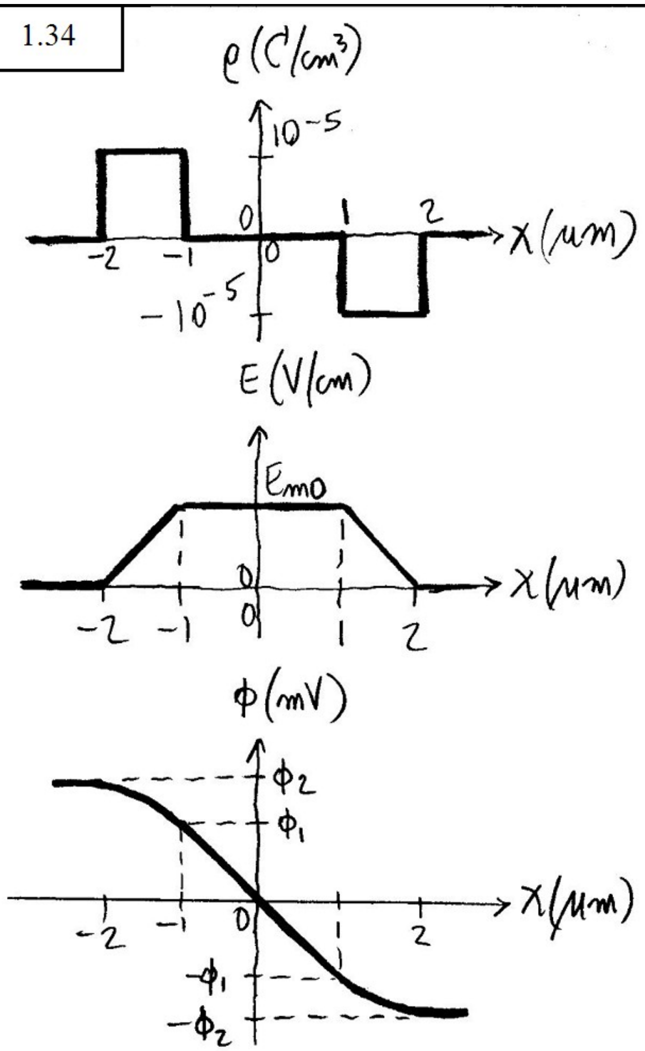
$\phi_0 = \phi_n + 0.35\text{V}$; $x_{po} = \sqrt{\frac{2\varepsilon_{si}\phi_0}{qN_A}\frac{N_D}{N_A+N_D}}$; $x_{no} = \sqrt{\frac{2\varepsilon_{si}\phi_0}{qN_D}\frac{N_A}{N_A+N_D}}$;

$E_{mo} = \sqrt{\frac{2q\phi_0}{\varepsilon_{si}}\frac{N_A N_D}{N_A+N_D}}$. Use the above to create the table:

N_D (cm^{-3})	10^{16}	4×10^{16}	10^{17}
ϕ_p (V)	−0.35	−0.35	−0.35
ϕ_n (V)	0.35	0.386	0.410
ϕ_0 (V)	0.700	0.736	0.760
x_{po} (nm)	213	277	300
x_{no} (nm)	213	69	30
ρ_p (mC/cm^3)	−1.6	−1.6	−1.6
ρ_n (mC/cm^3)	1.6	6.4	16
E_{mo} (kV/cm)	33	43	47



1.34



$$\frac{dE(x)}{dx} = \frac{\rho}{\varepsilon_{si}} \Rightarrow$$

E = constant for $|x| < 1\,\mu m$ and $|x| > 2\,\mu m$, and E = linear for $1\,\mu m < |x| < 2\,\mu m$.

$$\frac{E_{m0}}{(2-1)10^{-4}} = \frac{10^{-5}}{1.04\times10^{-12}} \Rightarrow$$

$E_{m0} = 962$ V/cm.

$$E = -\frac{d\phi}{dx} \Rightarrow$$

ϕ = linear for $|x| < 1\,\mu m$ and ϕ = quadratic for $1\,\mu m < |x| < 2\,\mu m$.

$\phi(1\,\mu m) = -E_m \times \mu m = -962\times10^{-4} = -96.2\,mV = -\phi_1$; $\phi(-1\,\mu m) = \phi_1$.

For $1\,\mu m < x < 2\,\mu m$ we have

$$\phi(x) = -\phi_1 - \int_{1\mu m}^{2\mu m} E(x)\,dx$$

$\phi(2\,\mu m) = -\phi_1 -$ (area under E from $1\,\mu m$ to $2\,\mu m$)

$$= -96.2\,mV - \frac{962\times10^{-4}}{2} = -144.3\,mV = -\phi_2;$$

$\phi(-2\,\mu m) = \phi_2$.

1.35 (a) Let $N = N_A = N_D$. Then, $0.7 = 0.026 \ln[N^2/(2\times10^{20})]$

$\Rightarrow N = 9.9\times10^{15}/cm^3$.

$$\mathcal{E}_{m0} = \sqrt{\frac{2\times1.6\times10^{-19}\times0.7}{10^{-12}}\,\frac{9.9}{2}10^{15}} = 33.3\ kV/cm,$$

$$x_{p0} = x_{n0} = \frac{10^{-12}\times33.3\times10^3}{1.6\times10^{-19}\times9.9\times10^{15}} = 0.21\ \mu m.$$

$$Q_{j0} = (10\times20)10^{-8}\sqrt{2\times10^{-12}\times1.6\times10^{-19}\times0.7\times\frac{9.9}{2}10^{15}} = 66.6\ fC.$$

(b) $0.7 = 0.026 \ln[10N_A\times N_A/(2\times10^{20})] \Rightarrow N_A = 3.14\times10^{15}/cm^3$,

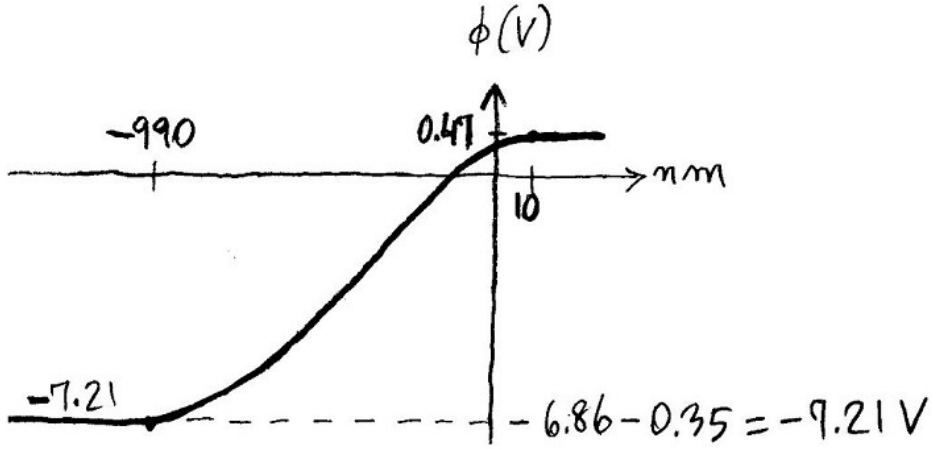
1.36 $\phi_n = 26 \ln\frac{10^{18}}{1.4\times10^{10}} = 470 mV$; $\phi_p = -350\ mV$; $\phi_0 = 0.82 V$.

$$X_{d0} = \sqrt{\frac{2\times10^{-12}(0.47+0.35)}{1.6\times10^{-19}}\,\frac{10^{16}+10^{18}}{10^{16}\times10^{18}}} = 346\ nm$$

(a) $1 = 0.346\sqrt{1 - v/0.82} \Rightarrow v = -6.86\ V$

(b) $\frac{x_p}{x_n} = \frac{N_D}{N_A} \Rightarrow x_p = 100x_n$. But, $x_p + x_n = 1\mu m$. So,

$x_p \cong 1\mu m$, $x_n \cong 10\ nm$.



(c) $C = \varepsilon_{si}\frac{A}{X_d} \Rightarrow 10^{-12} = 1.04\times10^{-12}\frac{A}{10^{-4}} \Rightarrow A = 10^{-4} = (100\ \mu m\times100\ \mu m)$.

1.37

$C_{j0} = C_j(0) = 10\,pF = 10^{-11}\,F$

$C_j = \dfrac{10}{(1 - v/\phi_0)^m} \Rightarrow m \log\left(1 - \dfrac{v}{\phi_0}\right) = \log \dfrac{10^{-11}}{C_j}.$

$m \log(1 + 2/\phi_0) = \log \dfrac{10}{6.87}$

$m \log(1 + 8/\phi_0) = \log \dfrac{10}{4.87}$. Let $x = 2/\phi_0$. Then,

$\dfrac{\cancel{m} \log(1+x)}{\cancel{m} \log(1+4x)} = \dfrac{\log(10/6.87)}{\log(10/4.87)} = 0.5218 \Rightarrow$

$\log(1+x) = 0.5218 \log(1+4x) \Rightarrow$

$1 + x = (1+4x)^{0.5218} \Rightarrow x = (1+4x)^{0.5218} - 1.$

Solve by iteration to find $x = 2.483 \Rightarrow$

$\phi_0 = 805\,mV.$

$m = [\log(10/6.87)] / \log(1 + 2.483) = 0.3 \Rightarrow$ graded.

1.38

$$\phi_0 = 0.026 \ln \frac{10^{17}\times 10^{19}}{2\times 10^{20}} = 0.94\,V.$$

$$Q_{j0} \cong (25\times10^{-4})(50\times10^{-4})\sqrt{2\times10^{-12}\times1.6\times10^{-19}\times0.94\times10^{17}} = 2.17\ pC.$$

(a) $Q_j(0V) = 2.17\,pC$; $Q_j(-1V) = 2.17\sqrt{1+\frac{1}{0.94}} = 3.12\ pC$

$\Delta Q_j = 3.12 - 2.17 = 0.95\,pC$ from source to junction.

$C_{eq} = \frac{\Delta Q}{\Delta V} = \frac{0.95}{1} = 0.95\ pF.$

(b) $Q(-2V) = 2.17\sqrt{1+\frac{2}{0.94}} = 3.84\ pC$

$\Delta Q_j = 3.84 - 3.12 = 0.72\ pC$ from source to junction.

$C_{eq} = 0.72\ pF.$

(c) $Q_j(-3V) = 2.17\sqrt{1+\frac{3}{0.94}} = 4.44\,pF$

$\Delta Q_j = 0.6\,pC$ from junction to source; $C_{eq} = 0.6\,pF.$

1.39

$I_p + I_n = 1\,mA$. By the diode equation,

$$\frac{I_p}{I_n} = \frac{D_p}{L_p N_D}\times\frac{L_n N_A}{D_n} = \frac{D_p}{D_n}\frac{L_n}{L_p}\frac{N_A}{N_D} = \frac{D_p}{D_n}\sqrt{\frac{D_p\tau_p}{D_n\tau_n}}\ \frac{N_A}{N_D}$$

$$= \left(\frac{D_p}{D_n}\right)^{3/2}\sqrt{\frac{\tau_p}{\tau_n}}\ \frac{N_A}{N_D} \cong \left(\frac{\mu_p}{\mu_n}\right)^{3/2}\times 1\times\frac{N_A}{N_D}$$

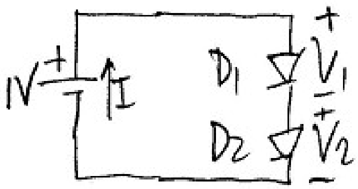
(a) $N_D = 10^{18}/cm^3$, $N_A = 10^{16}/cm^3 \Rightarrow$ n-region $\mu_p \cong 152\ cm^2/Vs$, p-region $\mu_n \cong 1183\ cm^2/Vs$. $I_p/I_n = (10^{16}/10^{18})(152/1183)^{3/2} = 1/2171 \Rightarrow I_n \cong 1\,mA$, $I_p \cong 10^{-3}/2171 = 0.46\,\mu A$.

(b) $N_D = 10^{16}/cm^3$, $N_A = 10^{18}/cm^3 \Rightarrow \mu_p \cong 430\ cm^2/Vs$, $\mu_n \cong 280\ cm^2/Vs$, $I_p/I_n = (10^{18}/10^{16})(430/280)^{3/2} = 190 \Rightarrow$ $I_p \cong 1\,mA$, $I_n \cong 10^{-3}/190 = 5.3\,\mu A$.

(c) $I_p/I_n = 1 \Rightarrow (10^{17}/N_D)(1/1.6)^{3/2} = 1 \Rightarrow N_D \cong 0.5\times10^{17}/cm^3.$

1.40

(a)



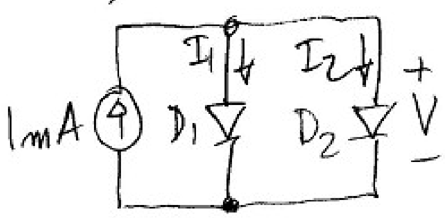
$V_1+V_2=1\,V=1000\,mV$

$I=I_{S1}e^{V_1/V_T}=I_{S2}e^{V_2/V_T}$

$\frac{I_{S2}}{I_{S1}}=e^{(V_1-V_2)V_T} \Rightarrow V_1-V_2=V_T\ln\frac{I_{S2}}{I_{S1}}$

$\Rightarrow V_1-V_2=0.026\ln 5=41.8\,mV \Rightarrow V_1=521\,mV,\ V_2=479\,mV,\ I=10^{-15}\times e^{521/26}=503\,nA.$

(b)



$I_1+I_2=1\,mA$

$I_1/I_2=I_{S1}/I_{S2}=1/5=0.2$

$\Rightarrow I_1=0.1\overline{6}\,mA,\ I_2=0.8\overline{3}\,mA,$

$V=26\times\ln\frac{0.1\overline{6}\times10^{-3}}{10^{-15}}=672\,mV.$

1.41 (a) $N_D = 10^{17}/cm^3 \Rightarrow \mu_n = 1414\ cm^2/Vs$; $N_A = 10^{16}/cm^3 \Rightarrow \mu_p = 430\ cm^2/Vs$. $D_n = 1414 \times 0.026 = 36.8\ cm^2/s$, $D_p = 430 \times 0.026 = 11.2\ cm^2/s$.

$$I_S = (25 \times 50)10^{-8} \times 2\times10^{20} \times 1.6\times10^{-19}\left(\frac{11.2}{10^{-4}\times10^{17}} + \frac{36.8}{10^{-4}\times10^{16}}\right)$$

$$= 0.45 + 14.7 = 15.2\ fA$$

$$i = (15.2\times10^{-15}) \times e^{650/26} = 1.092\ mA.$$

(b) $$\phi_0 = 0.026 \ln \frac{10^{16}\times10^{17}}{2\times10^{20}} = 0.760\ V$$

$$x_p \cong \sqrt{\frac{2\times10^{-12}\times0.76}{1.6\times10^{-19}\times10^{16}}\frac{10^{17}}{10^{16}+10^{17}}}\sqrt{1-\frac{650}{760}} = 0.112\ \mu m,$$

$x_n = x_p(N_A/N_D) = 0.011\ \mu m$. Applying the corrections,

$$I_S = 0.45\frac{1}{1-0.011} + 14.7\frac{1}{1-0.112} \cong 17\ fA,$$

$i = 1.092 \times \frac{17}{15.2} = 1.22\ mA$. Ignoring x_p and x_n we commit an error of about -11.7%.

1.42 (a) In the example it was found that $\phi_0 = 0.82\,V$ and $E_{m0} \cong 5\times10^4\,V/cm$. Impose

$300\times10^3 = 5\times10^4\sqrt{1-v/0.82}$ and get $v \cong -28.3\,V$.

(b) $\phi_0 = 820 + 18 = 838\,mV$.

$$E_{m0} = \sqrt{\frac{2\times1.6\times10^{-19}\times0.838}{10^{-12}}\;\frac{2\times10^{16}\times10^{18}}{2\times10^{16}\times10^{18}}} = 7.25\times10^4\ V/cm$$

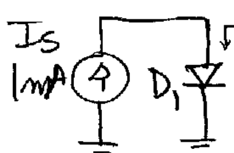
$$300\times10^3 = 7.25\times10^4\sqrt{1-v/0.838} \Rightarrow v = -13.5\ V.$$

1.43 Since $N_D << N_A$, $N_AN_D/(N_A+N_D) \cong N_D$. Also, $\phi_0 - v \cong -v$, so

$$E_{m0} \cong \sqrt{\frac{2q}{\varepsilon_{si}}N_D(-v)}$$

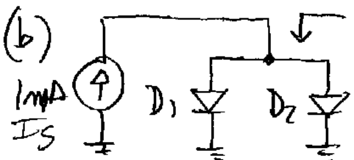
(a) $$300\times10^3 \cong \sqrt{\frac{2\times1.6\times10^{-19}}{10^{-12}}N_D(100)} \Rightarrow N_D = 2.9\times10^{15}/cm^3$$

1.45 (a)



$R = r_{d1} = \frac{nV_T}{I_D} = \frac{nV_T}{I_S} = \frac{50}{1} = 50\Omega.$

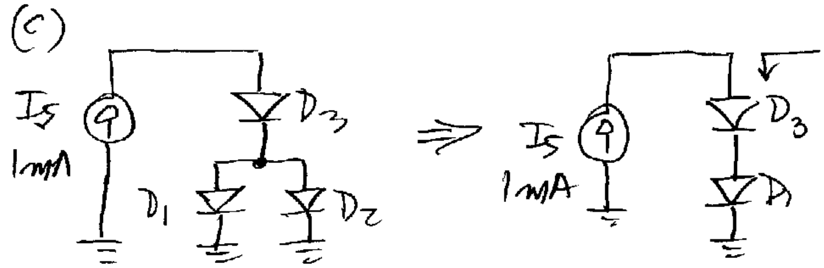
(b)



$R = r_{d1} // r_{d2} = \frac{1}{2}r_{d1} = \frac{1}{2}\frac{nV_T}{I_S/2} = \frac{1}{2}\frac{50}{0.5} = 50\Omega.$

Two diodes in // act as a single diode with twice the area. The dynamic resistance of a diode is independent of its area.

(c)



$R_{eq} = r_{d3} + r_{d1} = 2\frac{nV_T}{I_S} = 100\Omega.$

Now dynamic resistances add up and the result is twice as large.

1.46 (a) $900 - 750 = 150$ mV. T increases by $150/2 = 75°C$.

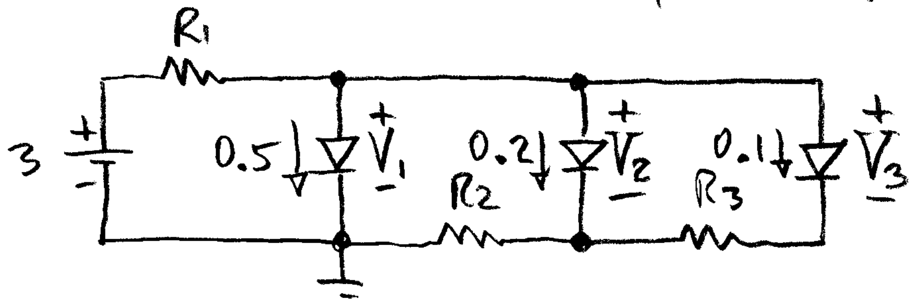
(b) $P = V_D I_D = 0.75 \times 10 = 7.5$ W. Thermal res $= 75/7.5 = 10$ °C/W.

(c) If connected in series, both diodes experience the same situation of (a), so T increases by 75°C, and $P = 7.5$ W for each device.

(d) If connected in parallel, each diode carries 1/2 the current, or 5A. So, initially, $V_D(0) = (900 - 2 \times 18)$ mV $= 0.864$ V, and $P(0) = 0.864 \times 5 = 4.32$ W. Thus, T increases by $(4.32 \text{ W}) \times (10 \text{ °C/W}) = 43.2$ °C, so $V_D(\infty) = 864 - 2 \times 43.2 = 0.778$ V. Iterate:
$P(\infty) = 0.778 \times 5 = 3.9$ W, $\Delta T = 39°C$, $V_D(\infty) = 864 - 2 \times 39 = 0.786$ V. Iterate once more, and get $P(\infty) = 0.786 \times 5 = 3.93$ W, $V_D(\infty) = 0.785$ V.

1.47 (a) With $I_S = 2\text{fA}$ and $nV_T = 26\text{mV}$, D_2 gives 1mA @ 700mV. $(700-340)\text{mV} = 360\text{mV} = 6\times 60\text{mV}$
$\Rightarrow I_R = (1\text{mA})/10^6 = 1\text{nA}$.
(b) $340+18 = 358\text{mV}$. (c) $340-18 = 322\text{mV}$.
(d) $I_R = (1\text{nA})\times 2^{50/10} = 32\text{nA}$. Because of the increase in I_R, V would increase by $5\times 18 = 90\text{mV}$. However, because of the increase in T, V would decrease by $2\times 50 = 100\text{mV}$. The final value is $V = 340+90-100 = 330\text{mV}$.

1.48 [mA, V, kΩ]: Use rules of thumb (18 mV, 60 mV):



$V_1 = 700 - 18 = 682\text{mV}$

$V_2 = 700 - 60 + 18 = 658\text{mV}$

$V_3 = 700 - 60 = 640\text{mV}$

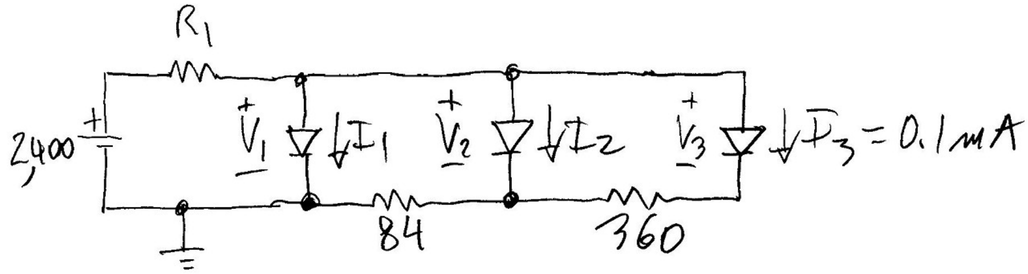
$R_3 = (V_2 - V_3)/0.1 = 18/0.1 = 180\,\Omega$

$R_2 = (V_1 - V_2)/(0.2+0.1) = 24/0.3 = 80\,\Omega$

$R_3 = (3 - 0.682)/(0.5+0.2+0.1) = 2.9\,\text{k}\Omega$.

1.49

$[mV, mA, \Omega]$



$I_3 = 0.1mA = (1mA)/10 \Rightarrow V_3 = 700 - 60 = 640\,mV.$

$V_2 = V_3 + R_3 I_3 = 540 + 360 \times 0.1 = 640 + 36 = 640 + 18 + 18$

$\Rightarrow I_2 = 0.1 \times 2 \times 2 = 0.4\,mA.$

$V_1 = V_2 + R_2(I_2 + I_3) = 676 + 84(0.4 + 0.1) = 676 + 42 =$
$718 = 700 + 18 \Rightarrow I_1 = 1 \times 2 = 2\,mA.$

$R_1 = (V_S - V_1)/(I_1 + I_2 + I_3) = (2400 - 718)/(2 + 0.4 + 0.1) =$
$672.8\ \Omega.$

1.50

$I_{D2} = 0.1\,mA \Rightarrow V_{D2} = 700 - 60 = 640\,mV.$

$V_{D3} = V_T \ln \frac{0.640 - V_{D3}}{1440 \times 2 \times 10^{-15}} = 0.026 \ln \frac{0.640 - V_{D3}}{2.88 \times 10^{-12}}.$

Start out with $V_{D3} = 0.62\,V$, and iterate till you get $V_{D3} = 604\,mV$. Then, $I_{D3} = (0.64 - 0.604)/1440 = 25\,\mu A$. KCL: $I_{D2} + I_{D3} = 100 + 25 = 125\,\mu A$.

$V_{D1} = 336 \times 0.125 \times 10^{-3} + V_{D2} = 682\,mV$. But, $700 - 682 = 18\,mV$, so $I_{D1} = (1mA)/2 = 0.5\,mA$. KCL: $I_{R_1} = I_{D1} + I_{D2} + I_{D3} = 0.5 + 0.125 = 0.625\,mA$. KVL: $V_S = V_{D1} + 2 \times 0.625 = 1.932\,V.$

1.51 (a) $V_{PTAT} = V_{D1} - V_{D2} = V_T\left(\ln\frac{I_1}{I_{S1}} - \ln\frac{I_2}{I_{S2}}\right) =$
$\frac{kT}{q}\ln\frac{I_1 I_{S2}}{I_2 I_{S1}} = KT$, $K = \frac{k}{q}\ln\frac{I_1 I_{S2}}{I_2 I_{S1}}$.

(b) $K = \frac{1.381\times10^{-23}}{1.602\times10^{-19}}\ln 10 = 198.5\ \mu V/°C$.

(c) Nothin changes, as the ratio I_2/I_1 remains constant.

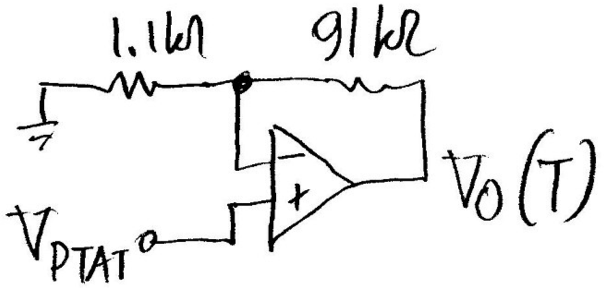
(d) $10\times10^{-3} = A\times198.5\times10^{-6} \Rightarrow A = 50.4$ V/V.

1.52 (a) $V_{PTAT} = V_{D1} - V_{D2} = V_T\left(\ln\frac{I_1 - I_2}{I_{S1}} - \ln\frac{I_2}{I_{S2}}\right) =$
$\frac{kT}{q}\ln\left[\left(\frac{I_1}{I_2}-1\right)\frac{I_{S2}}{I_{S1}}\right] = KT$, $K = \frac{k}{q}\ln\left[\left(\frac{I_1}{I_2}-1\right)\frac{I_{S2}}{I_{S1}}\right]$.

(b) $K = \frac{1.381\times10^{-23}}{1.602\times10^{-19}}\ln\left(\frac{100}{20}-1\right) = 119.5\ \mu V/°C$.

(c) $k = (86.2\ \mu V/°C)\ln\left[\left(\frac{100}{50}-1\right)2\right] = 59.75\ \mu V/°C$.

(d) Use the setup of (b). Then $A = (10\times10^{-3})/(119.5\times10^{-6}) = 83.7$ V/V. Use a noninverting amp:



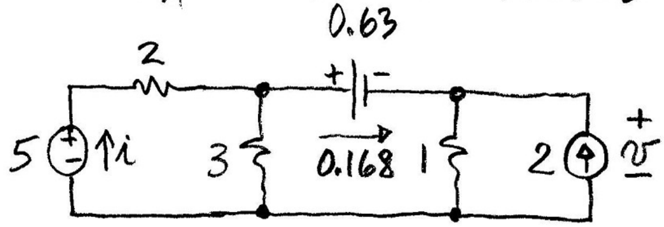
$A = 1 + \frac{91}{1.1} \cong 83$ V/V.

1.53 $[\mathrm{V}, \mathrm{mA}, \mathrm{k}\Omega]$:

$V_{OC} = \frac{3}{2+3} 5 - 2\times 1 = 1\ \mathrm{V}$, $R_{eq} = 2 // 3 + 1 = 2.2\ \mathrm{k}\Omega$.

$V_D = V_T \ln \frac{I_D}{I_S} = V_T \ln \frac{(V_{OC} - V_D)/R_{eq}}{I_S} = 0.026 \ln \frac{1 - V_D}{2.2\times 10^3 \times 5\times 10^{-15}}$

Iterate and find $V_D = 0.630$ V and $I_D = 0.168$ mA.



$v = 1(2 + 0.168) = 2.168\ \mathrm{V}$; $i = \frac{5 - (2.168 + 0.63)}{2} = 1.1\ \mathrm{mA}$.

Using the 0.7-V model we get

$V_D = 0.7\mathrm{V}$, $I_D = (1 - 0.7)/2.2 = 0.136\ \mathrm{mA}$; a current error of about 20%, a voltage error of about 10%.

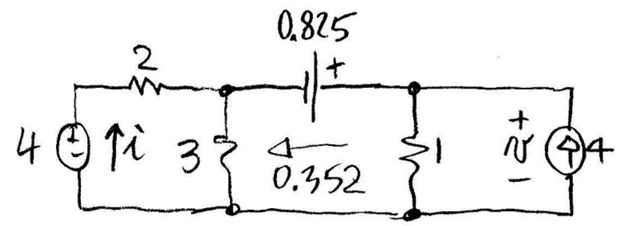
1.54 $[V, mA, k\Omega]$:

$V_{OC} = 1\times 4 - [3/(2+3)]4 = 1.6\,V$, $R_{eq} = 2 // 3 + 1 = 2.2\,k\Omega$.

$V_D = nV_T \ln \frac{V_{OC} - V_D}{R_{eq} I_S} = 0.035 \ln \frac{1.6 - V_D}{2.2\times 10^3 \times 20\times 10^{-15}}$, or

$V_D = 0.035 \ln \frac{1.6 - V_D}{4.4\times 10^{-11}}$. Iterate $\Rightarrow V_D = 0.825\,V \Rightarrow$

$I_D = (1.6 - 0.825)/2.2 = 0.352\,mA$.



$v = 1\times(4 - 0.352) = 3.648\,V$

$i = \frac{4 - (3.648 - 0.825)}{2} = 0.588\,mA$.

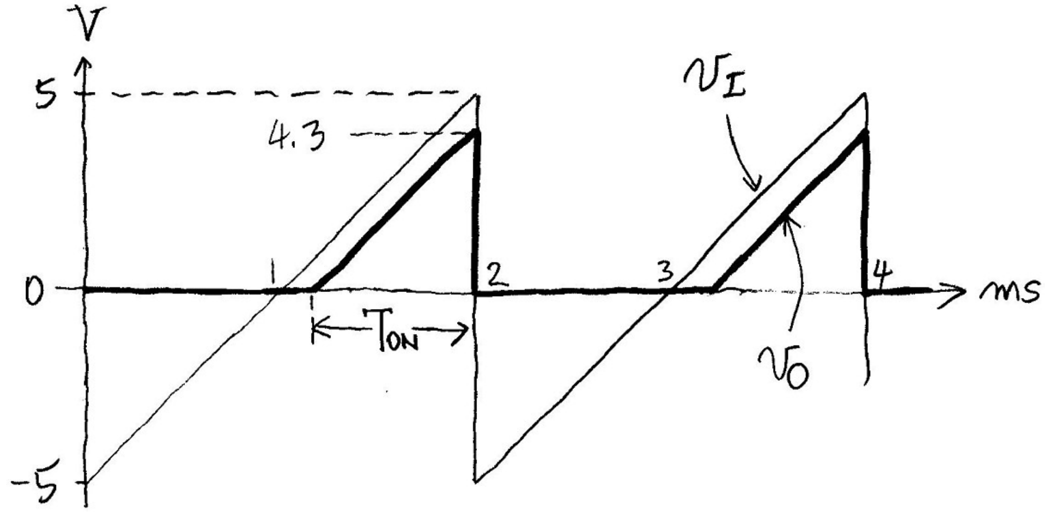
Using the 0.7-V diode model, we get

$I_D = \frac{1.6 - 0.7}{2.2} = 0.409\,mA$ (16% overestimate)

$v = 1(4 - 0.409) = 3.591\,V$ (1.6% underestimate)

$i = \frac{4 - (3.591 - 0.7)}{2} = 0.555\,mA$ (5.6% underestimate).

1.55



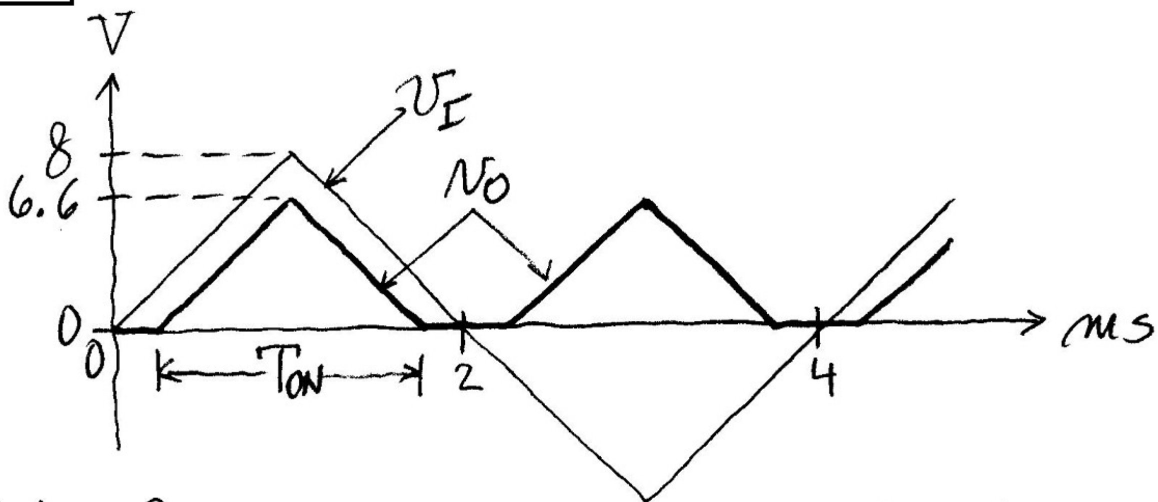
$$\frac{4.3}{T_{ON}} = \frac{5}{1\,ms} \Rightarrow T_{ON} = \frac{4.3}{5} = 0.86\,ms = 43\%\ \text{of}\ T.$$

$$v_O(avg) = \frac{1}{T}\int_0^T v_O(t)\,dt = \frac{\text{Area under } v_O}{T} = \frac{(0.86 \times 4.3)/2}{2}$$

$= 0.9245$ V.

If the diode were ideal, we'd have $T_{ON} = T/2 = 1$ ms (50% of T) and $v_O(avg) = \frac{(1 \times 5)/2}{2} = 1.25$ V. The error is therefore $100\,\frac{0.9245 - 1.25}{1.25} = -26\%$.

1.56



$$\frac{6.6}{T_{ON}} = \frac{8}{2} \Rightarrow T_{ON} = 1.65\ \text{ms} = 82.5\%\ \text{of}\ T.$$

$$v_{O(avg)} = \frac{0.5\,(1.65 \times 6.6)}{2} = 2.7225\ \text{V}.$$

Each diode conducts for $\frac{82.5}{2} = 41.25\%$.

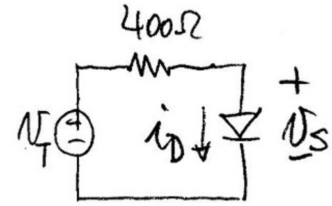
Ideally, $v_{O(avg)} = 4\text{V}$, conduction $= 50\%$.

1.57

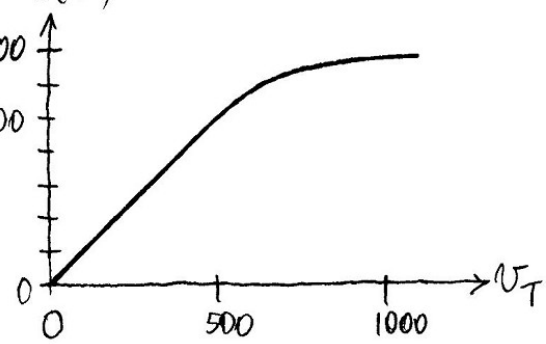
(a)

i_D (μA)	v_S (mV)	v_T (mV)
1	520	520
4	556	558
10	580	584
20	598	606
40	616	632
100	640	680
200	658	738
400	676	836
500	682	882
800	694	1014
1000	700	1100

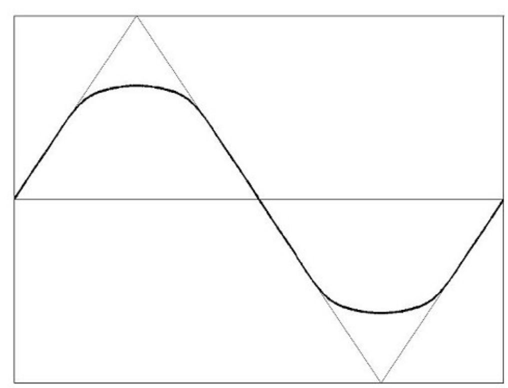
$v_T = v_S + 400 i_D$



(b)



(c)



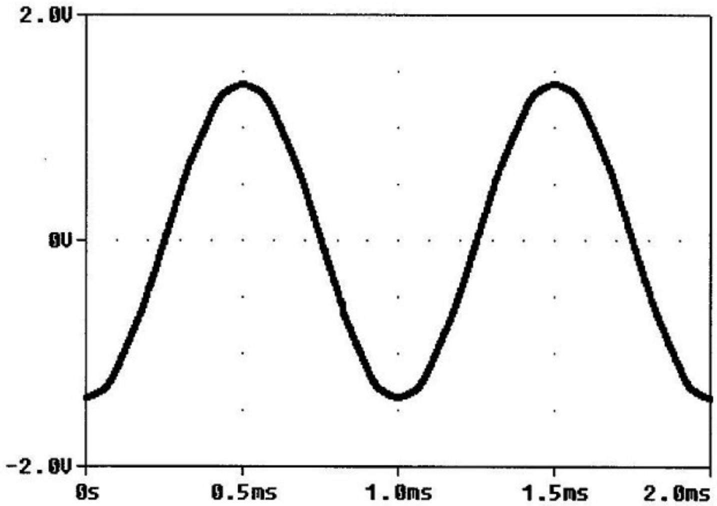
1.58 (a) Impose $I_{R_1} = 1\text{mA} + I_{R_2}$ at $v_T = V_{Tm} = 2.2\text{V}$:

$\frac{2.2-1.4}{R_1} = 1 + \frac{0.7}{R_2}$. Moreover, $\frac{R_2}{R_1+R_2} = \frac{1}{\sqrt{2}} \Rightarrow R_2 = \frac{R_1}{\sqrt{2}-1}$,

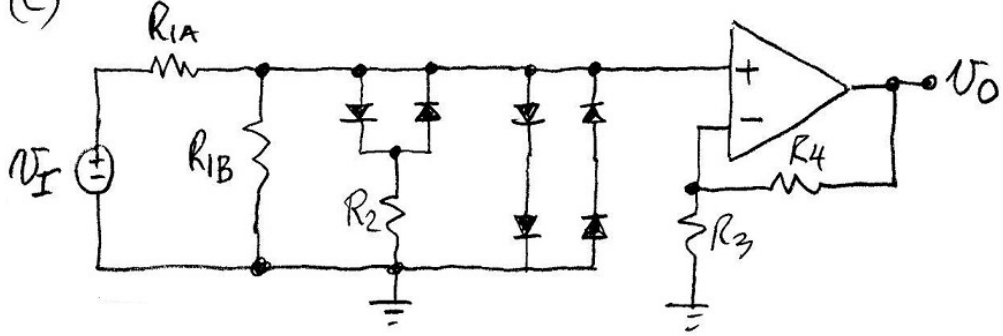
or $R_2 = 2.41 R_1$. Substituting R_2, we get

$\frac{0.8}{R_1} = 1 + \frac{0.7}{2.41 R_1}$, or $R_1 = 0.51\ \text{k}\Omega$, $R_2 = 1.3\ \text{k}\Omega$.

(b)



(c)



Impose $R_{1A} // R_{1B} = 0.51\ \text{k}\Omega$, or $\frac{1}{R_{1A}} + \frac{1}{R_{1B}} = \frac{1}{0.51}$, and

$\frac{1}{1+R_{1A}/R_{1B}} 5 = 2.2$, or $R_{1A}/R_{1B} = 1.2\overline{7}$. Eliminating R_{1A},

$1/(1.2\overline{7} R_{1B}) + 1/R_{1B} = 1/0.51 \Rightarrow R_{1B} = 0.91\text{k}\Omega$, $R_{1A} = 1.16\ \text{k}\Omega$.

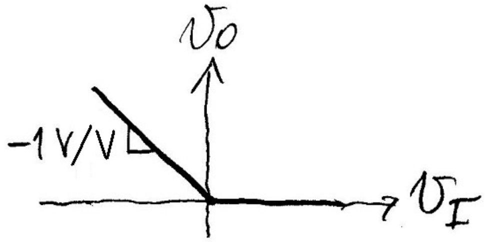
Finally, $5 = (1 + R_4/R_3) 1.4 \Rightarrow R_4/R_3 = 2.57 \Rightarrow R_3 = 20\text{k}\Omega$,

$R_4 = 51\ \text{k}\Omega$.

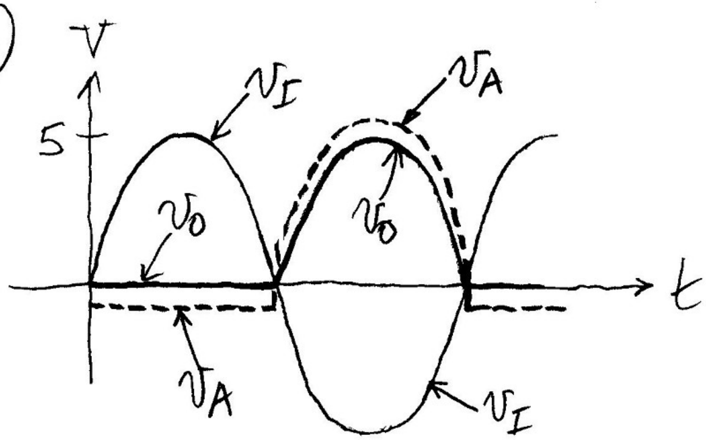
1.59 (a) $v_I > 0 \Rightarrow D_1 = \text{ON}, D_2 = \text{OFF}, v_O = 0, v_A = -0.7\text{ V}.$

$v_I < 0 \Rightarrow D_1 = \text{OFF}, D_2 = \text{ON}, v_O = (-R_2/R_1)\,v_I = -v_I,$

$v_A = v_O + 0.7\text{ V}$



(b)



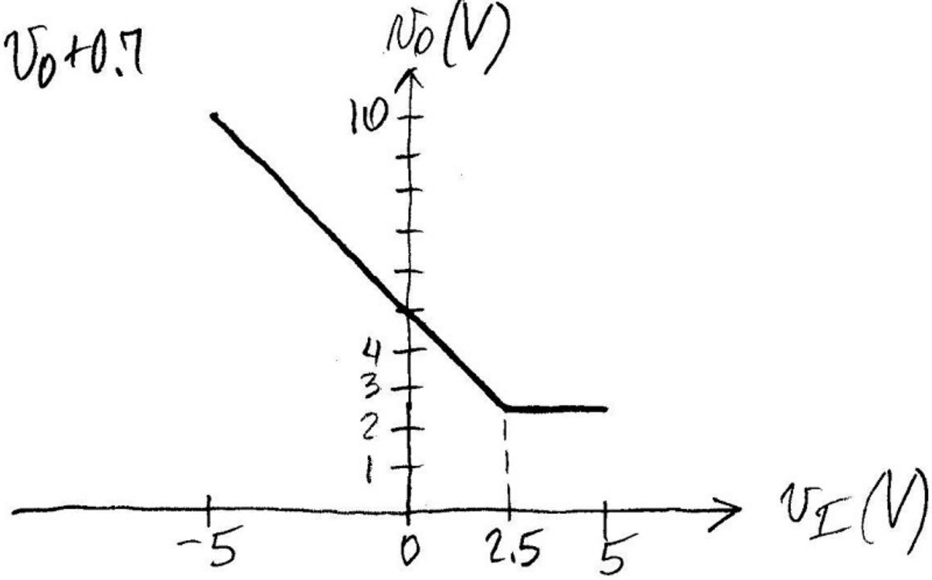
1.60 (a) $v_N = v_P = 2.5\text{ V}$; $v_I > 2.5\text{ V} \Rightarrow D_1 = \text{ON}, D_2 = \text{OFF}$,

$v_O = 2.5\text{ V}$, $v_A = 2.5 - 0.7 = 1.8\text{ V}$.

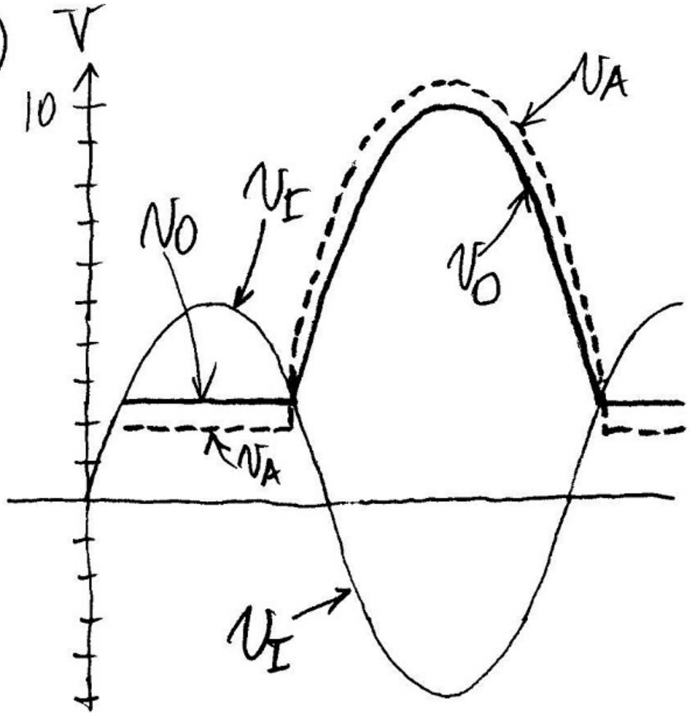
$v_I < 2.5\text{V} \Rightarrow D_1 = \text{OFF}, D_2 = \text{ON}$, $v_O = v_N + R_2 I_{R2}$

$= v_N + R_2 I_{R1} = v_N + R_2 (v_N - v_I)/R_1 = 5 - v_I$.

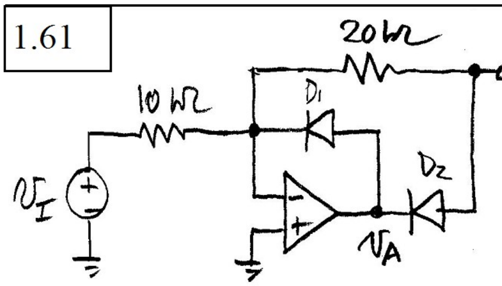
$v_A = v_O + 0.7$



(b)



1.61



$v_I > 0 \Rightarrow i_{10k\Omega}$ "→"

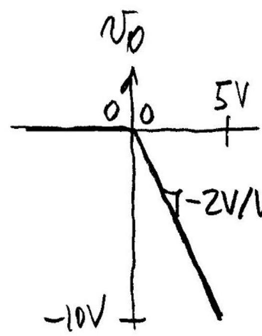
$\Rightarrow D_1 = CO,\ D_2 = ON,$

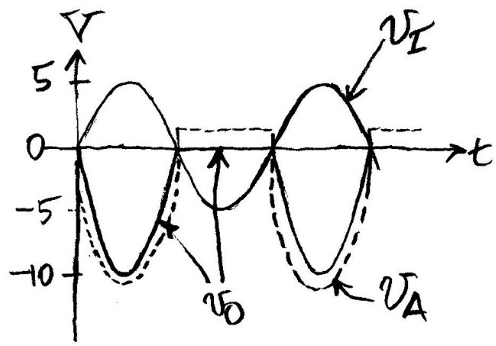
$v_O = -(20/10)v_I = -2v_I$

$\Rightarrow v_{OA} = v_O - V_{D2(on)} = -2v_I - 0.7V.$

$v_I < 0 \Rightarrow i_{10k\Omega}$ "←" $\Rightarrow D_1 = ON,\ D_2 = CO,\ i_{10k\Omega} = 0 \Rightarrow v_O = 0.$

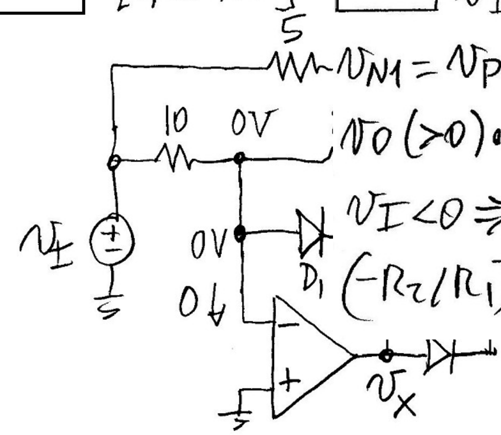
$v_A = v_N + V_{D1(on)} = 0 + 0.7 = 0.7\ V.$





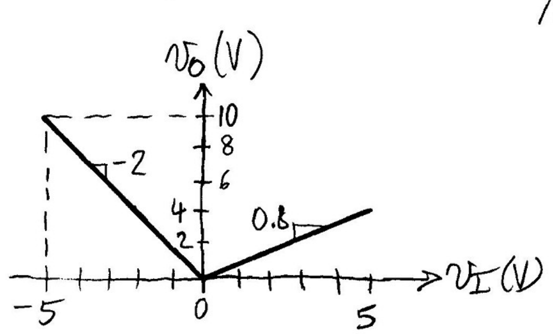
1.62

[V, mA, kΩ]



Inverting amp:

$v_O = -\frac{20}{10}v_I = -2v_I.$



1.63

$v_I > 0 \Rightarrow D = OFF \Rightarrow i_{R_3} = 0 \Rightarrow v_{P1} = v_I;$

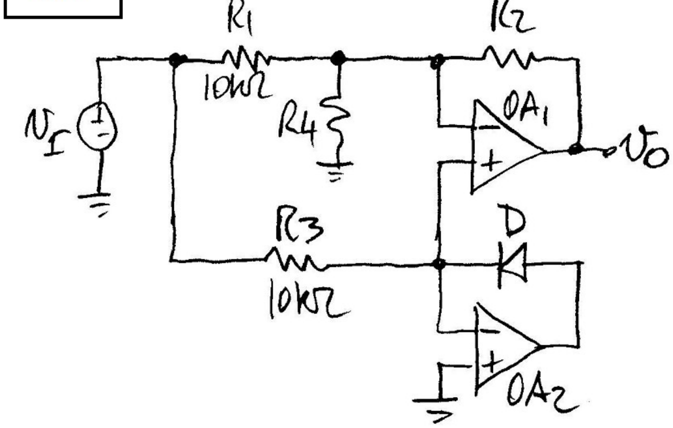
$v_{N1} = v_{P1} = v_I \Rightarrow i_{R1} = 0;\ i_{R2} = i_{R1} = 0 \Rightarrow v_O = v_{N1} = v_I,$

$v_O\ (>0).$

$v_I < 0 \Rightarrow D = ON \Rightarrow v_{N2} = v_{P2} = 0 \Rightarrow v_{P1} = 0 \Rightarrow v_O =$

$(-R_2/R_1)v_I = -v_I,\ v_O > 0.$ In summary, $v_O = |v_I|.$

1.64

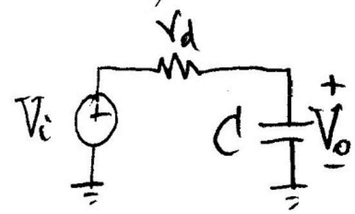


$v_I > 0 \Rightarrow D = OFF \Rightarrow i_{R_3} = 0 \Rightarrow v_{P1} = v_I$; $v_{N1} = v_{P1} = v_I \Rightarrow$
$i_{R_1} = 0$; $v_O = (1 + R_2/R_4)v_I$, $v_O > 0$.

$v_I < 0 \Rightarrow D = ON \Rightarrow v_{N2} = v_{P2} = 0$; $v_{N1} = v_{P1} = v_{N2} = 0$;
$i_{R_4} = 0$; $v_O = -(R_2/R_1)v_I$, $v_O > 0$.

To achieve $v_O = 2|v_I|$ we need $R_2/R_1 = 2 \Rightarrow R_2 =$ $20 k\Omega$, and $(1 + R_2/R_4) = 2 \Rightarrow R_4 = R_2 = 20 k\Omega$.
In summary, $R_1 = 10 k\Omega$, $R_2 = 20 k\Omega$, $R_3 = 10 k\Omega$, $R_4 = 20 k\Omega$.

1.65 (a)



$$H = \frac{V_o}{V_i} = \frac{1/j\omega C}{r_d + 1/j\omega C} = \frac{1}{1 + j\omega/\omega_0}, \quad \omega_0 = \frac{1}{r_d C}$$

$$= \frac{1}{(V_T/I_C)C} = \frac{I_d}{V_T C}.$$

(b) $10^5 = \dfrac{0.1}{26 \times C} \Rightarrow C = 38.5\ \text{nF}$

(c) $|H| = \dfrac{1}{\sqrt{1 + (\omega/\omega_0)^2}}$; $|H|_{dB} = -6 \Rightarrow |H = 10^{-6/20} = \dfrac{1}{2}$

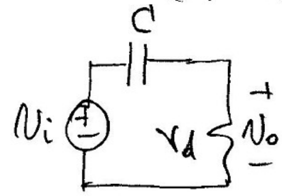
$$\frac{1}{2} = \frac{1}{\left[1 + \left(\frac{50 \times 10^3}{\omega_0}\right)^2\right]^{1/2}} \Rightarrow \omega_0 = 28.9 \times 10^3 = \frac{I_D}{0.026 \times 38.5 \times 10^{-9}}$$

$\Rightarrow I_D = 28.9\ \mu A.$

(d) $\measuredangle H = -\tan^{-1}\dfrac{\omega}{\omega_0} \Rightarrow -30^\circ = \tan^{-1}\dfrac{500 \times 10^3}{\omega_0} \Rightarrow \omega_0 = 866\ \text{kr/s}$

$\Rightarrow I_D = 0.866\ \text{mA}.$

1.66 (a) $r_d = V_T / I_D$, $H(j\omega) = \dfrac{r_d}{1/j\omega C + r_d} = \dfrac{j\omega r_d C}{1 + j\omega r_d C} = \dfrac{j\omega/\omega_0}{1 + j\omega/\omega_0}$,



$\omega_0 = \dfrac{1}{r_d C} = \dfrac{I_D}{V_T C}$

(b) $I_D = 0.1\,\text{mA} \Rightarrow r_d = 260\,\Omega \Rightarrow \omega_0 = \dfrac{1}{260 \times 33 \times 10^{-9}} = 116.6\ \dfrac{\text{krad}}{\text{s}}$.

(c) $\omega/\omega_0 = 10^5 / (2 \times 116.6 \times 10^3) = 0.429$;

$\dfrac{j0.429}{1 + j0.429} = \dfrac{0.429}{\sqrt{1 + 0.429^2}} \underline{/90^\circ - \tan^{-1} 0.429} = 0.394 \underline{/66.8^\circ}$;

$5\,\text{mV} \times 0.394 = 1.971\,\text{mV}$;

$v_o(t) = (1.971\,\text{mV}) \cos(10^5 t + 66.8^\circ)$.

$0.1\,\text{mA} = (1\,\text{mA})/10 \Rightarrow V_D = 700 - 60 = 640\,\text{mV}$.

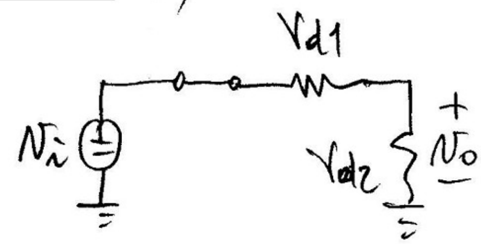
(d) $I_D = 50\,\mu\text{A} = (1\,\text{mA})/(10 \times 2) \Rightarrow V_D = 700 - 60 - 18 = 622\,\text{mV}$,

$r_d = 520\,\Omega$, $\omega_0 = 58.275\,\text{krad/s}$, $\omega/\omega_0 = 1.716$,

$H = 0.864 \underline{/40.8^\circ}$

$v_o(t) = (4.32\,\text{mV}) \cos(10^5 t + 40.8^\circ)$.

1.67 (a)



$r_{d1} = V_T/I$; $r_{d2} = V_T/(I_{REF} - I)$.

$$\frac{v_o}{v_i} = \frac{r_{d2}}{r_{d1}+r_{d2}} = \frac{1}{1+r_{d1}/r_{d2}}$$

$$= \frac{1}{1+(V_T/I)/[V_T/(I_{REF}-I)}$$

$$\frac{v_o}{v_i} = \frac{1}{1+(I_{REF}-I)/I} = \frac{1}{1+I_{REF}/I-1} = \frac{I}{I_{REF}}.$$

(b) With $I_{REF} = 1\,mA$, $v_o/v_i = I/10^{-3} = 10^3 I$, I in A.

For $v_o/v_i = 1\,V/V$, use $I = 1\,mA$; $R_{eq} = r_{d1} + \infty = \infty$.

For $v_o/v_i = 0.75\,V/V$, use $I = 0.75\,mA$; $R_{eq} = r_{d1} + r_{d2} = 26/0.75 + 26/0.25 \cong 139\,\Omega$.

For $v_o/v_i = 0.5\,V/V$, use $I = 0.5\,mA$; $R_{eq} = 52 + 52 = 104\,\Omega$.

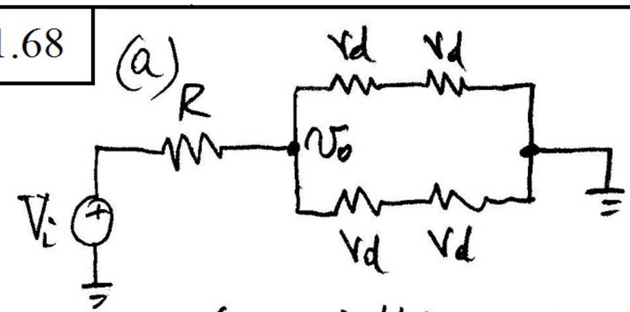
For $v_o/v_i = 0.25\,V/V$, use $I = 0.25\,mA$; $R_{eq} = 139\,\Omega$.

For $v_o/v_i = 0$, use $I = 0$; $R_{eq} = \infty + r_{d2} = \infty$.

(c) $R_{eq} = r_{d1} + r_{d2} = V_T/I + V_T/(1-I) = V_T/[(1-I)I]$; this is minimized for $I = 0.5\,mA$, where $R_{eq} = 26/0.5 + 26/0.5 = 104\,\Omega$. Impose $C >> 1/(10^6 \times 104) = 9.6\,nF$. Use $100\,nF$.

1.68

(a)



Since I splits evenly between the two halves, $r_d = \frac{V_T}{0.5I} = \frac{2V_T}{I}$.

But, $r = (r_d + r_d)//(r_d + r_d) = (2r_d)//(2r_d) = r_d = \frac{2V_T}{I}$.

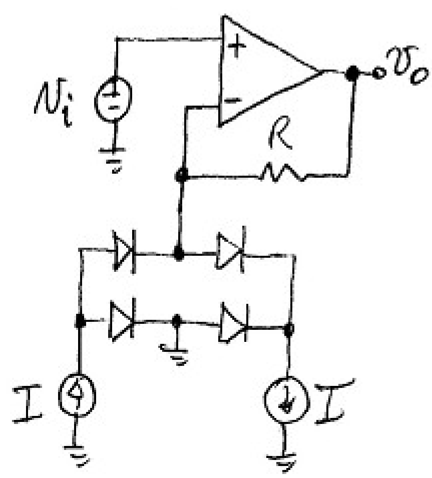
$$\frac{v_o}{v_i} = \frac{r}{R+r} = \frac{1}{1+R/r} = \frac{1}{1+R/(2V_T/I)} = \frac{1}{1+(R/2V_T)I}.$$

(b) since $v_o = 2v_d$, $|v_d| \le 5\,\text{mV} \Rightarrow |v_o| \le 10\,\text{mV}$.

(c) Impose $\frac{10\,\text{mV}}{1\,\text{V}} = \frac{1}{1+(10^4/0.052)I} \Rightarrow I = 515\,\mu\text{A}$.

1.69

(a) The diode bridge presents a net resistance towards ground of



$r = (2r_d)//(2r_d) = r_d$, where $r_d = \frac{V_T}{I/2} = 2\frac{V_T}{I}$. Then,

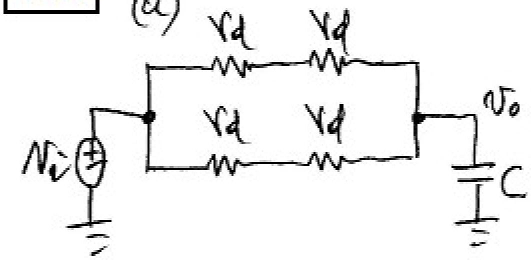
$$v_o = \left(1+\frac{R}{r}\right)v_i = \left(1+\frac{RI}{2V_T}\right)v_i$$

$$10 = 1 + \frac{R\times 0.5}{2\times 26} \Rightarrow R = 936\,\Omega.$$

(b) $v_o = (10\,\text{mV})\left(1+\frac{936\times 1}{2\times 26}\right)\cos\omega t = (190\,\text{mV})\cos\omega t$.

$v_o = (10\,\text{mV})\left(1+\frac{936\times 0.1}{2\times 26}\right)\cos\omega t = (28\,\text{mV})\cos\omega t$.

1.70 (a)



$r = (r_d + r_d) \,//\, (r_d + r_d) = r_d$
$= V_T / 0.5 I_S = 2V_T / I_S.$

(b) $H = \dfrac{1}{1 + j\omega/\omega_0}$, $\omega_0 = \dfrac{1}{rC} =$
$I_S / (2V_T C)$. (c) $10^6 = 0.1/(2 \times 26 \times C) \Rightarrow C = 1.92$ nF.

(d) $I_S = 1\text{mA} \Rightarrow \omega_0 = 10^7$ rad/s $\Rightarrow$

$H = \dfrac{1}{1 + j1/10} = \dfrac{1}{1 + j0.1} = 0.995 \angle -5.7^\circ.$

$v_o = (9.95\text{mV}) \cos(10^6 t - 5.7^\circ).$

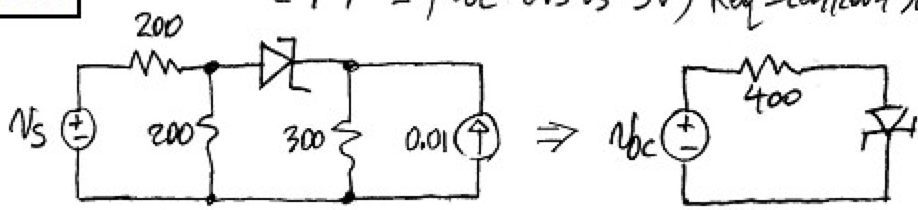
$I_S = 0.01\text{mA} \Rightarrow \omega_0 = 0.1 \times 10^6$ rad/s $\Rightarrow$

$H = \dfrac{1}{1 + j10/1} = 0.0995 \angle -84.3^\circ.$

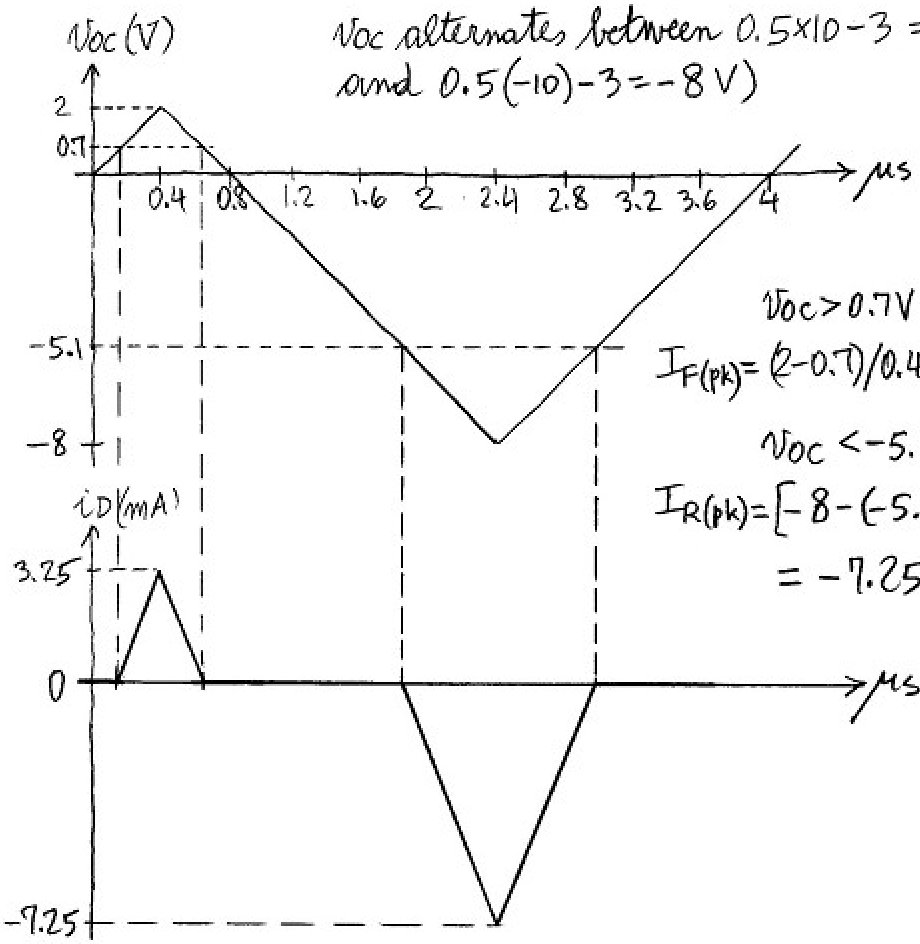
$v_o = (0.995\text{mV}) \cos(10^6 t - 84.3^\circ).$

1.71

[V, A, Ω]; $v_{OC} = 0.5 v_S - 3\,\text{V}$; $R_{eq} = 200 \| 200 + 300 = 400\,\Omega$



v_{OC} alternates between $0.5 \times 10 - 3 = +2\,\text{V}$ and $0.5(-10) - 3 = -8\,\text{V}$)



$v_{OC} > 0.7\,\text{V} \Rightarrow$ FB

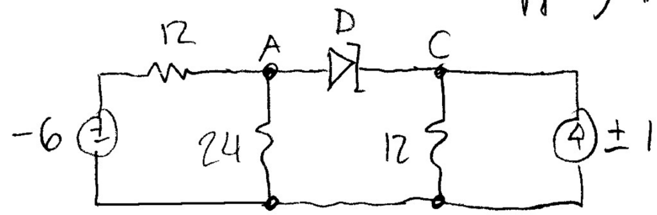
$I_{F(pk)} = (2 - 0.7)/0.4 = 3.25\,\text{mA}$

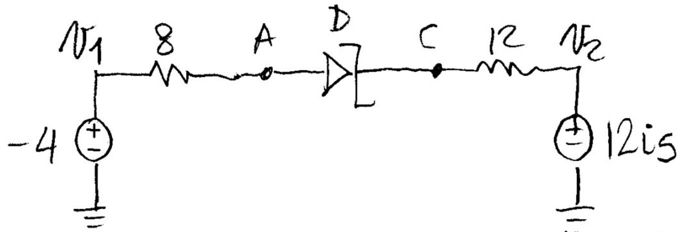
$v_{OC} < -5.1\,\text{V} \Rightarrow$ RB

$I_{R(pk)} = [-8 - (-5.1)]/0.4$

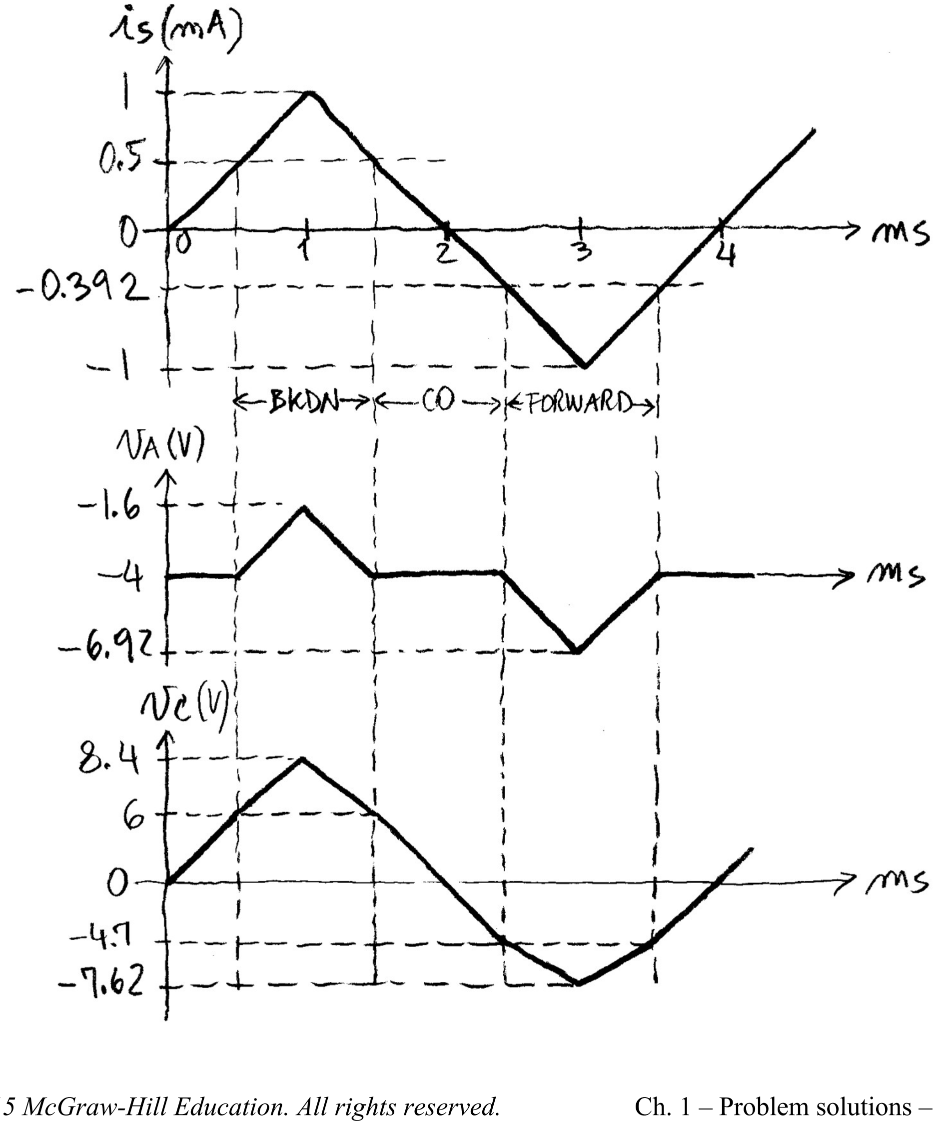
$= -7.25\,\text{mA}$

1.72 [V, mA, kΩ]. Apply Thévenin to the circuit left of A, a source transformation to the circuit right of C.





D = OFF for $(-4-0.7)\text{V} < v_2 < 6\text{V}$, or $(-4.7/12) < i_S < (6/12)$, or $-0.392\text{ mA} < i_S < 0.5\text{ mA}$.



1.72 cont.d

$D = CO \Rightarrow v_A = -4V,\ v_C = v_Z = 12\,i_S.$

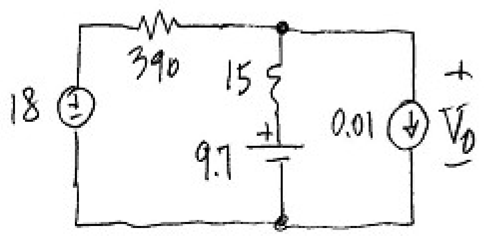
$D = BkDN:\ v_A = -4 + 8\left[\left(v_Z - 10 - -4\right)/(8+12)\right] = -6.4 + 4.8\,i_S,$

$v_C = v_A + 10V.\ v_A(1ms) = -1.6V,\ v_C(1ms) = 8.4\,V.$

$D = FORWARD:\ v_C = -4 - 8\left[(-4 - 0.7 - 12 i_S)/20\right] = -2.12 + 4.8 i_S.$

$v_C = v_A - 0.7V.\ v_A(3ms) = -2.12 - 4.8 = -6.92V;\ v_C(3ms) =$
$-6.92 - 0.7 = -7.62\,V.$

1.73 (a) [V, Ω, A]:



$$r_Z = \frac{10.0 - 9.85}{(20-10)\times 10^{-3}} = 15\Omega$$

$$V_{Z0} = 10.0 - 15\times 20\times 10^{-3} = 9.7V.$$

$$V_O = \frac{15}{390+15}18 + \frac{390}{390+15}9.7 - \frac{390\times 15}{390+15}0.01 = 9.863V.$$

(b) V_O is minimized (maximized) when V_I, V_{Z0}, and r_Z are minimized (maximized), and R and I_L are maximized (minimized).

$$V_{O(min)} \cong \frac{(0.9\times15)(0.9\times18) + (1.1\times390)(0.9\times9.7) - (390\times15)(1.1\times0.01)}{(1.1\times390) + (0.9\times15)} \cong 8.9\,V$$

$$V_{O(max)} \cong \frac{(1.1\times15)(1.1\times18) + (0.9\times390)(1.1\times9.7) - (390\times15)(0.9\times0.01)}{(0.9\times390) + (1.1\times15)} \cong 11.0\,V$$

1.74 $V_{Z0} = 12 - 0.012 \times 25 = 11.7\ V;$

$V_Z(4\,mA) = 11.7 + 0.012 \times 4 = 11.75\,V.$

(a) $R \le [(24-6) - 11.75]/[11.75/3 + 8 + 4] = 390\,\Omega.$

(b) line reg $= \dfrac{12 /\!/ 3000}{390 + 12/\!/3000} \cong 31\,mV/V$

Load reg $= -370 /\!/ 12 /\!/ 3000 \cong -11.6\,mV/mA.$

(c) $V_{O(min)} = \dfrac{12(24-6) + 390 \times 11.7 - (390 \times 12)(12/3 + 8) \times 10^{-3}}{390 + 12}$

$= 11.75\ V$

$V_{O(max)} = \dfrac{12(24+6) + 390 \times 11.7 - (390 \times 12)(12/3) \times 10^{-3}}{390 + 12}$

$= 12.2\ V$. Total variation is $< 4\%$.

1.75 (a) $V_{Z0} = 6.2 - 10 \times 0.020 = 6.0\text{V}.$

$$R \le \frac{(15-3)-6}{3+4+6/12} = 600\,\Omega \text{ (use } 580\,\Omega,\ 5\%\text{)}.$$

(b) Line regulation $= \dfrac{10//2500}{580+(10//2500)} \cong 16.9$ mV/V

(c) Load regulation $= +(580//10//2500) \cong +9.78$ mV/mA

(positive because an increase in I_L increases V_O (which is negative).

(d) V_O (which is negative) is maximized (minimized) when $V_I = -12\text{V}(-18\text{V})$, $R_L = 2\text{k}\Omega$ $(3\text{k}\Omega)$, and $I_L = 4\text{mA}$ (0 mA). Using superposition:

$$V_O(max) = (-12)\frac{10//2000}{580+(10//2000)} + (-6)\frac{580//2000}{10+(580//2000)} + (580//10//2000)0.004$$

$$= -0.202 - 5.869 + 0.039 = -6.032 \text{ V}$$

$$V_O(min) = (-18)\frac{10//3000}{580+(10//3000)} + (-6)\frac{580//3000}{10+(580//3000)} + 0$$

$$= -0.304 - 5.879 + 0 = -6.183 \text{ V}.$$

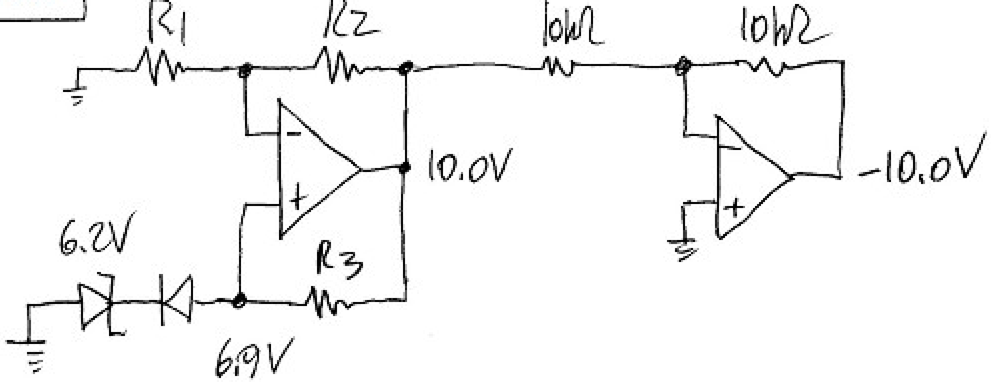
1.76 (a) $R = \dfrac{12-6.9}{3+2} \simeq 1.0\,\text{k}\Omega.$

(b) $r_d = 26/3 = 8.7\,\Omega$; $r = r_d + r_Z = 16.7\,\Omega.$

Line regulation $= \dfrac{16.7}{16.7+1000} = 16.4$ mV/V.

Load regulation $= -(1000//16.7) = -16.4$ mV/mA.

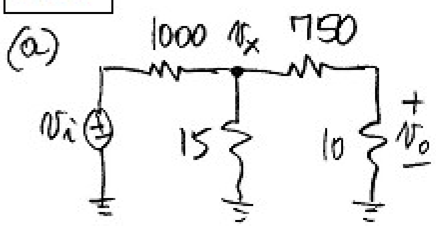
1.77



$R_3 = (10-6.9)/3 = 620\ \Omega$; $10 = (1+R_2/R_1)6.9 \Rightarrow R_2/R_1 = 0.45$. Use $R_1 = 6.8\text{ k}\Omega$, $R_2 = 3.0\text{ k}\Omega$

1.78

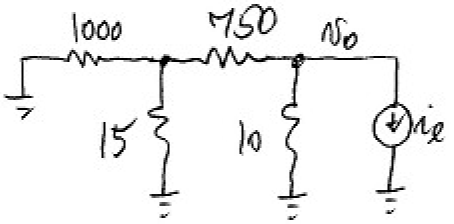
(a)



$v_o = \frac{10}{750+10} v_x = \frac{1}{76} v_x$.

$v_x = \frac{15 // (750+10)}{1000 + (15//760)} v_i = \frac{1}{70} v_i$

Line reg $= \frac{1}{76 \times 70} = 0.19\text{ mV/V}$!



$v_o = -i_L \{10 // [750 + (1000 // 15)]\}$

Load reg $= -9.87\text{ mV/mA}$

(b) $\frac{v_o}{v_i} = \frac{10}{1750+10} = \frac{1}{176} \Rightarrow$ line reg $= \frac{1}{176} = 5.68\text{ mV/V}$, quite an increase!

Load reg $= -10 // 1750 \cong -10\text{ mV/mA}$ (about the same as with D_1 in place.

1.79 (a) $V_{Z1(min)} = 14.7 + 15 \times 0.005 = 14.8\ V$

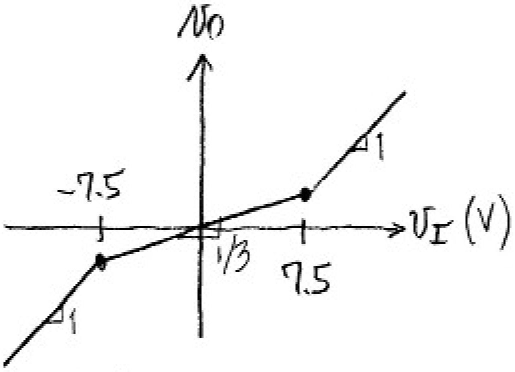
$V_{Z2(min)} = 9.8 + 10 \times 0.005 = 9.85V.$

$R_2 \leq \frac{14.8 - 9.85}{5+10} = 330\Omega$; $R_1 \leq \frac{(30-5) - 14.8}{5+5+10} = 510\ \Omega.$

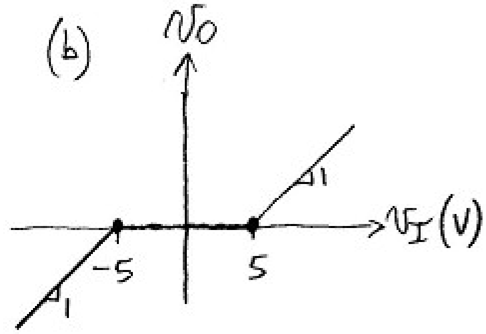
Line reg $\cong \frac{10}{340} \times \frac{15}{525} = 0.84\ mV/V.$

Load reg $\cong -10 // 345 = -9.7\ mA/mV.$

1.80 (a) When $D_1 = D_2 = OFF$, $v_O = [10/(10+20)]v_I = (1/3)v_I$. Either diode goes on for $|v_I - v_O| = 4.3 + 0.7 = 5\text{V}$, or for $|v_I - v_I/3| = 5 \Rightarrow v_I = \pm 7.5\text{V}$. For $|v_I| > 7.5\text{V}$ we have $v_O = v_I - 5$ for $v_I > 7.5$, $v_O = v_I + 5$ for $v_I < -7.5$.

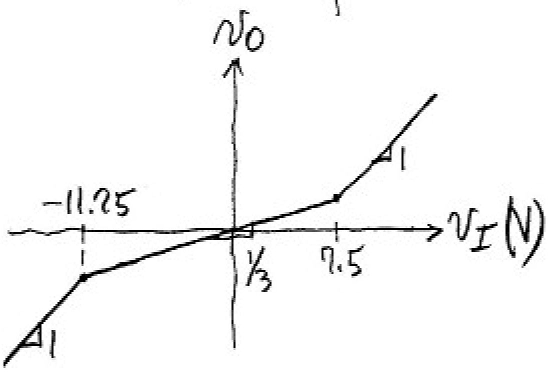


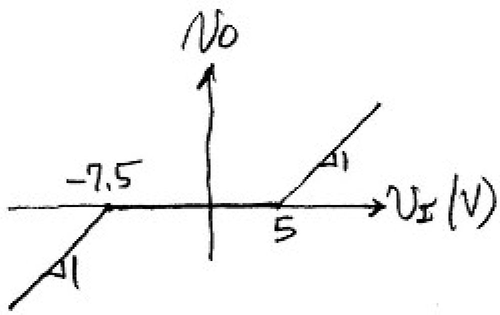
(b)



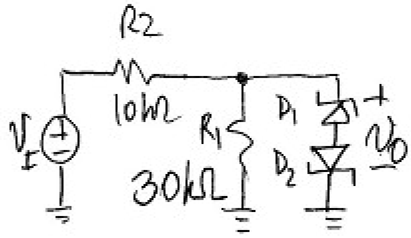
With the 20-kΩ resistance removed, $v_O = 0$ for $|v_I| \le 5\text{V}$, $v_O = v_I - 5$ for $v_I > 5$, and $v_O = v_I + 5$ for $v_I < -5\text{V}$.

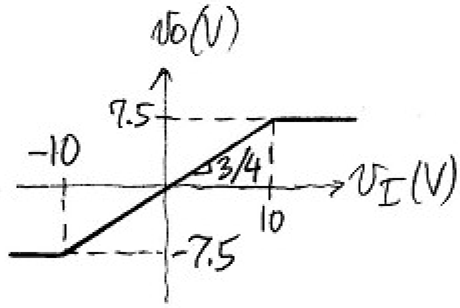
(c) With $V_{Z1} = 6.8$ V, the location of the breakpoint on the negative v_I-axis changes from -5V to -7.5 V in (b), and from -7.5V to $(3/2)(-7.5) = -11.25$V in (b).





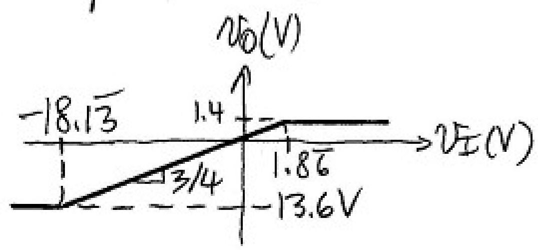
1.81 (a)





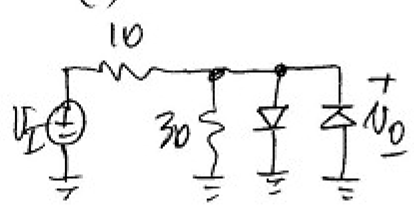
As long as both diodes are off, $v_O = (3/4)v_I$. When diodes go on, they clamp v_O at $\pm(V_Z + V_D) = \pm(6.8 + 0.7) = \pm 7.5$ V. Clamping occurs for $|v_I| \geq \frac{4}{3} \times 7.5 = 10$ V.

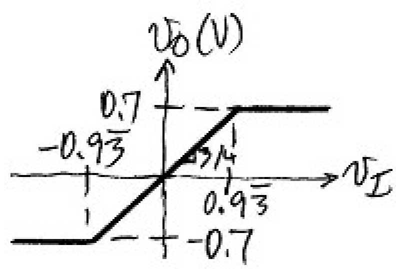
(b)



Now v_O is clamped at $+2V_D = 1.4$ V, and at $-2V_Z = -13.6$ V. Positive clamping occurs for $v_I \geq \frac{4}{3} \times 1.4 = 1.8\overline{6}$ V, and negative clamping for $v_I \leq -\frac{4}{3} \times 13.6 = -18.1\overline{3}$ V

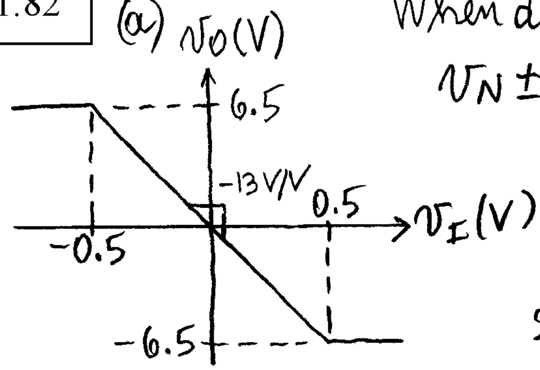
(c)





Now v_O is clamped at ± 0.7V, and clamping occurs for $|v_I| > \frac{4}{3} \times 0.7 = 0.9\overline{3}$ V

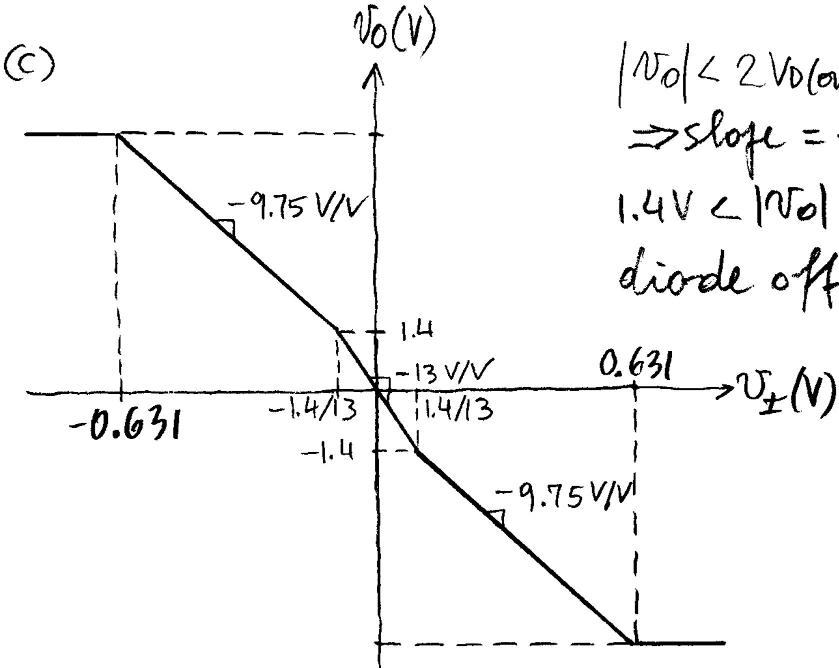
1.82 (a) When diodes go on, v_O is clamped at $v_N \pm (V_Z + 2V_{D(on)}) = 0 \pm (5.1 + 1.4) = \pm 6.5\text{V}$



When diodes are off, gain is $-13/1 = -13$ V/V. Clamping starts when $v_I = \frac{\pm 6.5}{13} = \mp 0.5$ V.

(b) Slope is still −13 V/V, but output clamping occurs at $v_O = \pm 3V_{D(on)} = \pm 2.1$ V instead of ±6.5V.

(c)



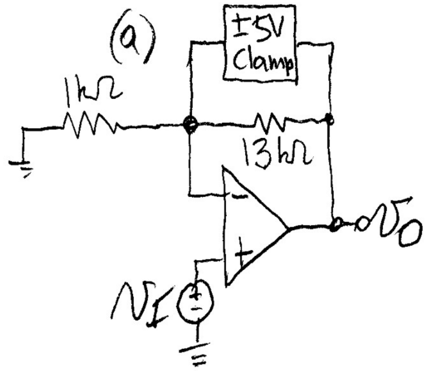
$|v_O| < 2V_{D(on)} = 1.4\text{V} \Rightarrow$ Diodes off $\Rightarrow$ slope $= -13$ V/V

$1.4\text{V} < |v_O| < 6.5\text{V} \Rightarrow$ Zener diode off $\Rightarrow$ slope $=$

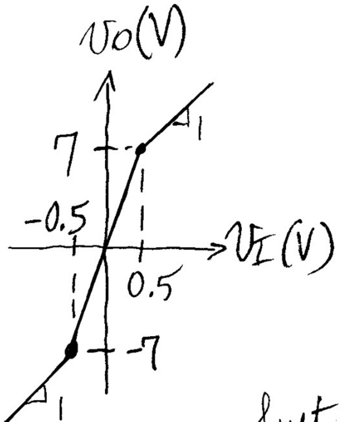
$$-\frac{R_2 // R_3}{R_1} = -13/39 = -9.75 \text{ V/V}.$$

v_O reaches ±6.5V for $v_I = \pm\left(\frac{1.4}{13} + \frac{6.5 - 1.4}{9.75}\right) = \pm 0.631$ V

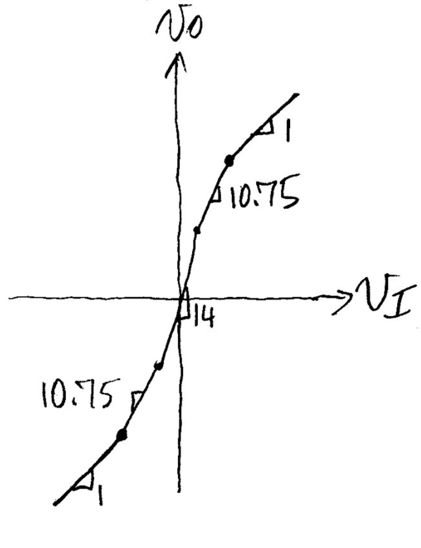
(a)



When diodes are off, we have $v_O = (1+\frac{13}{1})v_I = 14\,v_I$.
Clamping occurs for $|v_O - v_N| = |v_O - v_I| = V_Z + 2V_{D(on)}$
$= 5.1 + 1.4 = 6.5$ V. This occurs for $|14v_I - v_I| = 6.5$, or $v_I = \pm 0.5$ V. For $|v_I| > 0.5$ V, we have $v_O = v_I - 7$ for $v_I > 0.5$, $v_O = v_I + 7$ for $v_I < -0.5$.



(b) We still have $v_O = 14v_I$, but only for $|v_O - v_I| \le 2V_{D(on)}$ $= 1.4$V, or for $|v_I| \le \frac{1.4}{13}$ V $=$ 0.1077 V. Once the diode bridge starts conducting, but D_Z is still off, slope changes to $1 + (13 /\!/ 39) = 10.75$ V/V. Once D_Z goes on, slope $= 1$ V/V. D_Z goes on for $|v_I| = 0.5$V.



1.84 (a) $V_p = 24 \times \sqrt{2} \cong 34\text{V}$; $C = \dfrac{V_p}{2fRV_r} = \dfrac{34}{2 \times 60 \times 10^3 \times 2} \cong 142\mu\text{F}$.

(b) $V_O = V_p - V_{D(on)} - \frac{1}{2}V_r \cong 34 - 0.8 - 2/1 = 32.2\text{V}$.

$i_{D(max)} = \dfrac{34}{1}\left(1 + 2\pi\sqrt{34/(2\times2)}\right) = 657\text{mA}$.

$i_{D(avg)} \cong \frac{1}{2}657 \cong 330$ mA. $T_{ON} \cong \dfrac{1}{2\pi 60}\sqrt{2\dfrac{2}{34}} \cong 0.91\text{ms}$

(5.5%). $PIV = 2V_p \cong 68\text{V}$ (Use 100V to be safe).

(c) Circuit becomes a 1/2-wave rectifier.

$V_r \cong 2 \times 2 = 4\text{V}$; $V_O \cong 34 - 0.8 - \frac{1}{2}4 = 31.2\text{V}$

$i_{D(max)} \cong \dfrac{34}{1}\left(1 + 2\pi\sqrt{2\times34/4}\right) \cong 915\text{mA}$ (an increase by appx $(\sqrt{2}-1)$, or 41%). $i_{D(avg)}$ and T_{ON} also increase by appx 41%. PIV remains the same.

1.85 (a) $V_p = 18\sqrt{2} = 25.5\text{V}$, $I_L = 10\text{ mA}$

$$C = \frac{I_L}{2fV_r} = \frac{10\times10^{-3}}{2\times60\times1.5} = 56\,\mu\text{F}.$$

(b) $V_O = 25.5 - 2\times0.8 - 1.5/2 = 23.2\text{ V}$

$$i_{D(max)} = 10\left(1+2\pi\sqrt{\frac{25.5}{2\times1.5}}\right) = 193\text{ mA}$$

$i_{D(avg)} \cong 100\text{ mA}$

$$T_{ON} = \frac{1}{2\pi60}\sqrt{\frac{2\times1.5}{25.5}} = 0.91\text{ ms} = 5.5\%\text{ of }T.$$

$PIV \cong V_p \cong 25\text{V}$ (use 40 V for safety).

(c) If D_4 becomes an open, D_1 will never go on. Only D_2 and D_3 will conduct during the negative alternations of v_S, in effect resulting in half-wave rectification, but with two diode drops. So, V_r doubles to $2\times1.5 = 3\text{V}$; $V_O = 25.5 - 2\times0.8 - 3/2 = 22.4\text{ V}$.

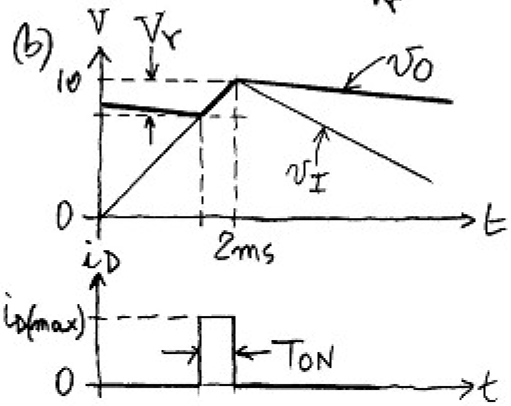
$i_{D(max)} \cong 10\left(1+2\pi\sqrt{\frac{2\times25.5}{3}}\right) \cong 270\text{mA}$ (an increase by approximately $(\sqrt{2}-1)$, or 41%). A similar increase affects $i_{D(avg)}$. The conduction interval of D_2 & D_3 is

$$T_{ON} = \frac{1}{2\pi60}\sqrt{2\times3/25.5} = 1.29\text{ms}\ (41\%\text{ increase}).$$

$PIV = \frac{1}{2}V_p \sim 13\text{V}$ (specify 20 V for safety).

1.86 (a) $V_O = V_m - V_{D(on)} - \frac{1}{2}V_r = 10 - 0.7 - \frac{0.5}{2} \cong 9\text{ V}$. $T_{OFF} \cong T = 6\text{ ms}$. $C \cong \frac{I_{total} \times T_{OFF}}{V_r} \cong \frac{(10+9/1)10^{-3} \times 6\times10^{-3}}{0.5} \cong 230\ \mu F$.

(b)



Proportionality:

$$\frac{V_r}{T_{ON}} = \frac{V_m}{2\text{ms}} \Rightarrow T_{ON} = 2\frac{V_r}{V_m} = 2\frac{0.5}{10}$$

$= 0.1\text{ ms}$ ($\ll T_{OFF} \cong T$)

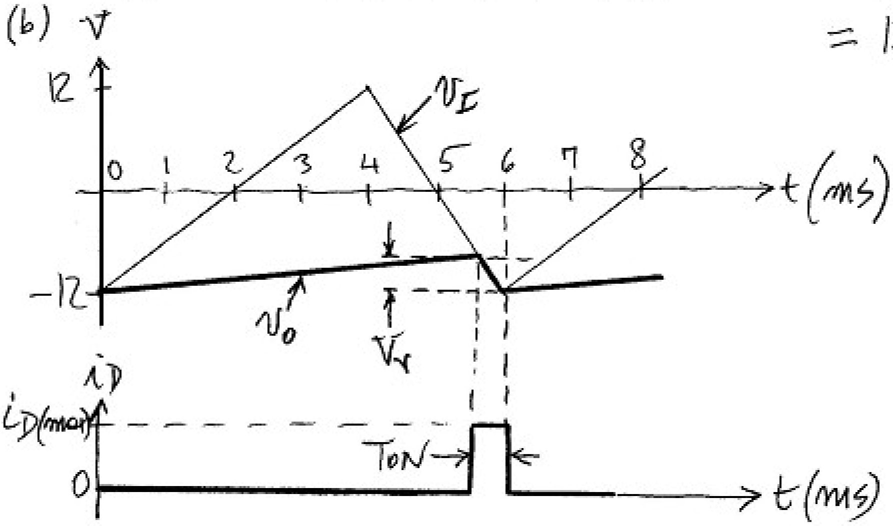
(c) $V_O \cong 9\text{V}$; $i_{D(avg)} = i_{D(max)} = C\frac{V_r}{T_{ON}} = 230\times10^{-6}\frac{0.5}{0.1\times10^{-3}}$
$\cong 1.15\text{ A}$ (!). $PIV = 2V_m = 20\text{V}$ (Use 30 V).

doubles to $2\times1.5 = 3\text{ V}$; $V_O = 25.5 - 2\times0.8 - 3/2 = 22.4\text{ V}$.
$i_{D(max)} \cong 10\left(1 + 2\pi\sqrt{\frac{2\times25.5}{3}}\right) \cong 270\text{ mA}$ (an increase by approximately $(\sqrt{2}-1)$, or 41%). A similar increase affects $i_{D(avg)}$. The conduction interval of D_2 & D_3 is
$T_{ON} = \frac{1}{2\pi 60}\sqrt{2\times3/25.5} = 1.29\text{ ms}$ (41% increase).
$PIV = \frac{1}{2}V_p \sim 13\text{V}$ (specify 20 V for safety).

1.87 (a) $CV_r \cong I_L T_{OFF} \cong I_L T \Rightarrow C \cong (10\times10^{-3}\times 6\times10^{-6})/0.5$

$= 120\ \mu F.$

(b)



(c) $V_O \cong -12+0.85+0.5/2 = -10.9$ V.

$i_{D(avg)} = i_{D(max)} = C\dfrac{dv_O}{dt} = 120\times10^{-6}\dfrac{12}{1\times10^{-3}} = 1.44\,A$

Proportionality:

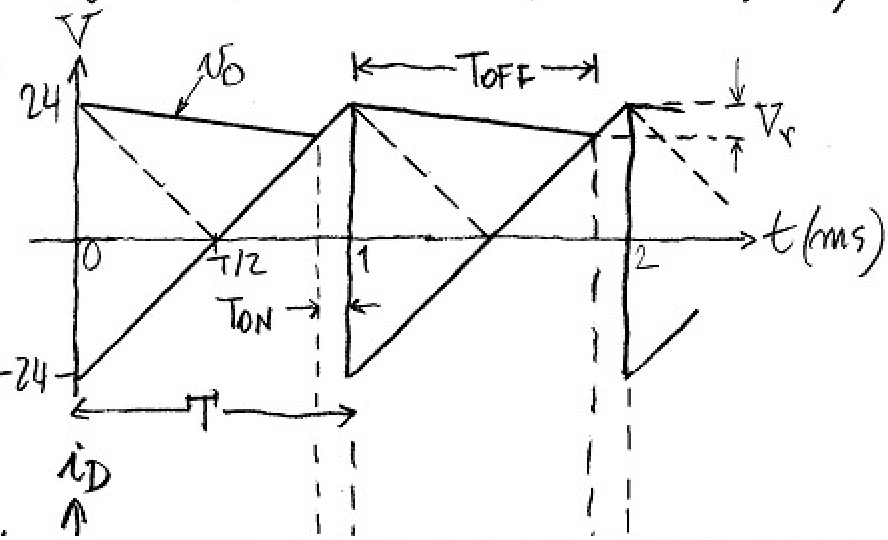
$V_r/T_{ON} = V_m/1ms \Rightarrow T_{ON} = \dfrac{V_r}{V_m}1ms = \dfrac{0.5}{12}10^{-3} \cong 42\,\mu s\ (0.7\%).$

$PIV = 2V_p = 24V$ (use 40 V to be safe).

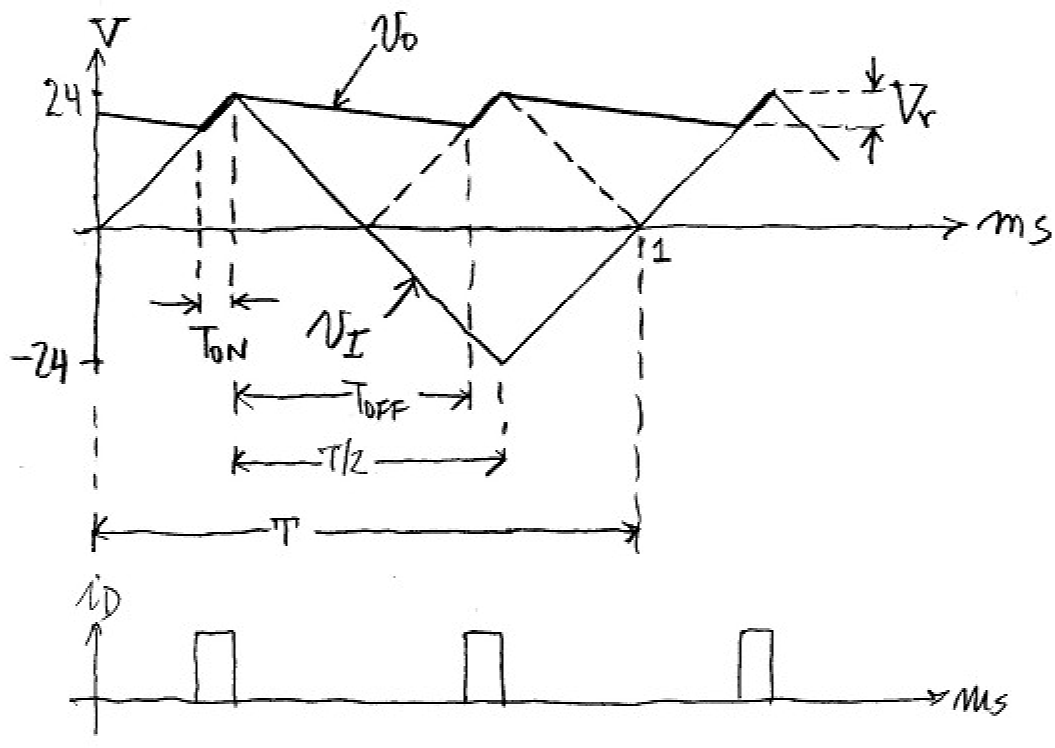
1.88 (a) $V_O = 24 - 2\times0.75 - \frac{1}{2}\times1 = 22\,V$; $I = 22/2 = 11\,mA$.

$CV_r = I_O T_{OFF} \cong I_O T = I_O/f \Rightarrow C = (11\times10^{-3})/(10^3\times1) = 11\,\mu F$.

(b)



1.89



$V_O = 24 - 2\times0.75 - \frac{1}{2}1 = 22\,V$; $I_O = 22/2 = 11\,mA$.

$CV_r = I_O T_{OFF} \cong I_O T/2 = I_O/(2f) \Rightarrow C \cong 11\times10^{-3}/(2\times10^3\times1) =$ $5.5\,\mu F$. $T_{ON} = (1/24)(T/4) = (1/24)(10^{-3}/4) \cong 10.4\,\mu s$

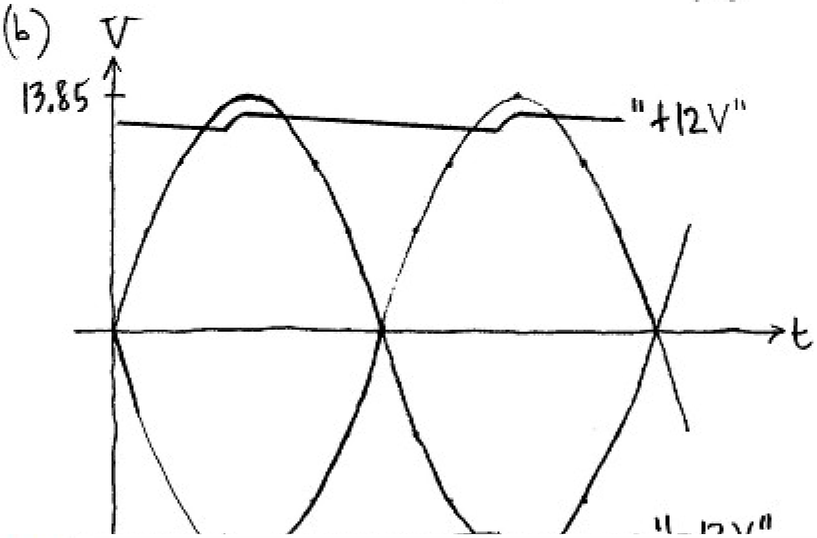
$i_{D(avg)} = i_{D(max)} = C\frac{V_r}{T_{ON}} + I_O = (5.5\times10^{-6})\frac{1}{10.4\times10^{-6}} + 11\times10^{-3}$ $= 540\,mA$. PIV = 24V (make 35V to be safe).

1.90

(a) We want $12 = V_p - 2\times 0.8 - 0.5/2 \Rightarrow V_p = 13.85\,V$

$2V_p = 27.7\,V$. $C_1 = C_2 = \frac{I_L \times T_{OFF}}{V_r} = \frac{0.1\times 1/(2\times 60)}{0.5} = 1.67\,mF$.

(b)



1.91 (a) Let $V_p \cong 25V$. Then, $n = 25/(120\times\sqrt{2}) = 0.1473$. Pick $n = 0.15$ (easier number). Then, $V_p = 0.15\times 120\sqrt{2} = 25.5V$. Let $V_r = 2V$. Then, $V_{I(min)} = 25.5 - 0.8 - 2 = 22.7\,V$. $V_{Z0} = 15 - 0.01\times 25 = 14.75V$. Let $I_{Z(min)} = 5\,mA$. Then,

$R \le \frac{22.7 - 15}{5 + 25} = 253\Omega$. Use 240Ω to be safe.

During capacitor discharge, $I_C \sim I_R = \frac{22.7 + 2/2 - 15}{0.240} \cong 36\,mA$. $CV_r \simeq I_R T_{OFF} \cong I_R T \Rightarrow C \cong [36\times 10^{-3}/60]/2 = 300\,\mu F$. In summary, $n = 0.15$, $R = 240\Omega$, $C = 300\,\mu F$. Diode D_1, beside $V_{D(on)} = 0.8\,V$, must be capable of carrying

$i_{D(max)} \cong 36\left(1 + 2\pi\sqrt{\frac{2\times 25.5}{2}}\right) = 1.2A$, $i_{D(avg)} \cong 0.6A$, and $PIV = 2V_p = 51V$ (use 80 V to be safe).

(b) $V_{ro} \cong \frac{10}{10 + 240} V_{ri} = \frac{1}{25}2 = 80\,mV$.