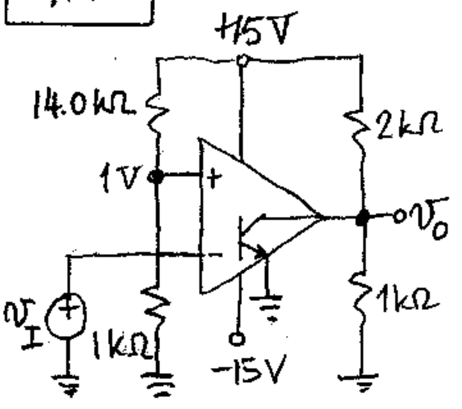
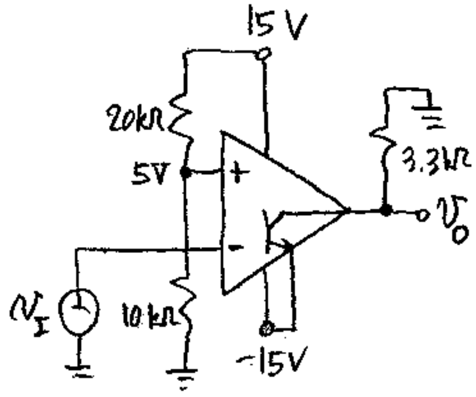
(9.1)

9.1

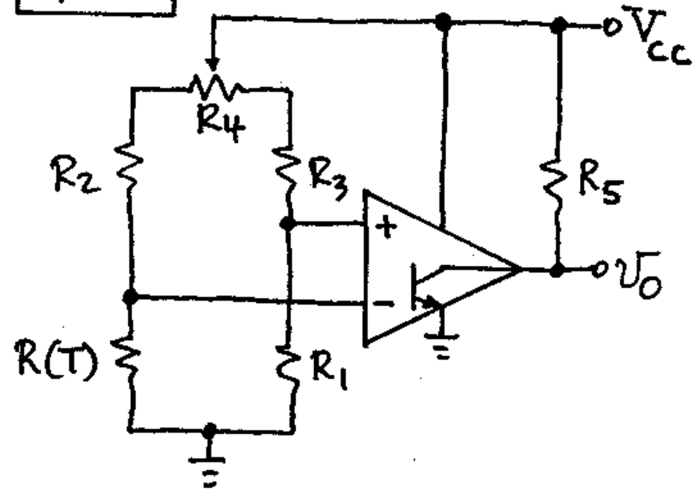



(a)




(b)

9.2

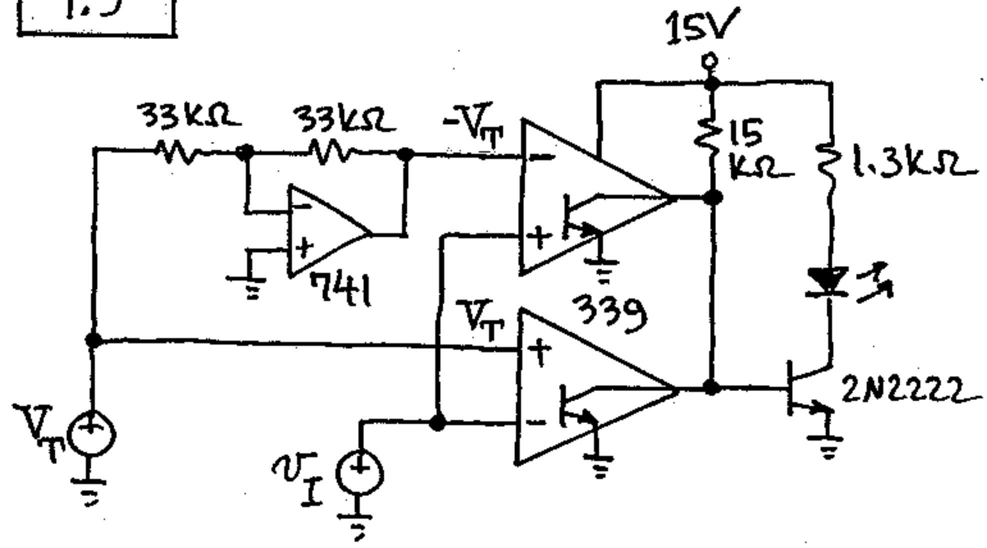



Since the voltage developed by the thermistor decreases with T, it must be applied to the inverting input. $R(100°C) = 100\,k\Omega \times \exp[4000(1/373.2 - 1/298.2)] = 6.75\,k\Omega$. Make all bridge resistors nominally $6.75\,k\Omega$. To allow exact calibration, let $R_4 = 1\,k\Omega$ pot and $R_2 = R_3 = 6.75 - 0.5 = 6.25\,k\Omega$. The closest 1% standard values are $R_1 = 6.81\,k\Omega$ and $R_2 = R_3 = 6.19\,k\Omega$. Moreover, let $R_5 = 3.3\,k\Omega$. To calibrate, place the thermistor in

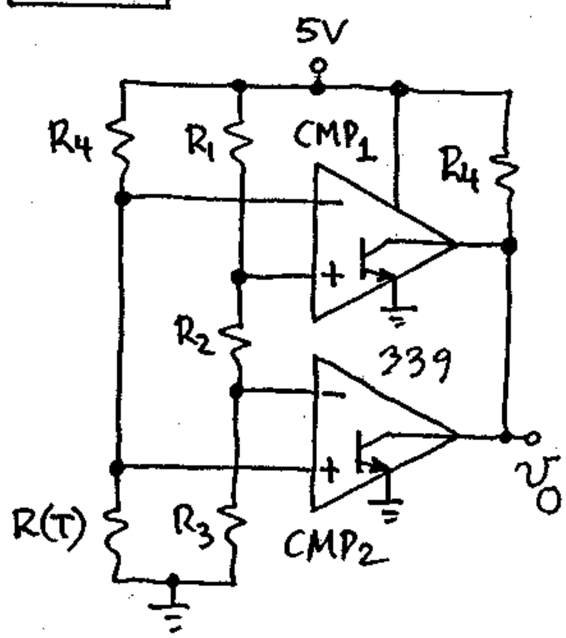
9.2

boiling water and adjust $R_4$ until $V_o$ bounces back and forth between 0 and $V_{CC}$.

9.3




9.4




$R(0°C) = 34.12\,k\Omega$.

$R(5°C) = 26.23\,k\Omega$.

Let $R_4 = 30\,k\Omega$.

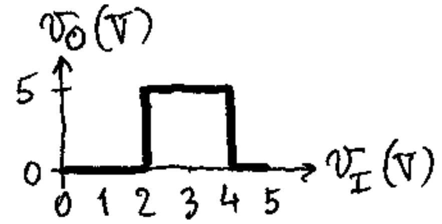
Then, $V_{TL} = 5 \times \dfrac{26.23}{26.23+30} = 2.33V$

$V_{TH} = 5\,\dfrac{34.12}{34.12+30} =$ 2.66V. Use

$R_3 = 23.2\,k\Omega$,

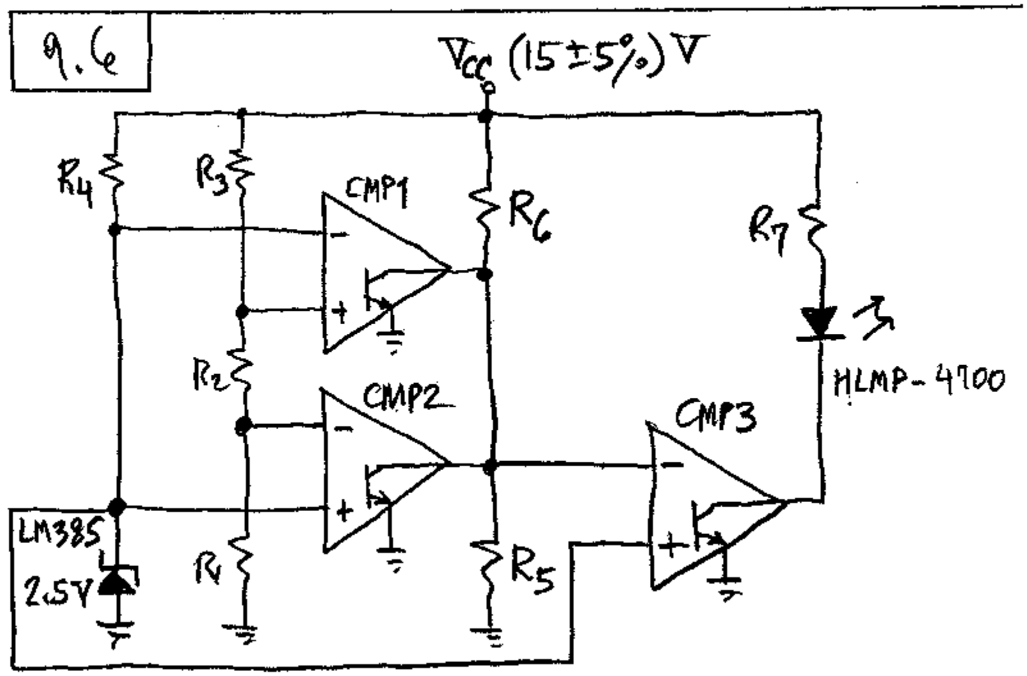
$R_2 = 3.32\,k\Omega$, $R_1 = 23.4\,k\Omega$.

**9.5** We have $v_{N1} = v_I/2$, $v_{P1} = (v_1 + v_2)/2$, $v_{P2} = (v_I + v_2)/2$, $v_{N2} = v_1/2$. Thus, $v_O = V_{OH}$ for $v_{P1} > v_{N1}$ and $v_{P2} > v_{N2}$, that is, $v_O = V_{OH}$ $v_1 + v_2 > v_I$ and $v_I + v_2 > v_1$. Summarizing, $v_O = V_{OH}$ for $(v_1 - v_2) < v_I < (v_1 + v_2)$, $v_O = V_{OL}$ otherwise. As exemplified in the figure,




the center of the VTC is $v_1$, and the width is $v_2$.

**9.6**

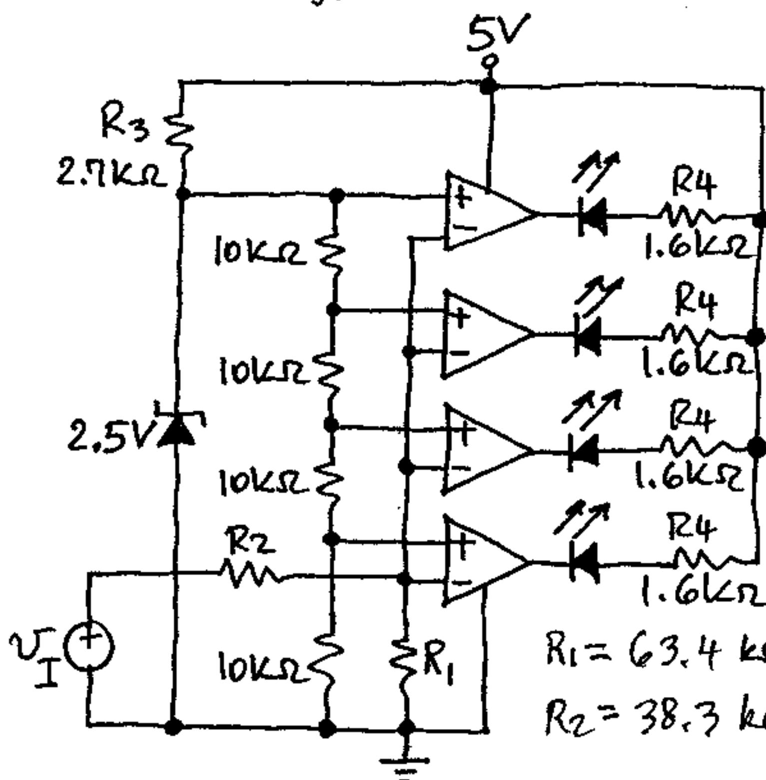



$$\frac{R_1}{R_1+R_2+R_3} = \frac{2.5}{15.75}, \quad \frac{R_1+R_2}{R_1+R_2+R_3} = \frac{2.5}{14.25} \Rightarrow R_1 = 10.0$$

k$\Omega$, $R_2 = 1.05$ k$\Omega$, $R_3 = 52.3$ k$\Omega$, 1%; $R_4 \doteq R_5 =$ 10 k$\Omega$, $R_6 = 20$ k$\Omega$ $\Rightarrow v_{N3} \cong 5$ V for $V_{CC}$ within tolerance, $v_{N3} \cong 0$V otherwise; $v_{P3} = 2.5$V;

$R_7 = (15 - 1.8)/2 \cong 6.8$ k$\Omega$.

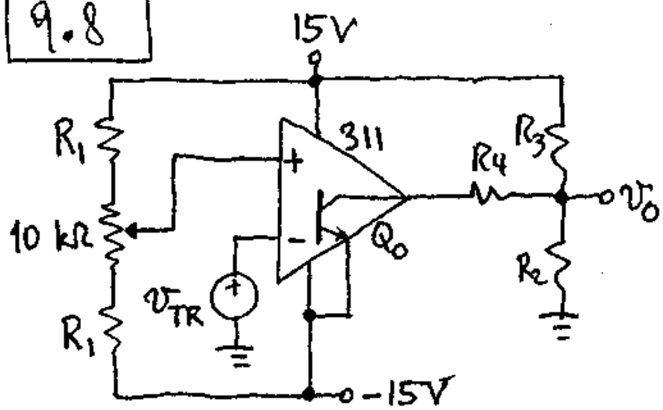
**9.7** Use four 10-kΩ resistors to split the reference range into four equal intervals. Bias the reference diode and the four resistors with $R_3 = 2.7\,k\Omega$. Use $R_1$ and $R_2$ to scale the 4 V input range to the 2.5V reference range. This requires $R_2 = 0.6R_1$, or $R_1 = 62.5\,k\Omega$ and $R_2 = 37.5\,k\Omega$. Finally, $R_4 = (5-1.8)/2 = 1.6\,k\Omega$.




$R_1 = 63.4\,k\Omega$

$R_2 = 38.3\,k\Omega$

**9.8**



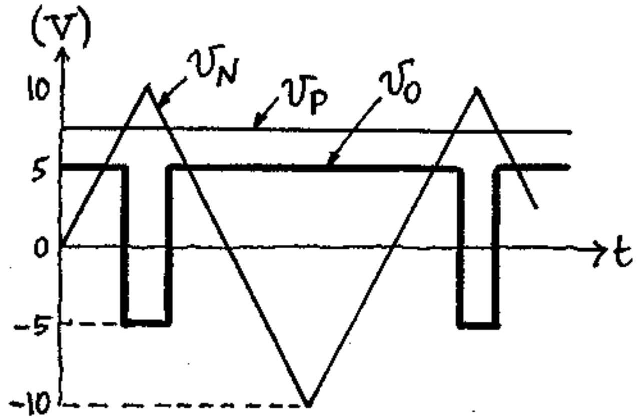

Wiper up ⇒

$D(\%) = 95$ ⇒

$$\frac{5}{5+R_1}15 = 9$$

⇒ $R_1 = 3.32\,k\Omega$, 1%.

9.5




$Q_0 = \text{OFF} \Rightarrow$

$v_O = \frac{R_2}{R_2+R_3} 15 = 5$

$\Rightarrow R_2 = 10.0\ \text{k}\Omega$

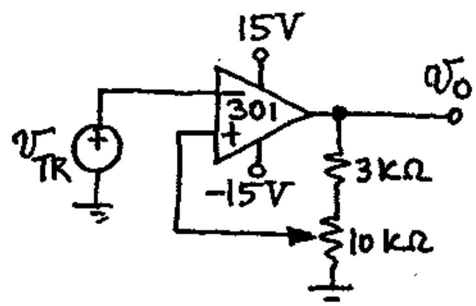
$R_3 = 20.0\ \text{k}\Omega.$

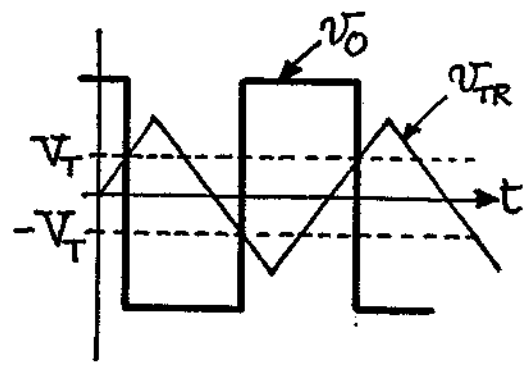
$Q_0 = \text{SAT} \Rightarrow$

$v_O = -5\text{V} \Rightarrow \frac{15-(-5)}{20} + \frac{0-(-5)}{10} = \frac{-5-(-15)}{R_4} \Rightarrow$

$R_4 = 6.67\ \text{k}\Omega$ (use $6.65\ \text{k}\Omega$, 1%).

9.9 Use a $3\text{k}\Omega$ series resistor to make $V_T$ variable from 0V to 10V.




9.10 (a) Imposing $v_P = v_N$ with $v_O \cong 0$ and $v_I = V_{TH}$ gives $V_{TH} \times R_4/(R_3+R_4) = V_{CC}R_1/(R_1+R_2)$. Imposing $v_P = v_N$ with $v_O \cong V_{CC}$ and $v_I = V_{TL}$ gives $V_{TL}R_4/(R_3+R_4) + V_{CC}R_3/(R_3+R_4) = V_{CC} \times R_1/(R_1+R_2)$. Combining the two equations,

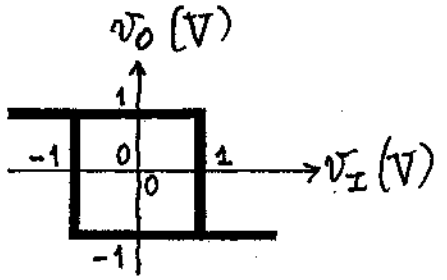
$$\frac{R_3}{R_4} = \frac{V_{TH}-V_{TL}}{V_{CC}} \qquad \frac{R_2}{R_1} = \frac{V_{CC}-V_{TH}}{V_{TH}}.$$

(9.6)

(b) $R_3/R_4 = (2.5-1.5)/5 = 0.2$; $R_2/R_1 = (15-1.5)/2.5 = 1.4$. To ensure $V_{OH} \cong 5$ V, impose $R_5 \ll R_3 + R_4$. To minimize the effect of the input bias current, impose $R_1 \| R_2 = R_3 \| R_4 \ll V_{OS}/I_{OS}$. Assuming a 339 comparator, $V_{OS}/I_{OS} = (2\text{ mV})/(5\text{ nA}) = 400$ kΩ. Let $R_5 = 2.2$ kΩ and $R_4 = 220$ kΩ; then $R_3 = 44$ kΩ (use 44.2 kΩ), $R_1 = 62.8$ kΩ (use 63.4 kΩ), and $R_2 = 88$ kΩ (use 88.7 kΩ).

---

9.11 When the 301 saturates at +13V, $D_3 = D_2 = \text{ON}$, $D_1 = D_4 = \text{OFF}$, $v_O = 1 \times (15-0.7)/((13.3+1)) = 1$ V. Likewise, when the 301 saturates at −13 V, $D_1 = D_4 = \text{ON}$, $D_2 = D_3 = \text{OFF}$, and $v_O = -1$ V ⇒




Schmitt trigger with $v_O = \pm 1$ V and $\pm V_T = \pm 1$ V.

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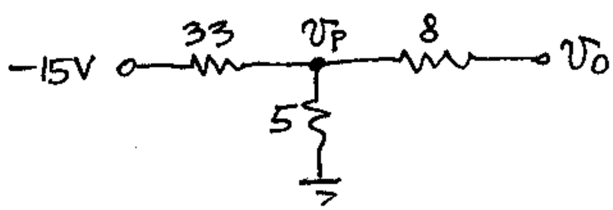
9.12 (a)



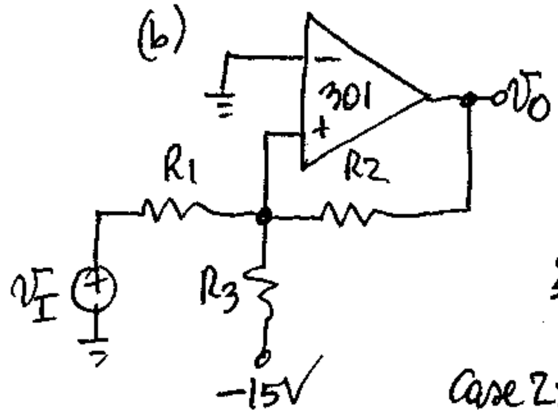

$$v_P = \frac{33\|5}{33\|5+8} v_O + \frac{8\|5}{33+8\|5}(-15) = 0.352 v_O - 1.279 \text{ V}.$$

$V_{TH} = v_P|_{v_O = 13\text{V}} = 3.29$ V; $V_{TL} = v_P|_{v_O=-13\text{V}} = -5.85$V.

The result is a VTC with $V_{OH} = 13$ V, $V_{OL} = -13$ V, $V_{TH} = 3.29$ V, $V_{TL} = -5.85$V. Effect of 33 kΩ is to shift the VTC toward the left.

9.7

(b)




$v_P = 0$ in two cases:
Case 1: $v_O = V_{OL}$ and $v_I = V_{TH}$: KCL:

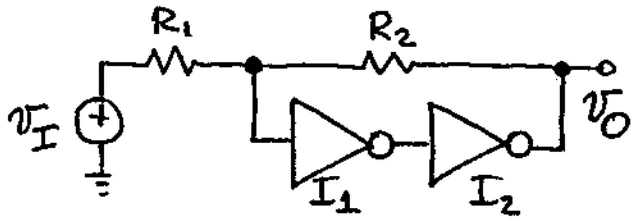
$$\frac{2-0}{R_1} = \frac{0-(-15)}{R_3} + \frac{0-(-13)}{R_2}$$

Case 2: $v_O = V_{OH}$ and $v_I = V_{TL}$:

KCL: $\frac{13-0}{R_2} + \frac{1-0}{R_1} = \frac{0-(-15)}{R_3}$. Two equations, three unknowns. Fix $R_1 = 10\ \text{k}\Omega$; then, $R_3 = 100\ \text{k}\Omega$ and $R_2 = 260\ \text{k}\Omega$ (use 261 kΩ).

---

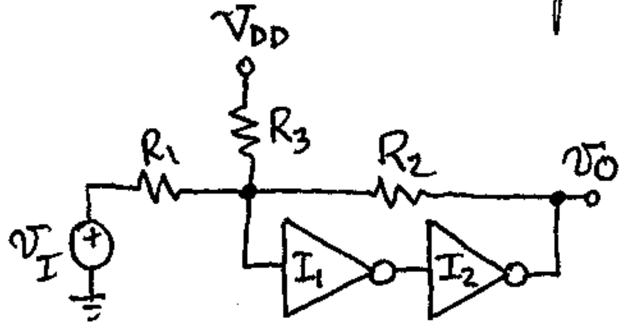
9.13 (a) With $v_O = 0$ and $v_I = V_{TH} = (2/3)V_{DD}$




we want the voltage at $I_1$'s input to be $V_T$.

Thus, $\frac{R_2}{R_1+R_2}\frac{2}{3}V_{DD} = \frac{1}{2}V_{DD}$, that is, $R_2 = 3R_1$.
Use $R_1 = 10\ \text{k}\Omega$, $R_2 = 30\ \text{k}\Omega$.

(b) We need a pullup resistor to shift the $V_{TC}$ downward.




With $v_O = 0$ we have

$$\frac{V_{DD}-V_T}{R_3} + \frac{V_{TH}-V_T}{R_1} = \frac{V_T - 0}{R_2}.$$

Letting $V_T = \frac{1}{2}V_{DD}$ and $V_{TH} = \frac{1}{2}V_{DD}$ gives $R_2 = R_3$. With

(9.8)

with $v_O = V_{DD}$ we have $\frac{V_{DD}-V_T}{R_2 /\!/ R_3} = \frac{V_T - V_{TL}}{R_1}$. Letting $V_T = \frac{1}{2}V_{DD}$ and $V_{TL} = \frac{1}{5}V_{DD}$ gives $R_1 = 0.3R_3$. Use $R_2 = R_3 = 100\ \text{k}\Omega$, $R_1 = 30\ \text{k}\Omega$.

(c) Use an additional inverter at the output.

---

9.14 $R(100.5°C) = 100\ \text{k}\Omega \times \exp[4000 \times (1/373.7 - 1/298.2)] = 6.65\ \text{k}\Omega$. Thus, a temperature change of 0.5°C near 100°C induces a thermistor voltage change of value $V_{CC}/2 - V_{CC}\,6.65/(6.65+6.75) = 3.6 \times 10^{-3}\,V_{CC}$. Connect a resistor $R_6$ between output and noninverting input to produce a hysteresis width $V_H = 7.2 \times 10^{-6} \times V_{CC}$. Since $V_{OH} - V_{OL} \cong V_{CC}$, impose

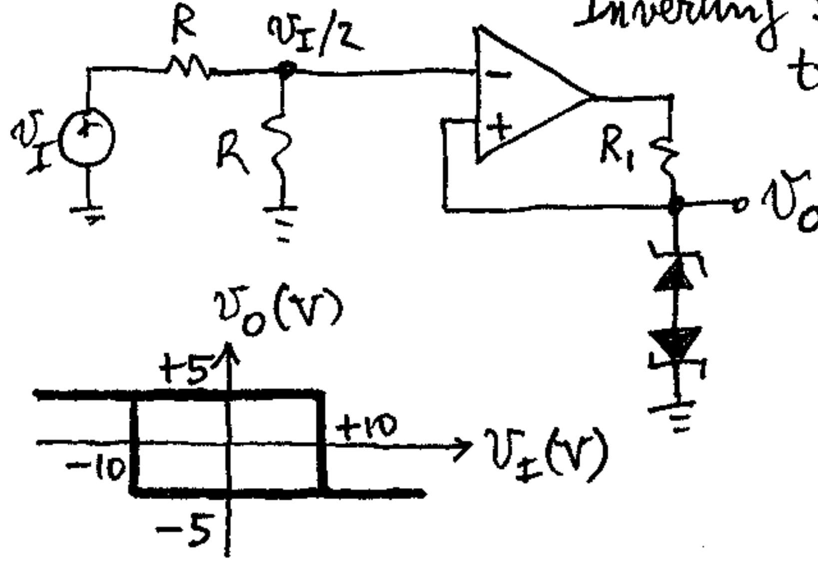
$$\frac{R_1 /\!/ (R_3 + R_4/2)}{R_1 /\!/ (R_3 + R_4/2) + R_6} V_{CC} = V_H,$$ that is,

$$\frac{6.75/2}{6.75/2 + R_6} V_{CC} = 7.2 \times 10^{-3}\,V_{CC}.$$ Solving yields $R_6 \cong 470\ \text{k}\Omega$. To calibrate, place the thermistor in boiling water and find the wiper settings that just cause $v_O$ to change state. Then, set the wiper halfway.

(9.9)

## 9.15

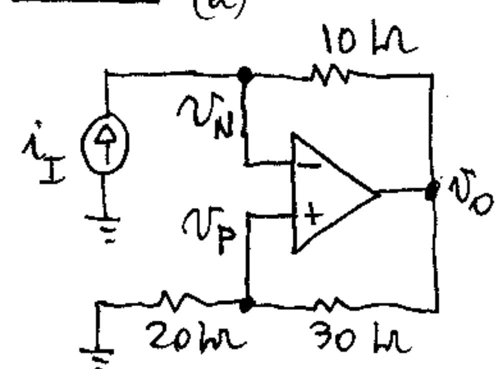
Inverting Schmitt trigger.




$v_O = \pm(4.3+0.7) = \pm 5V$. $v_O$ trips whenever $v_I/2 = \pm 5V$, i.e. whenever $v_I = \pm 10V$.

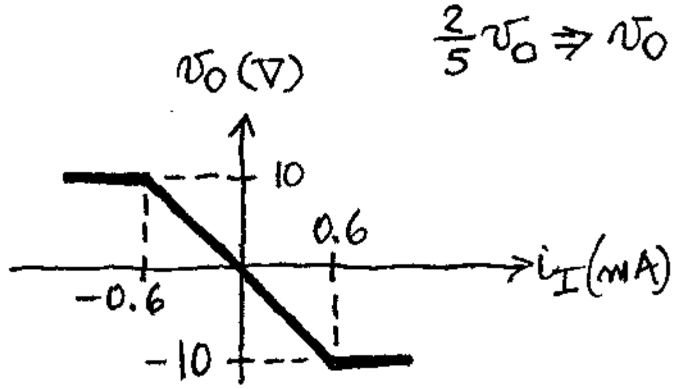
## 9.16

(a)



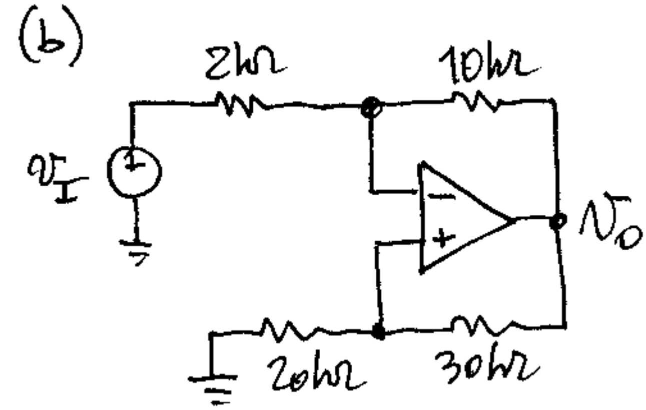

$\beta_N = 1$, $\beta_P = 2/5 = 0.4$ $\Rightarrow$ negative feedback prevails over positive feedback $\Rightarrow v_N = v_P$.

$v_N = 10^4 i_I + v_O = v_P = \frac{2}{5} v_O \Rightarrow v_O = -\frac{10\times10^3}{0.6} i_I$



9.10

(b)



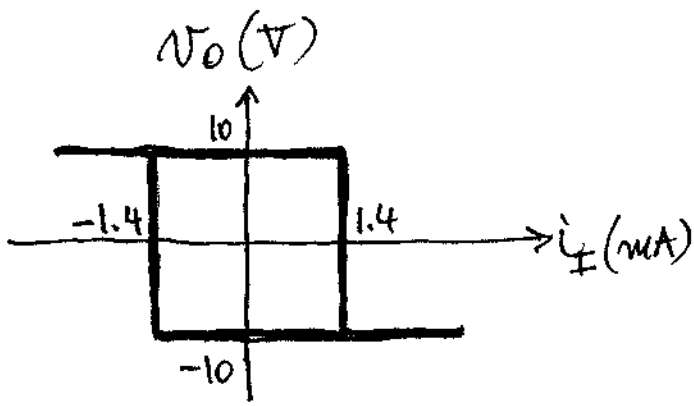

Perform a source transformation, as shown, with $v_I = 2\times10^3 i_I$. $\beta_N = 2/10$, $\beta_P = 2/5$, $\beta_P > \beta_N \Rightarrow$ positive feedback $\Rightarrow$ Schmitt-trigger operation (inverting type).

$v_O = \pm V_{sat} = \pm 10\text{V}$; $v_P = \pm(2/5)10 = \pm 4\text{V}$.

For $v_O = -10\text{V}$, $v_P = -4\text{V}$ and the value $V_{TL}$ of $v_I$ for which the comparator trips is such that

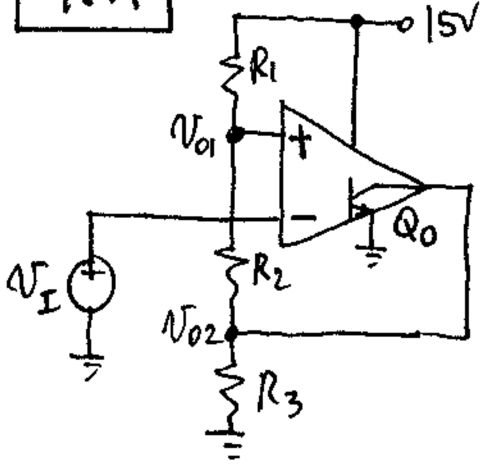
$$\frac{V_{TL}-(-4)}{2} = \frac{-4-(-10)}{10}, \text{ or } V_T = -2.8\text{V} = -V_{TH}.$$

The threshold values of $i_I$ are $I_T = \pm V_T/2\text{k}\Omega = \pm 1.4\text{ mA}$.



9.11

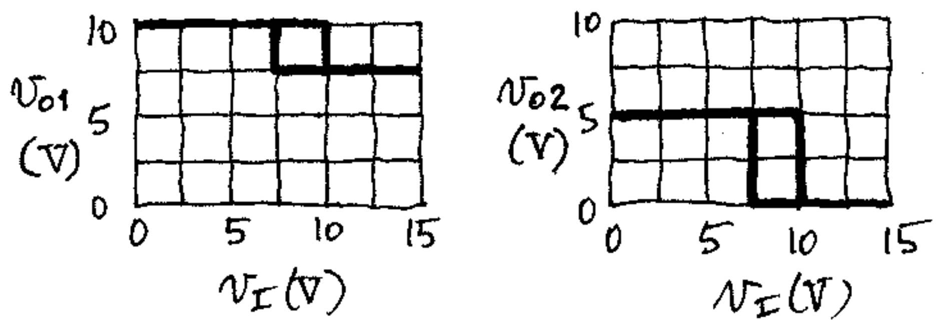
**9.17**




$Q_0$ = OPEN $\Rightarrow v_{O2} = 5V$, $v_{O1} = 10$ V.

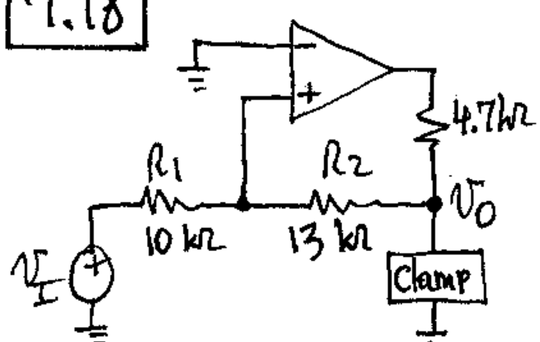
$Q_0$ = SAT $\Rightarrow v_{O2} \cong 0V$, $v_{O1} = 7.5$ V.

$V_{TL} = 7.5V$, $V_{TH} = 10$ V.




(a) (b)

**7.18**

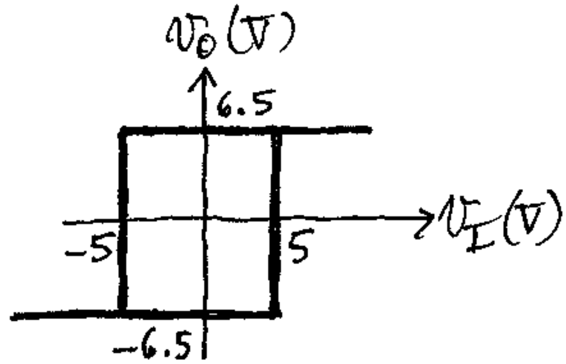



The diode network clamp $v_O$ at

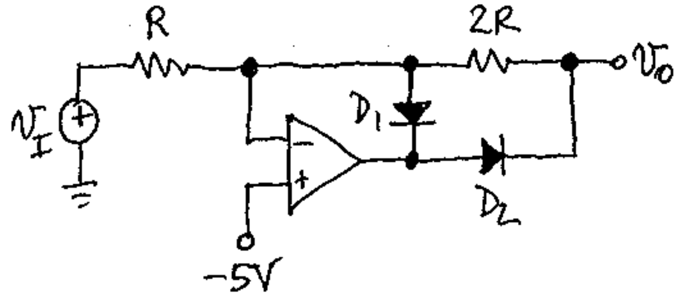
$$v_O = \pm(5.1 + 2 \times 0.7) = \pm 6.5V$$

$$V_T = \pm \frac{10}{13} 6.5 = \pm 5V.$$

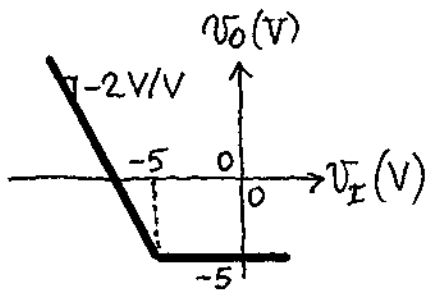
The VTC is thus:

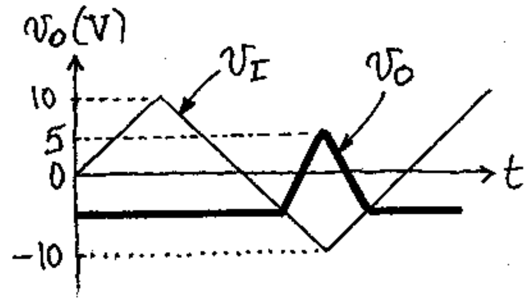


**9.19**

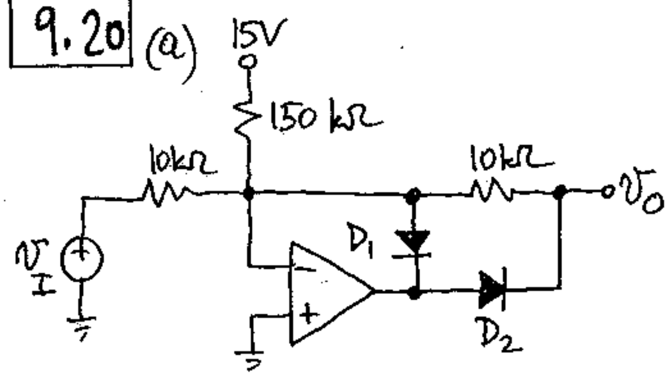



$v_I > -5\text{ V} \Rightarrow (i_R \rightarrow) \Rightarrow D_1 = \text{ON}, D_2 = \text{OFF}, i_{2R} = 0,$ $v_O = v_N = -5\text{ V}$. $v_I < -5\text{ V} \Rightarrow (i_R \leftarrow) \Rightarrow D_2 = \text{ON}, D_1 = \text{OFF}, v_O = v_N + 2R \times i_R = -5 + 2R(-5 - v_I)/R = -5 - 10 - 2v_I = -15 - 2v_I$.




**9.20** (a)

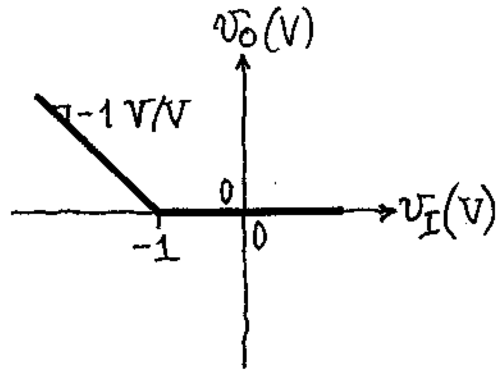


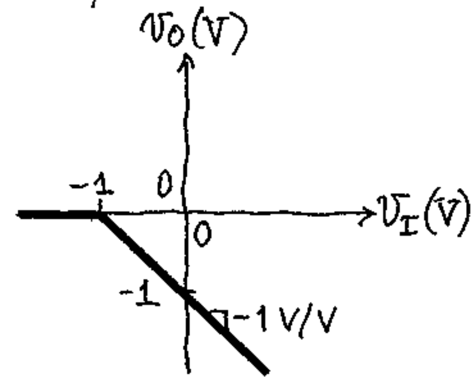

The value of $v_I$ necessary to offset the current supplied by the 150-kΩ resistor is $v_I = -(10/150)15 = -1\text{ V}$. We thus have two cases: $v_I > -1\text{ V}$, and $v_I < -1\text{ V}$. $v_I > -1\text{ V} \Rightarrow v_O = 0$, and $v_I < -1\text{ V} \Rightarrow v_O/10 + 15/150 = -v_I/10 \Rightarrow$ $v_O = -v_I - 1\text{ V}$.

(b) Reversing the diode polarities we

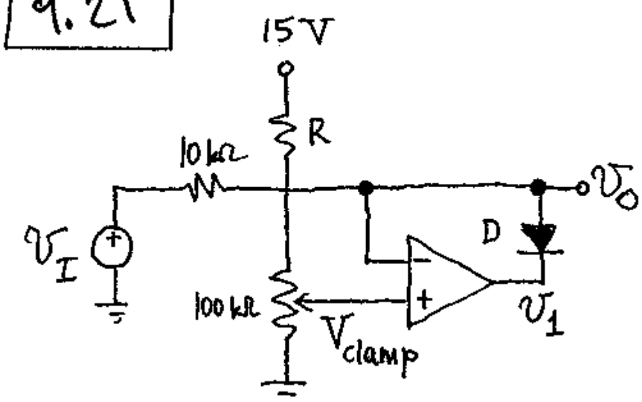
9.13

get $v_O = 0$ for $v_I < -1$ V, and $v_O = -v_I - 1$ V for $v_I > -1$ V. VTCs are as follows:




9.21




$0 \le V_{clamp} \le 10$ V $\Rightarrow R = 50$ kΩ (use 49.9 kΩ).

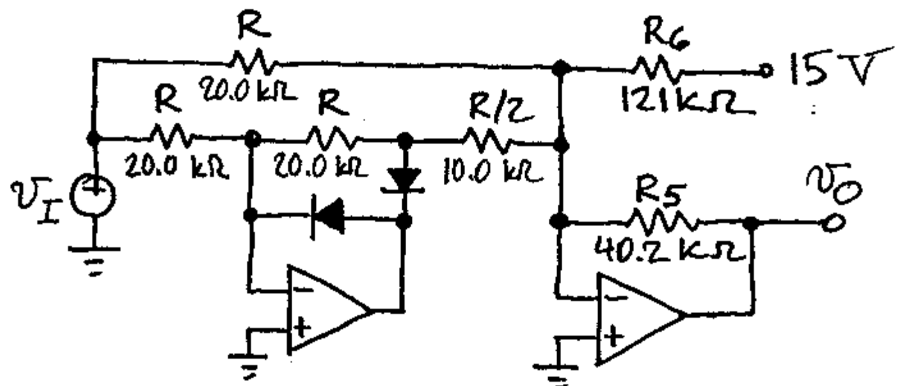
$v_I > V_{clamp} \Rightarrow (i_{10k\Omega} \rightarrow) \Rightarrow D = ON \Rightarrow v_O = V_{clamp}$.

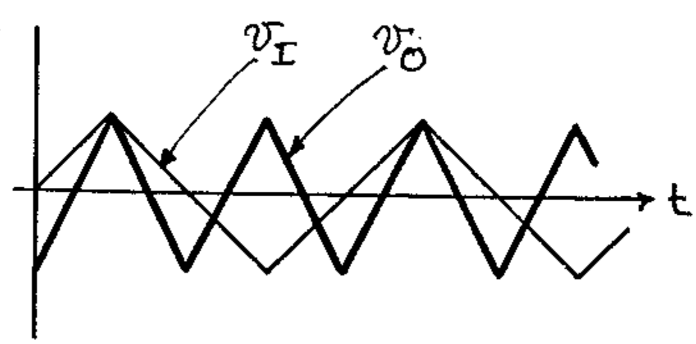
$v_I < V_{clamp} \Rightarrow D = OFF \Rightarrow v_O = v_I \Rightarrow v_1 = V_{OH}$.

Advantage: superdiode precision; disadvantage: op amp saturation when $v_I < V_{clamp}$ $\Rightarrow$ recovery time.

9.14

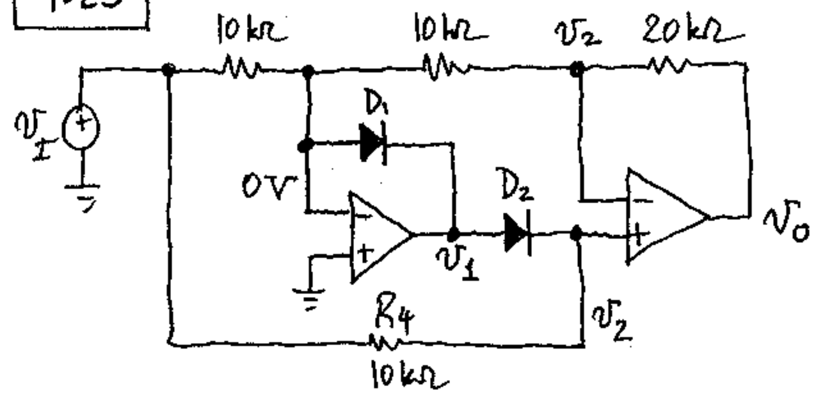
**9.22** A unity-gain absolute value circuit, when fed with a triangular wave, yields another triangular wave but with twice the frequency and half the amplitude. Thus, we need a gain of two ($R_5 = 2R$).
Moreover, to center the output about 0 V, we must offset it by 5V in the negative direction. Use $R_6$ and +15V, as shown. We want $-5 = -(R_5/R_6)15$
$\Rightarrow R_6 = 3R_5 = 6R$. Use $R = 20.0\ k\Omega$, $R_5 = 40.2\ k\Omega$, and $R_6 = 121\ k\Omega$.



9.15

**9.23**




$v_I = 10$ mV $\Rightarrow D_1 = $ ON, $D_2 = $ OFF; $v_2 = 10$ mV; $v_O = 30$ mV; $i_{D1} = 2 \times (10\text{ mV})/(10\text{ k}\Omega) = 2\ \mu A$; $v_1 = -(26\text{mV}) \times \ln[(2\times10^{-6})/(20\times10^{-15})] = -479$ mV.

$v_I = 1$ V $\Rightarrow v_2 = 1$ V, $v_O = 3$ V, $v_1 = -(26\text{ mV}) \times \ln[(200\times10^{-6})/(20\times10^{-15})] = -599$ mV.

$v_I = -1$ V $\Rightarrow D_1 = $ OFF, $D_2 = $ ON; $v_2 = -v_I = 1$ V; $v_O = 3$ V; $i_{D2} = (v_2 - v_I)/R_4 = 200\ \mu A$; $v_1 = v_2 + v_{D2} = 1 + 0.599 = 1.599$ V.

**9.24** $A_p$ is maximized when $R_2$ is minimized and $A_n$ is minimized when $R_2$ is minimized and $R_1$ is maximized.

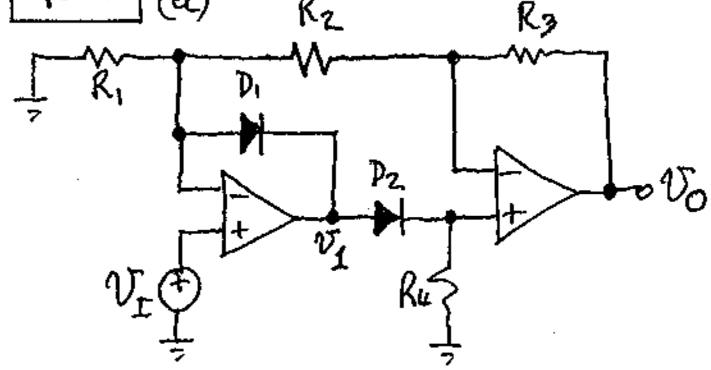
$$|A_p - A_n|_{max} = \left[1 + \frac{(A-1)R}{R(1-p)}\right] - \left[\frac{R(1-p)}{R(1+p)} + \frac{(A-1)R}{R(1+p)}\right] \cong$$

$1 + (A-1)(1+p) - [(1-2p) + (A-1)(1-p)] = 2Ap$. Thus,

$100\,|(A_p - A_n)/A|_{max} \cong 200p$, which is much better than $800p$.

9.16

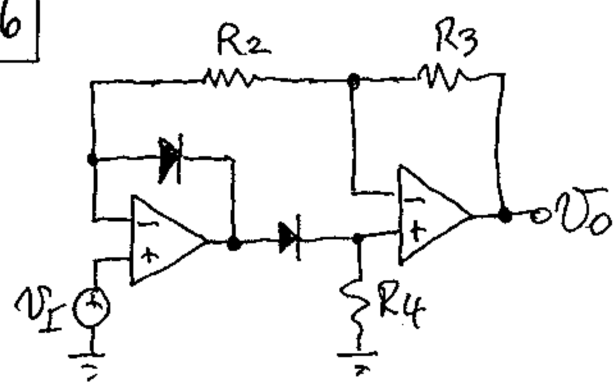
**9.25** (a)




$v_I > 0 \Rightarrow v_1 > 0 \Rightarrow D_2 = ON$ and $D_1 = OFF \Rightarrow v_O \times R_1/(R_1+R_2+R_3) = v_I \Rightarrow A_p = v_O/v_I = 1+(R_2+R_3)/R_1$. $v_I < 0 \Rightarrow D_1 = ON$ and $D_2 = OFF \Rightarrow v_{P2} = 0$, $v_O = (-R_3/R_2)v_{N1} = (-R_3/R_2)v_I \Rightarrow A_n = -v_O/v_I = R_3/R_2$. In either case, $v_O > 0$.

(b) $R_3/R_2 = 5$, $1+(R_2+R_3)/R_1 = 5 \Rightarrow R_1/R_2 = 1.5$. Pick $R_2 = 20.0\ k\Omega$, $R_1 = 30.0\ k\Omega$, $R_3 = 100\ k\Omega$. Advantages: high input resistance, needs only three matched resistances. Disadvantage: gain must be $> 1$ V/V.

**9.26**




$v_I > 0 \Rightarrow v_O = v_I$, $A_p = 1$ V/V; $v_I < 0 \Rightarrow v_O = -(R_3/R_2)v_I$, $A_n = -R_3/R_2 = -1$ V/V; $v_O = |v_I|$.

**9.17**

$|A_n|_{min} = \frac{R(1-p)}{R(1+p)} \cong 1+2p$ ; $A_p = 1$ regardless of resistance tolerances. Thus, $100|(A_p - A_n)/A|_{max} \cong 200p$. For instance, with 1% resistances, $A_n$ may depart from 1 V/V by as much as 2%.

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**9.27** (a) $v_I > 0 \Rightarrow v_{O2} = -13\text{ V} \Rightarrow D_1 = \text{OFF} \Rightarrow v_{N1} = v_{P1} = v_I \Rightarrow v_O = v_I$. $v_I < 0 \Rightarrow D_1 = \text{ON} \Rightarrow v_{P1} = v_{N2} = v_{P2} = 0 \Rightarrow v_O = -(R_2/R_1)v_I = -v_I$. Thus, $v_O = |v_I|$.

(b) $v_I = +3\text{ V} \Rightarrow v_{N2} = 3\text{V}, v_{O2} = -13\text{ V}, v_O = 3\text{V}$. $v_I = -5\text{V} \Rightarrow v_{N2} = 0\text{ V}, v_{O2} = 0.7\text{V}, v_O = +5\text{V}$.

(c) Advantages: requires only two matched resistances and one diode. Disadvantage: $OA_2$ saturates during $v_I > 0$, implying a long recovery time when $v_I$ changes from positive to negative.

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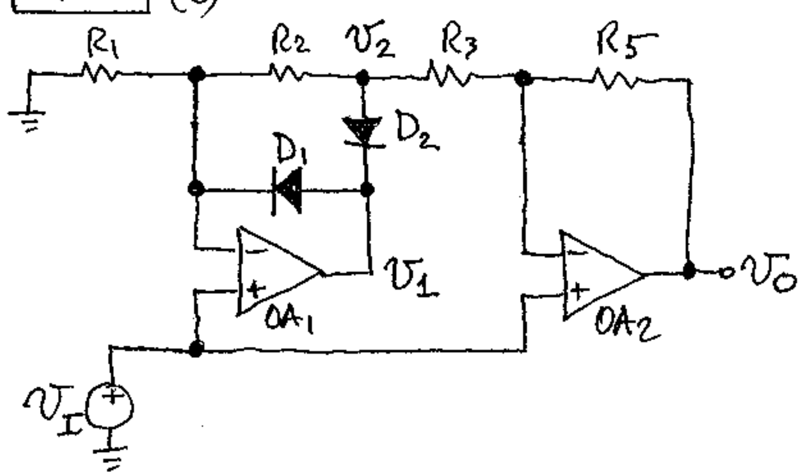
**9.28** (a)



**9.18**

$v_I > 0 \Rightarrow D_1 = ON$ and $D_2 = OFF$; $v_{N1} = v_{N2} = v_I$ $\Rightarrow i_{R_5} = i_{R_3} = i_{R_2} = 0 \Rightarrow v_O = v_I$.
$v_I < 0 \Rightarrow D_1 = OFF$ and $D_2 = ON$; $v_2 = (1 + R_2/R_1) \times v_I = 2v_I$; $v_O = -(R_5/R_3)v_2 + (1 + R_5/R_3)v_I = -2 \times 2v_I + 3v_I = -v_I$. Consequently, $v_O = |v_I|$.

(b) $v_I = 2\text{ V} \Rightarrow v_{N1} = 2\text{ V}$, $v_1 = 2.7\text{ V}$, $v_{N2} = 2\text{ V}$, $v_2 = 2\text{ V}$, $v_O = 2\text{ V}$. $v_I = -3\text{ V} \Rightarrow$ $v_{N1} = -3\text{ V}$, $v_2 = -6\text{ V}$, $v_1 = -6.7\text{ V}$, $v_{N2} = -3\text{ V}$, $v_O = +3\text{ V}$.

(c) $A_p = 1$ regardless of resistance tolerances. $A_n = (R_5/R_3)(1 + R_2/R_1) - (1 + R_5/R_3) = R_2R_5/R_1R_3 - 1$. $A_p - A_n = 2 - R_2R_5/R_1R_3$.

$$|A_p - A_n|_{max} = 2 - \frac{R(1-p)\,2R(1-p)}{R(1+p)\,R(1+p)} \cong 2 - 2(1-4p)$$

$= 8p$, indicating that with 1% resistances, $A_n$ can depart from unity by as much as 8%.

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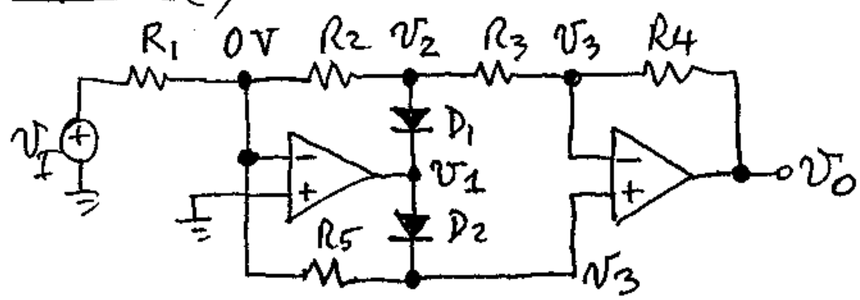
**9.29** (a)



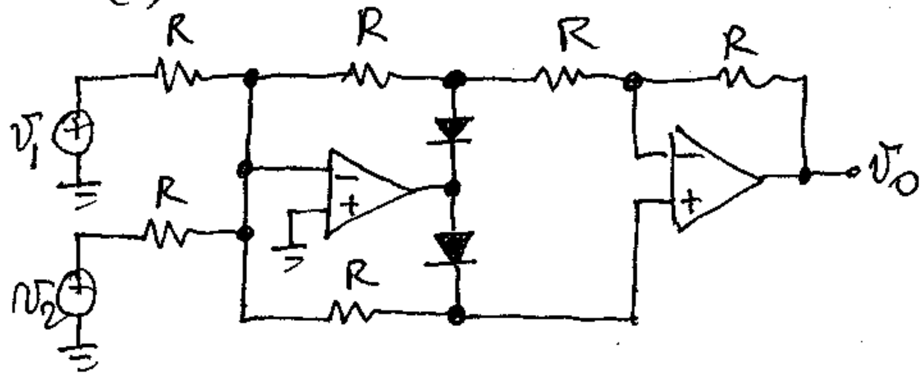

$v_I > 0 \Rightarrow D_1 = ON$ and $D_2 = OFF \Rightarrow v_3 = 0$, $v_2 = -(R_2/R_1)v_I = -v_I$, $v_O = -(R_4/R_3)v_2 = +v_I$.

9.19

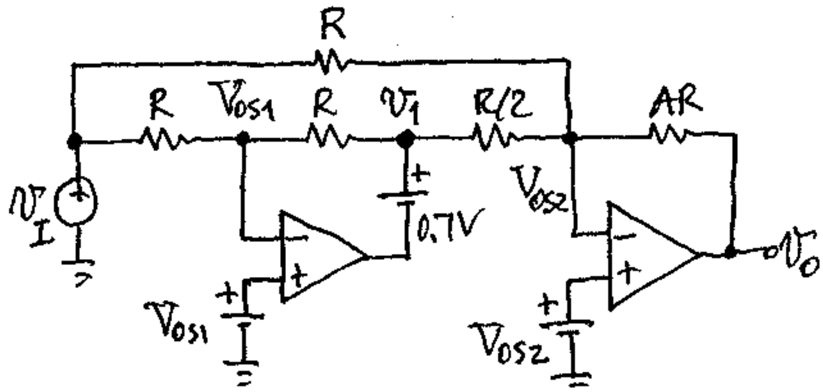
$v_I < 0 \Rightarrow D_1 = \text{OFF}$ and $D_2 = \text{ON}$. KCL:
$v_3/R_5 + v_3/(R_2+R_3) = -v_I/R_1 \Rightarrow v_3 = -\frac{2}{3}v_I$,
$v_O = v_3 + R_4 v_3/(R_2+R_3) = \frac{3}{2}v_3 = -v_I$. Combining, $v_O = |v_I|$.

(b) $v_I = 1\text{ V} \Rightarrow v_2 = -1\text{ V}$, $v_3 = 0$, $v_1 = -1.7\text{ V}$, $v_O = +1\text{ V}$. $v_I = -3\text{ V} \Rightarrow v_3 = +2\text{ V}$, $v_1 = 2.7\text{ V}$, $v_2 = v_3/2 = 1\text{ V}$, $v_O = +3\text{ V}$.

(c)



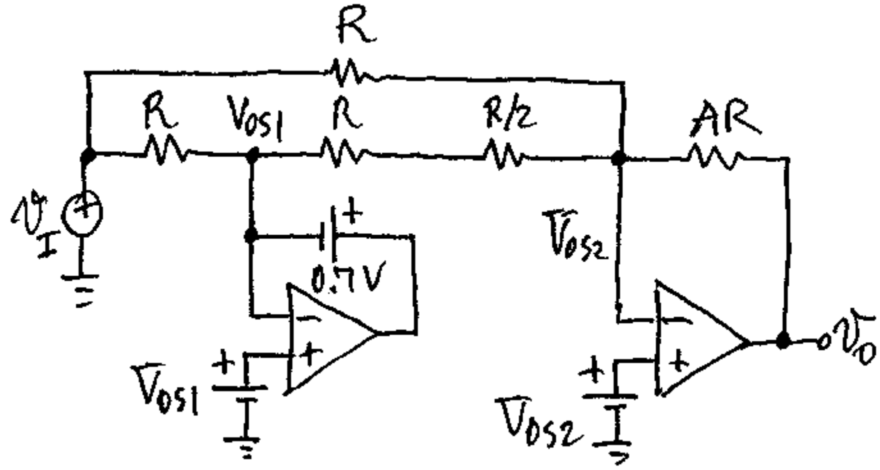

9.30 For $v_I > V_{OS1}$, $D_1 = \text{OFF}$ and $D_2 = \text{ON}$:



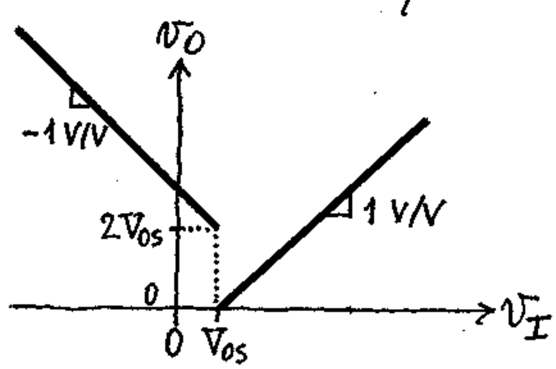

Superposition: $v_1 = -v_I + 2V_{OS1}$; $v_O = -Av_I - 2Av_1 + [1 + AR/(R\|0.5R)]V_{OS2} = -Av_I - 2A(-v_I + 2V_{OS1}) + (1+3A)V_{OS2} = Av_I + (3A+1)V_{OS2} - 4AV_{OS1}$. For $A = 1$ V/V, $v_O = v_I + 4(V_{OS2} - V_{OS1})$. The output error can be as large as $8V_{OS}$.

(9.20)

For $v_I < V_{OS1}$, $D_1 = ON$ and $D_2 = OFF$:

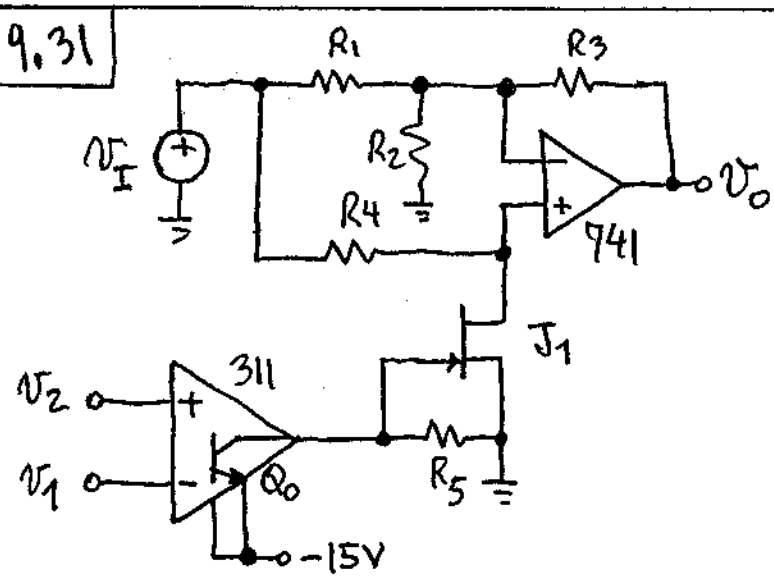



Superposition: $v_O = -Av_I - [AR/(R+0.5R)]V_{OS1} + [1 + AR/(R\|1.5R)]V_{OS2} = -Av_I + (5A/3+1)V_{OS2} - (2/3)V_{OS1}$. For $A = 1$ V/V, $v_O = -v_I + \frac{1}{3}(8V_{OS2} - 2V_{OS1})$. The output error can be as large as $(10/3)V_{OS}$. The accompanying figure illustrates the case $A = 1$ V/V, and $V_{OS1} = V_{OS2} = V_{OS}$.



9.21

**9.31**




$v_1 > v_2 \Rightarrow Q_0 = \text{Sat} \Rightarrow J_1 = \text{OFF} \Rightarrow i_{R_4} = 0 \Rightarrow i_{R_1} = 0$
$\Rightarrow v_O = (1 + R_3/R_2)v_I \Rightarrow R_3 = 9R_2$.
$v_1 < v_2 \Rightarrow Q_0 = \text{OFF} \Rightarrow J_1 = \text{ON} \Rightarrow v_{R_2} = 0 \Rightarrow$
$v_O = -(R_3/R_1)v_I \Rightarrow R_3 = 10R_1$. Use $R_2 = 20\,k\Omega$,
$R_3 = 180\,k\Omega$, $R_1 = 18\,k\Omega$; moreover, let $R_4 =$
$20\,k\Omega$, $R_5 = 3.3\,k\Omega$.

**9.32** For $v_I = +5V$, $v_{GSn} = 0 \Rightarrow M_n = \text{OFF}$,
and $|v_{GSp}| = 10\,V$; so, $r_{dsn(on)} = \infty$, and $r_{dsp(on)}$
$= 1/[100 \times 10^{-6} \times (10 - 2.5)] = 1.33\,k\Omega$.

For $v_I = 2.5\,V$, $v_{GSn} = 2.5\,V \Rightarrow M_n$
still off, and $|v_{GSp}| = 7.5V$; so, $r_{dsn(on)} = \infty$,
and $r_{dsp(on)} = 1/[10^{-4}(7.5 - 2.5)] = 2\,k\Omega$.

For $v_I = 0V$, $v_{GSn} = 5V$ and $|v_{GSp}| =$
$5V$; $r_{dsn} = r_{dsp} = 1/[10^{-4} \times (5 - 2.5)] = 4\,k\Omega$;
$r_{dsp(on)} \| r_{dsn(on)} = 2\,k\Omega$. Proceeding in similar

9.22

fashion, we find that
$r_{ds}(\pm 5V) = 1.33\ k\Omega$, $r_{ds}(\pm 2.5V) = 2\ k\Omega$, $r_{ds}(0) = 2\ k\Omega$; $v_O(\pm 5V) = (100/101.33)(\pm 5) = \pm 4.934$ V, $v_O(\pm 2.5V) = (100/102)(\pm 2.5) = \pm 2.451$ V, $v_O(0) = 0$.

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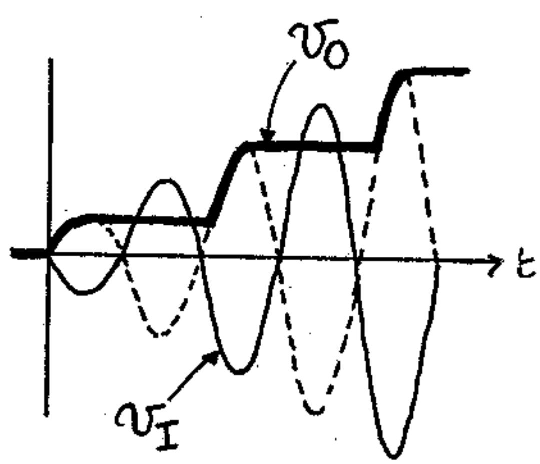
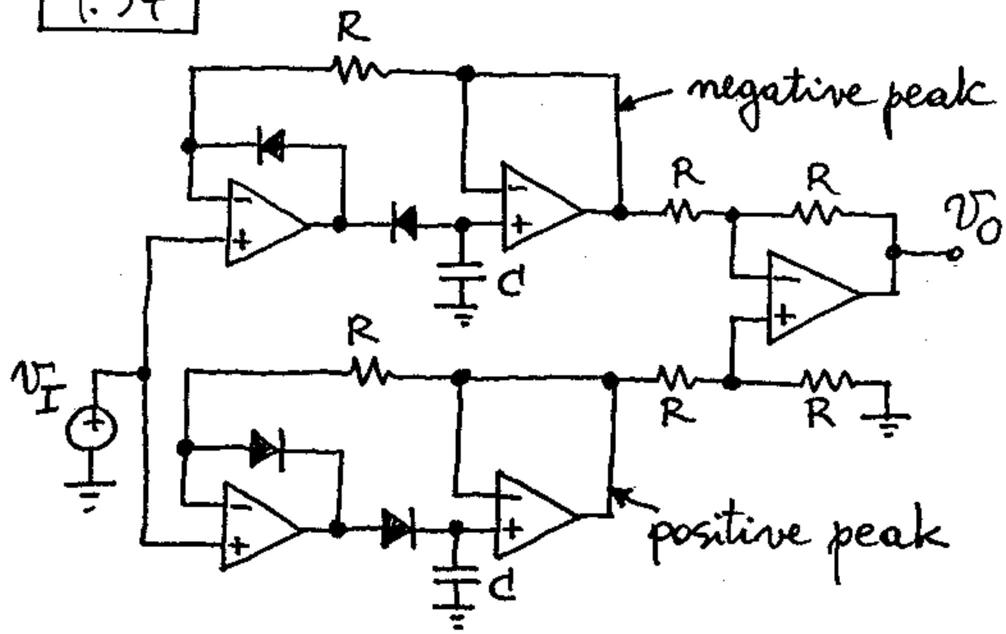
$\boxed{9.33}$ As $v_I$ swings in the negative direction, $D_1$ goes off and $D_2$ goes on, charging $C_H$ so as to make $v_O = -v_I$. After $v_I$ peaks out in the negative direction, the circuit holds the output at $v_O = -(R_2/R_1)v_{I(min)}$. If $R_2 > R_1$, the circuit will also provide gain.

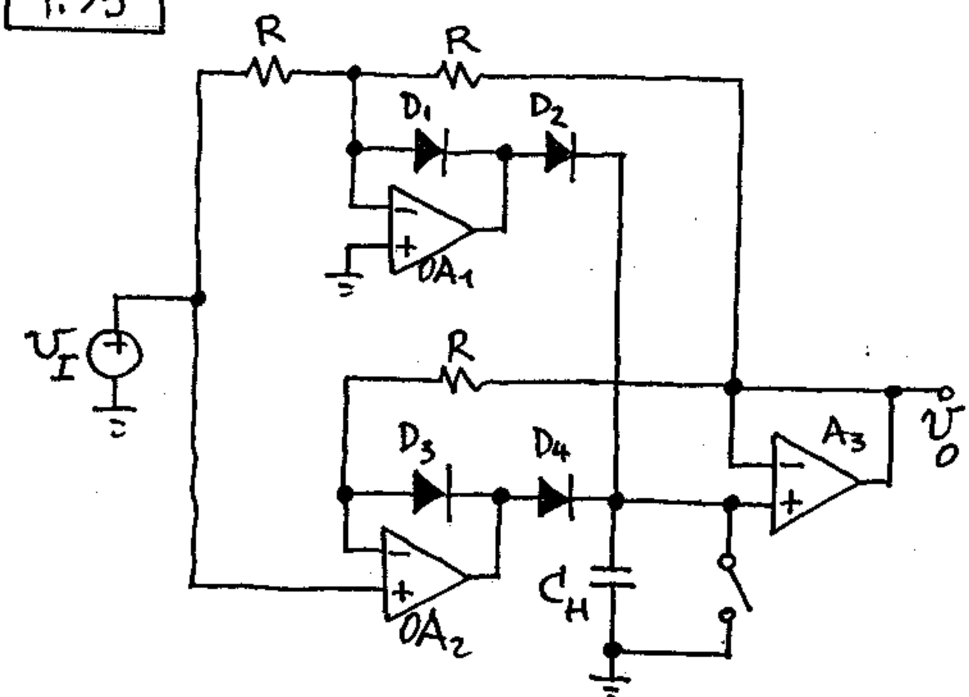


(9.23)

9.34



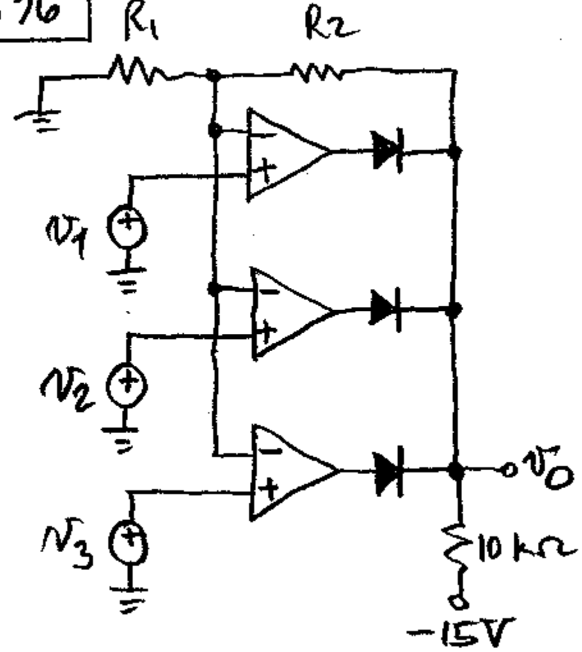

9.35




$OA_2$ works as a voltage follower for positive peaks. $OA_2$, a unity-gain inverting amplifier, processes negative peaks.

9.24

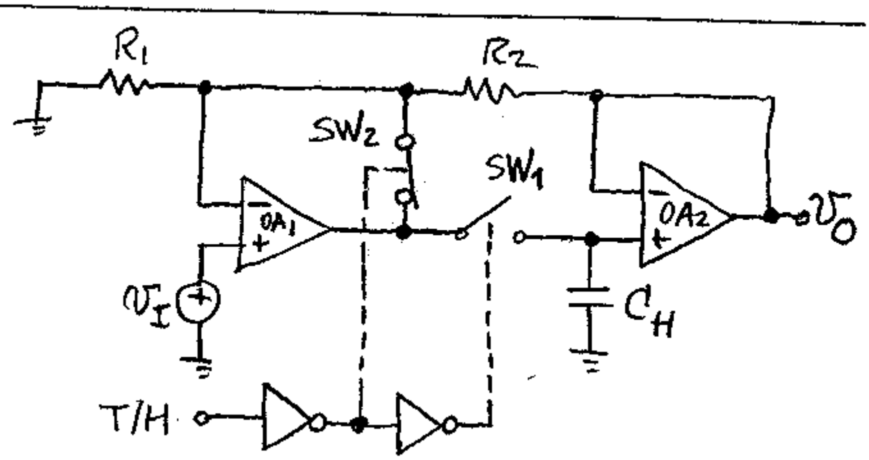
9.36




The op amp whose input is the most positive will succeed in making $v_N = v_P$. The remaining op amps will saturate at $V_{OL}$. With $R_1 = \infty$ and $R_2 = 0$, the circuit thus gives $v_O = \max(v_1, v_2, v_3)$. With the voltage divider present, $v_O = (1 + R_2/R_1) \times \max(v_1, v_2, v_3)$. If the diode polarities are reversed (and the 10-kΩ resistance is returned to +15 V!), the circuit gives $v_O = (1 + R_2/R_1) \times \min(v_1, v_2, v_3)$.

9.25

**9.37**




For a gain of 2 V/V, use $R_1 = R_2$. Because of the nonzero voltage difference between $v_{O1}$ and $v_{N1}$ during the track mode, the diodes must be removed. To pevent $OA_1$ from saturating during the hold mode, use an additional switch $SW_2$ and drive it in antiphase with respect to $SW_1$ to close the loop around $OA_1$ during the hold mode.

**9.38** (a) SW = CLOSED $\Rightarrow v_O = -(R/R)v_I = -1.000$ V. As the SW driver swings from 0V to −15V to open SW, a charge $\Delta Q = 15\text{V} \times 1\text{pF} = 15\text{pC}$ is pulled out of $C_H$, thus causing an output change $\Delta v_O = \Delta Q/C_H = 15 \times 10^{-12}/10^{-9} = 15$ mV, so $v_O = -1.000 + 0.015 = -0.985$ V.

(b) $C_H \Delta v_O = I_L \times \Delta T \Rightarrow \Delta v_O = 1\text{nA} \times 50\text{ms}/1\text{nF} = 50\text{mV}$. Thus, $v_O = -0.985 + 0.050 = -0.935$ V.

9.26

9.39 (a) $T/H = -15V \Rightarrow J_1$ = closed and $J_2 = J_3$ = open. This is the hold mode, during which the droop due to leakage in $C_H$ is compensated for by the droop due to leakage in $C_F$. Moreover, $J_1$ provides unity-feedback around $A_1$ to prevent saturation and speed up recovery when switching from T to S.

$T/H = +15V \Rightarrow J_1$ = open and $J_2 = J_3$ = closed. This is the sample mode, during which $J_3$ closes the path from $A_1$ to $C_H$ and $J_2$ discharges $C_F$ and provides unity-feedback around $A_2$.

(b) 5% of 1 nA is 50pA. Thus, $\Delta v_O/\Delta t = 50\times10^{-12}/10^{-9} = 50$ mV/s $= 0.05$ μV/μs. Without droop compensation we would have $\Delta v_O/\Delta t = 1$ V/s $= 1$ μV/μs.