CHAPTER 10

Exercises

E10.1 Solving Equation 10.1 for the saturation current and substituting values, we have

$$\begin{aligned}
I_s &= \frac{i_D}{\exp(v_D / nV_T) - 1} \\
&= \frac{10^{-4}}{\exp(0.600/0.026) - 1} \\
&= 9.502 \times 10^{-15}\ \text{A}
\end{aligned}$$

Then for $v_D = 0.650$ V, we have

$$\begin{aligned}
i_D &= I_s\left[\exp(v_D / nV_T) - 1\right] = 9.502\times10^{-15} \times \left[\exp(0.650/0.026) - 1\right] \\
&= 0.6841\ \text{mA}
\end{aligned}$$

Similarly for $v_D = 0.700$ V, $i_D = 4.681$ mA.

E10.2 The approximate form of the Shockley Equation is $i_D = I_s \exp(v_D / nV_T)$. Taking the ratio of currents for two different voltages, we have

$$\frac{i_{D1}}{i_{D2}} = \frac{\exp(v_{D1} / nV_T)}{\exp(v_{D2} / nV_T)} = \exp\left[(v_{D1} - v_{D2}) / nV_T\right]$$

Solving for the difference in the voltages, we have:

$$\Delta v_D = nV_T \ln(i_{D1} / i_{D2})$$

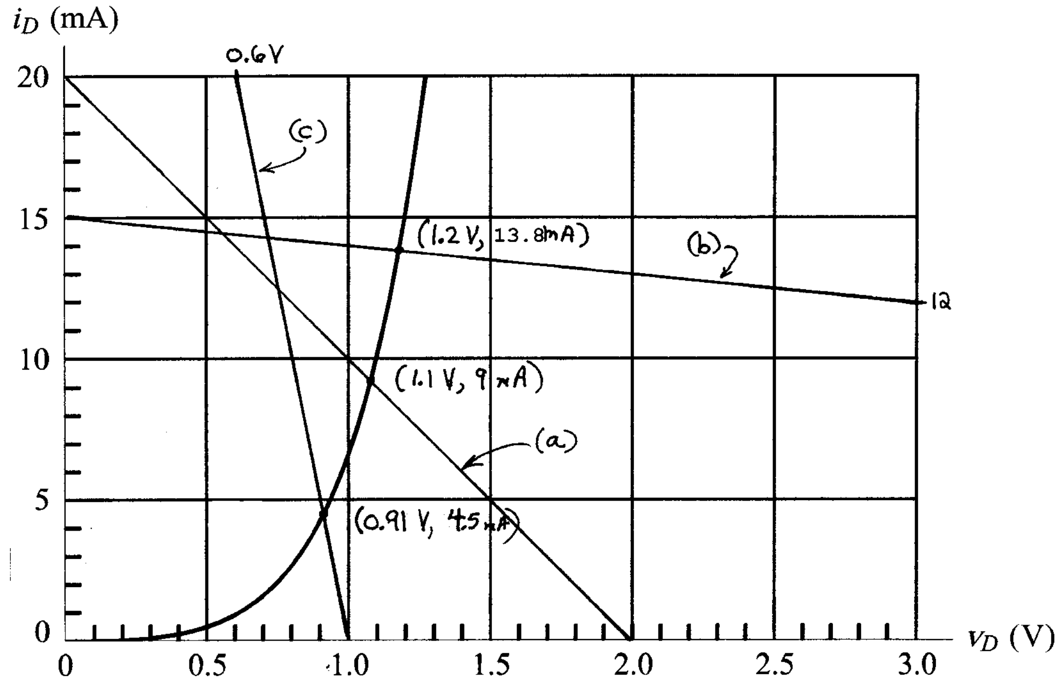
Thus to double the diode current we must increase the voltage by $\Delta v_D = 0.026\ln(2) = 18.02$ mV and to increase the current by an order of magnitude we need $\Delta v_D = 0.026\ln(10) = 59.87$ mV

E10.3 The load line equation is $V_{SS} = Ri_D + v_D$. The load-line plots are shown on the next page. From the plots we find the following operating points:

(a) $V_{DQ} = 1.1$ V $\quad I_{DQ} = 9$ mA

(b) $V_{DQ} = 1.2$ V $\quad I_{DQ} = 13.8$ mA

(c) $V_{DQ} = 0.91$ V $\quad I_{DQ} = 4.5$ mA

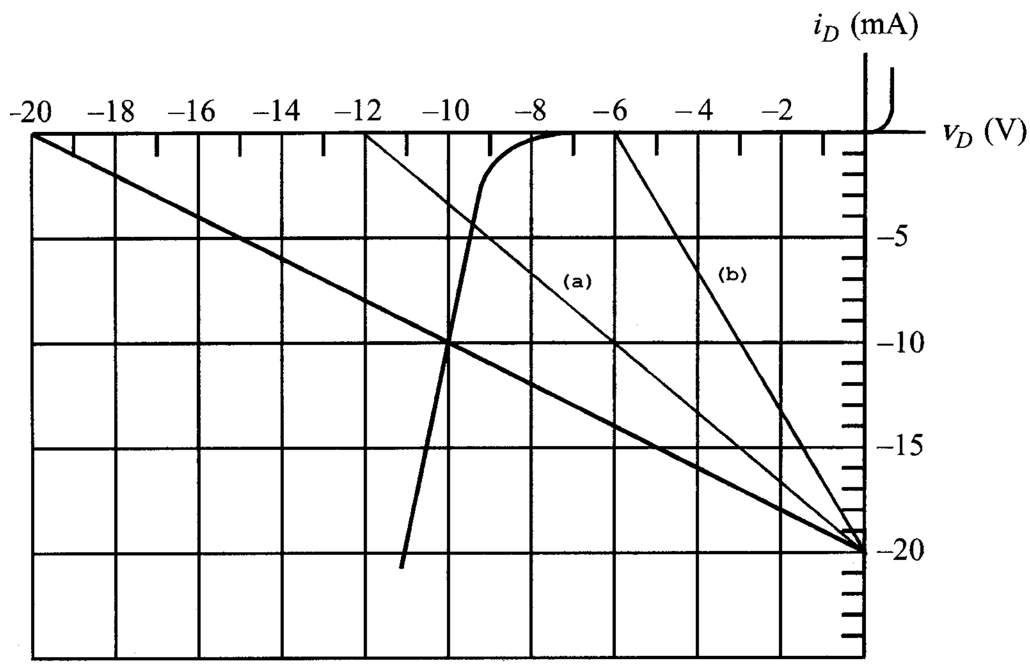


E10.4 Following the methods of Example 10.4 in the book, we determine that:

(a) For $R_L = 1200\ \Omega$, $R_T = 600\ \Omega$, and $V_T = 12$ V.

(b) For $R_L = 400\ \Omega$, $R_T = 300\ \Omega$, and $V_T = 6$ V.

The corresponding load lines are:

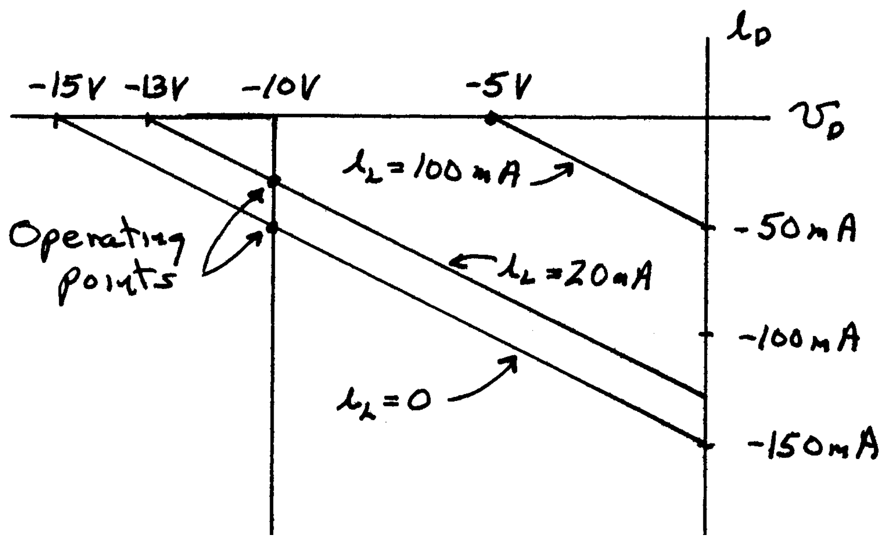


At the intersections of the load lines with the diode characteristic we find (a) $v_L = -v_D \cong 9.4$ V; (b) $v_L = -v_D \cong 6.0$ V.

E10.5 Writing a KVL equation for the loop consisting of the source, the resistor, and the load, we obtain:

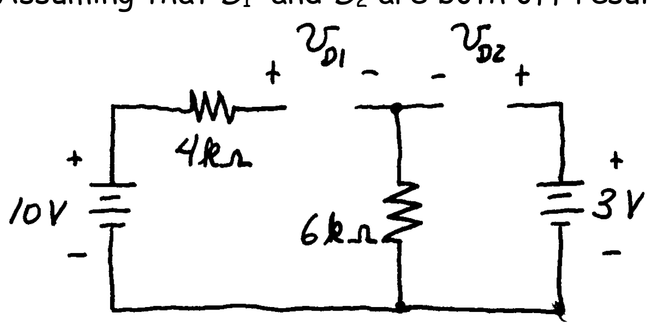
$$15 = 100(i_L - i_D) - v_D$$

The corresponding load lines for the three specified values of i_L are shown:



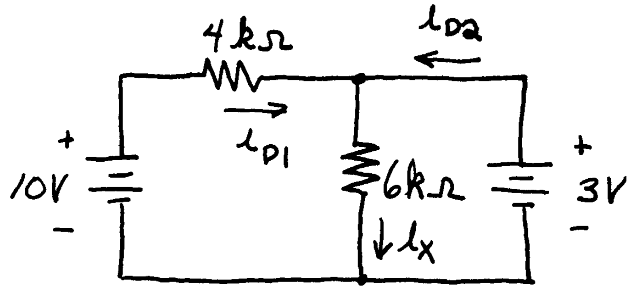
At the intersections of the load lines with the diode characteristic, we find (a) $v_o = -v_D = 10$ V; (b) $v_o = -v_D = 10$ V; (c) $v_o = -v_D = 5$ V. Notice that the regulator is effective only for values of load current up to 50 mA.

E10.6 Assuming that D_1 and D_2 are both off results in this equivalent circuit:



Because the diodes are assumed off, no current flows in any part of the circuit, and the voltages across the resistors are zero. Writing a KVL equation around the left-hand loop we obtain $v_{D1} = 10$ V, which is not consistent with the assumption that D_1 is off.

E10.7 Assuming that D_1 and D_2 are both on results in this equivalent circuit:

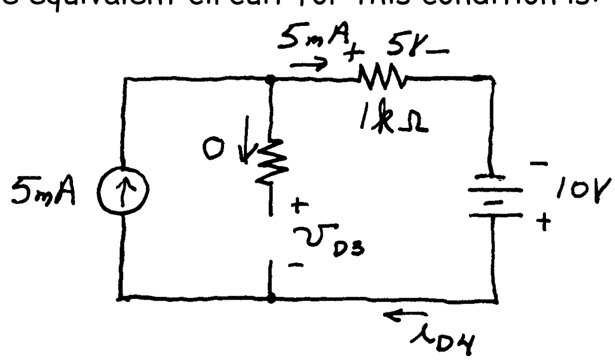


Writing a KVL equation around the outside loop, we find that the voltage across the 4-kΩ resistor is 7 V and then we use Ohm's law to find that i_{D1} equals 1.75 mA. The voltage across the 6-kΩ resistance is 3 V so i_x is 0.5 mA. Then we have $i_{D2} = i_x - i_{D1} = -1.25$ mA, which is not consistent with the assumption that D_2 is on.

E10.8 (a) If we assume that D_1 is off, no current flows, the voltage across the resistor is zero, and the voltage across the diode is 2 V, which is not consistent with the assumption. If we assume that the diode is on, 2 V appears across the resistor, and a current of 0.5 mA circulates clockwise which is consistent with the assumption that the diode is on. Thus the diode is on.

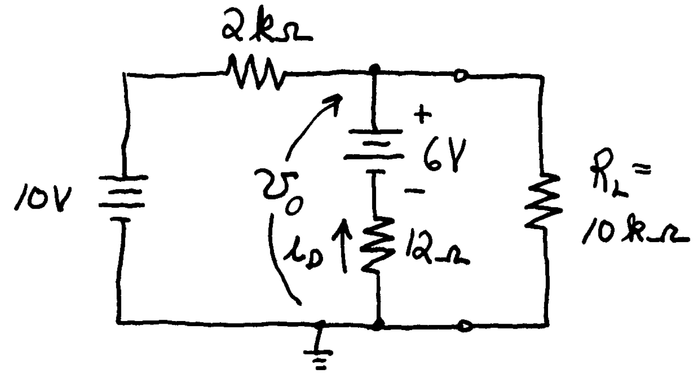
(b) If we assume that D_2 is on, a current of 1.5 mA circulates counterclockwise in the circuit, which is not consistent with the assumption. On the other hand, if we assume that D_2 is off we find that $v_{D2} = -3$ where as usual we have referenced v_{D2} positive at the anode. This is consistent with the assumption, so D_2 is off.

(c) It turns out that the correct assumption is that D_3 is off and D_4 is on. The equivalent circuit for this condition is:



For this circuit we find that $i_{D4} = 5$ mA and $v_{D3} = -5$ V. These results are consistent with the assumptions.

E10.9 (a) With R_L = 10 kΩ, it turns out that the diode is operating on line segment *C* of Figure 10.19 in the book. Then the equivalent circuit is:

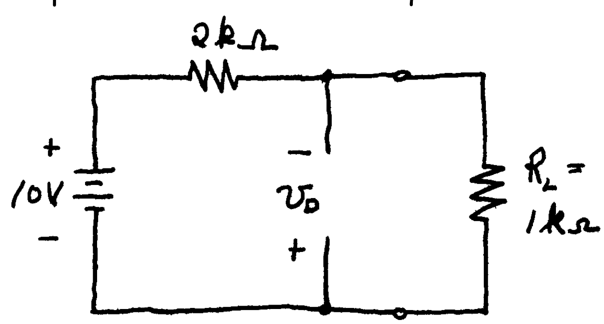


We can solve this circuit by using the node-voltage technique, treating v_o as the node voltage-variable. Notice that $v_o = -v_D$. Writing a KCL equation, we obtain

$$\frac{v_o - 10}{2000} + \frac{v_o - 6}{12} + \frac{v_o}{10000} = 0$$

Solving, we find $v_D = -v_o = -6.017$ V. Furthermore, we find that $i_D = -1.39$ mA. Since we have $v_D \le -6$ V and $i_D \le 0$, the diode is in fact operating on line segment *C*.

(b) With R_L = 1 kΩ, it turns out that the diode is operating on line segment *B* of Figure 10.19 in the book, for which the diode equivalent is an open circuit. Then the equivalent circuit is:



Using the voltage division principle, we determine that $v_D = -3.333$ V. Because we have $-6 \le v_D \le 0$, the result is consistent with the assumption that the diode operates on segment *B*.

E10.10 The piecewise linear model consists of a voltage source and resistance in series for each segment. Refer to Figure 10.18 in the book and notice that the *x*-axis intercept of the line segment is the value of the voltage source, and the reciprocal of the slope is the resistance. Now look at Figure 10.22a and notice that the intercept for segment *A* is zero and the reciprocal of the slope is (2 V)/(5 mA) = 400 Ω. Thus as shown in Figure 10.22b, the equivalent circuit for segment *A* consists of a 400-Ω resistance.

Similarly for segment *B*, the *x*-axis intercept is +1.5 V and the reciprocal slope is (0.5 mA)/(5 V) = 10 kΩ.

For segment *C*, the intercept is -5.5 V and the reciprocal slope is 800 Ω. Notice that the polarity of the voltage source is reversed in the equivalent circuit because the intercept is negative.

E10.11 Refer to Figure 10.25 in the book.

(a) The peak current occurs when the sine wave source attains its peak amplitude, then the voltage across the resistor is $V_m - V_B = 20 - 14 = 6$ V and the peak current is 0.6 *A*.

(b) Refer to Figure 10.25 in the book. The diode changes state at the instants for which $V_m \sin(\omega t) = V_B$. Thus we need the roots of $20\sin(\omega t) = 14$. These turn out to be $\omega t_1 = 0.7754$ radians and $\omega t_2 = \pi - 0.7754$ radians.

The interval that the diode is on is $t_2 - t_1 = \dfrac{1.591}{\omega} = \dfrac{1.591T}{2\pi} = 0.2532T$.

Thus the diode is on for 25.32% of the period.

E10.12 As suggested in the Exercise statement, we design for a peak load voltage of 15.2 V. Then allowing for a forward drop of 0.7 V we require $V_m = 15.9$ V. Then we use Equation 10.10 to determine the capacitance required. $C = (I_L T)/V_r = (0.1/60)/0.4 = 4167\ \mu\text{F}$.

E10.13 For the circuit of Figure 10.28, we need to allow for two diode drops. Thus the peak input voltage required is $V_m = 15 + V_r/2 + 2 \times 0.7 = 16.6$ V.

Because this is a full-wave rectifier, the capacitance is given by Equation 10.12. $C = (I_L T)/(2V_r) = (0.1/60)/0.8 = 2083\ \mu\text{F}$.

E10.14 Refer to Figure 10.31 in the book.

(a) For this circuit all of the diodes are off if $-1.8 < v_o < 10$. With the diodes off, no current flows and $v_o = v_{\text{in}}$. When v_{in} exceeds 10 V, D_1 turns on and D_2 is in reverse breakdown. Then $v_o = 9.4 + 0.6 = 10$ V. When v_{in} becomes less than -1.8 V diodes D_3, D_4, and D_5 turn on and $v_o = -3 \times 0.6 = -1.8$ V. The transfer characteristic is shown in Figure 10.31c.

(b)) For this circuit both diodes are off if $-5 < v_o < 5$. With the diodes off, no current flows and $v_o = v_{\text{in}}$.

When v_{in} exceeds 5 V, D_6 turns on and D_7 is in reverse breakdown. Then a current given by $i = \dfrac{v_{in} - 5}{2000}$ (i is referenced clockwise) flows in the circuit, and the output voltage is $v_o = 5 + 1000i = 0.5v_{\text{in}} + 2.5$ V

When v_{in} is less than -5 V, D_7 turns on and D_6 is in reverse breakdown. Then a current given by $i = \dfrac{v_{\text{in}} + 5}{2000}$ (still referenced clockwise) flows in the circuit, and the output voltage is $v_o = -5 + 1000i = 0.5v_{\text{in}} - 2.5$ V

E10.15 Answers are shown in Figure 10.32c and d. Other correct answers exist.

E10.16 Refer to Figure 10.34a in the book.

(a) If $v_{\text{in}}(t) = 0$, we have only a dc source in the circuit. In steady state, the capacitor acts as an open circuit. Then we see that D_2 is forward conducting and D_1 is in reverse breakdown. Allowing 0.6 V for the forward diode voltage the output voltage is -5 V.

(b) If the output voltage begins to fall below -5 V, the diodes conduct large amounts of current and change the voltage v_C across the capacitor. Once the capacitor voltage is changed so that the output cannot fall below -5 V, the capacitor voltage remains constant. Thus the output voltage is $v_o = v_{\text{in}} - v_C = 2\sin(\omega t) - 3$ V.

(c) If the 15-V source is replaced by a short circuit, the diodes do not conduct, $v_C = 0$, and $v_o = v_{\text{in}}$.

E10.17 One answer is shown in Figure 10.35. Other correct answers exist.

E10.18 One design is shown in Figure 10.36. Other correct answers are possible.

E10.19 Equation 10.22 gives the dynamic resistance of a semiconductor diode as $r_d = nV_T / I_{DQ}$.

I_{DQ} (mA)	r_d (Ω)
0.1	26,000
1.0	2600
10	26

E10.20 For the Q-point analysis, refer to Figure 10.42 in the book. Allowing for a forward diode drop of 0.6 V, the diode current is

$$I_{DQ} = \frac{V_C - 0.6}{R_C}$$

The dynamic resistance of the diode is

$$r_d = \frac{nV_T}{I_{DQ}}$$

the resistance R_p is given by Equation 10.23 which is

$$R_p = \frac{1}{1/R_C + 1/R_L + 1/r_d}$$

and the voltage gain of the circuit is given by Equation 10.24.

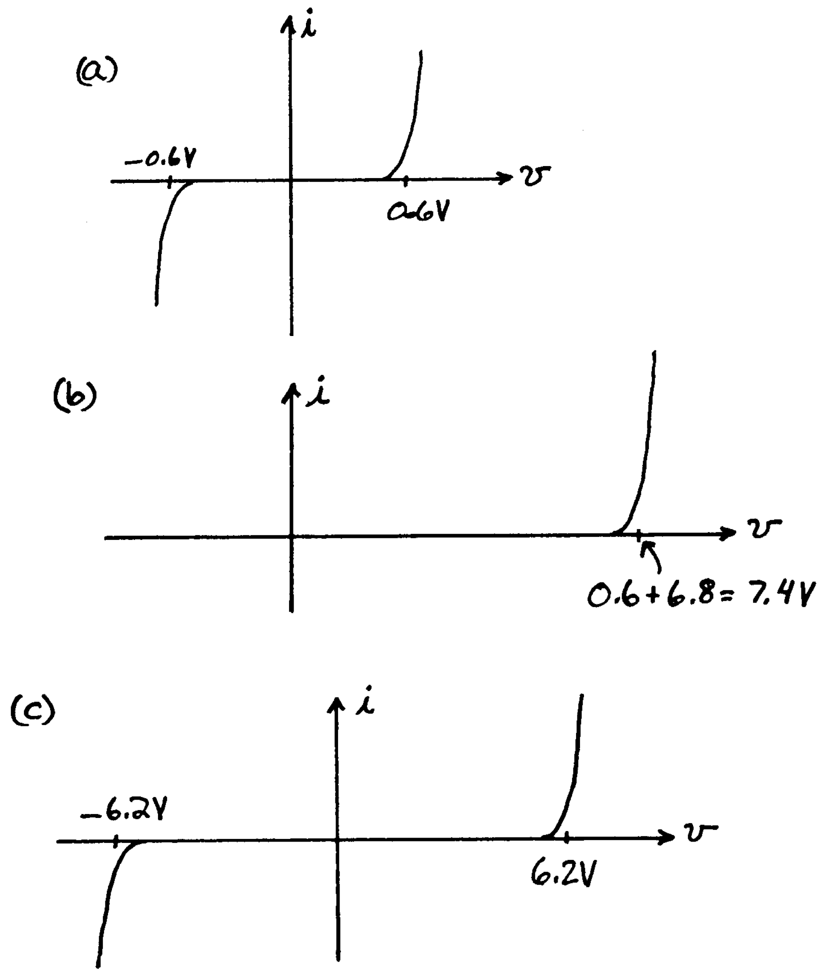
$$A_v = \frac{R_p}{R + R_p}$$

Evaluating we have

V_C (V)	1.6	10.6
I_{DQ} (mA)	0.5	5.0
r_d (Ω)	52	5.2
R_p (Ω)	49.43	5.173
A_v	0.3308	0.04919

Answers for Selected Problems

P10.6*



P10.8* $n = 1.336$

$I_s = 3.150 \times 10^{-11}$ **A**

P10.13* With $n = 1$, $v = 582$ mV .

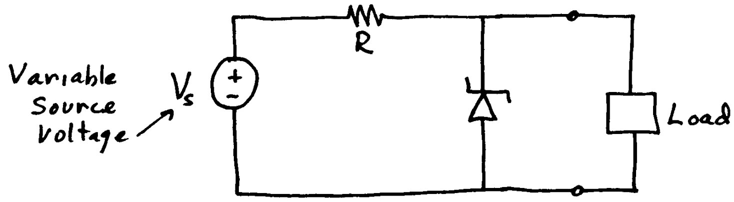
With $n = 2$, $v = 564$ mV .

P10.15* (a) $I_A = I_B = 100$ mA

(b) $I_A = 87$ mA and $I_B = 113$ mA

P10.16* $v_x = 2.20$ V $\quad i_x = 0.80$ A

P10.26* The circuit diagram of a simple voltage regulator is:



P10.33* $i_{ab} \cong 1.4\ A \qquad v_{ab} \cong 2.9\ \text{V}$

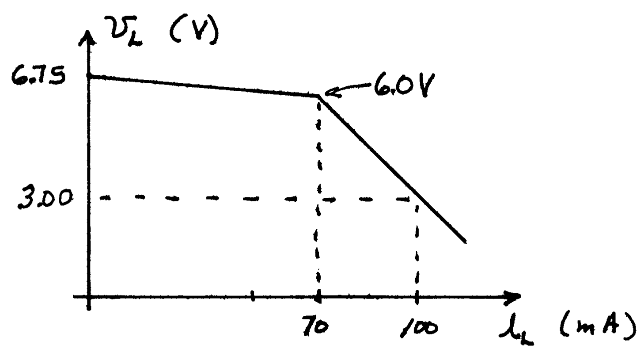
P10.37* (a) D_1 is on and D_2 is off. $V = 10$ volts and $I = 0$.

(b) D_1 is on and D_2 is off. $V = 6$ volts and $I = 6$ mA.

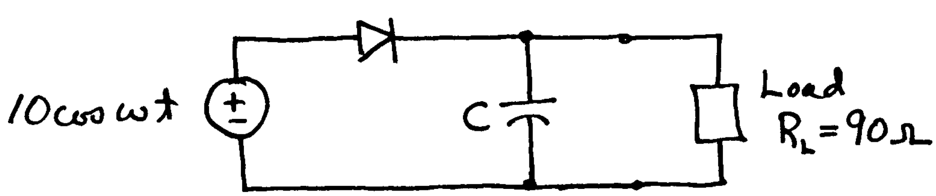
(c) Both D_1 and D_2 are on. $V = 30$ volts and $I = 33.6$ mA.

P10.46* For the circuit of Figure P10.46a, $v = 0.964$ V.
For the circuit of Figure P10.46b, $v = 1.48$ V.

P10.47*

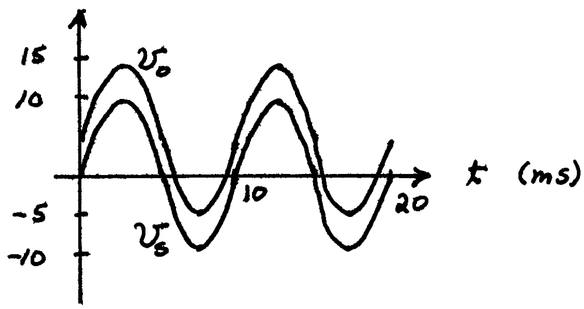


P10.54* $C = 833\ \mu\text{F}$

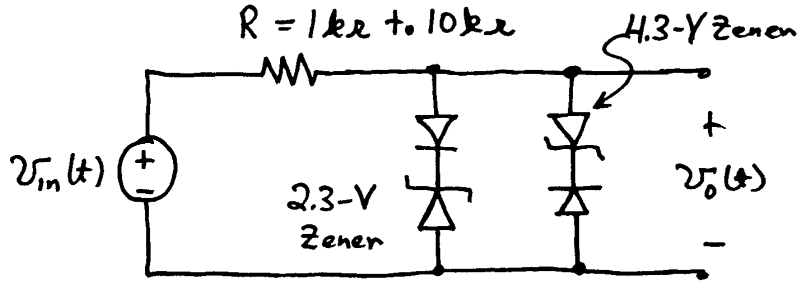


P10.58* For a half-wave rectifier, $C = 20833\ \mu\text{F}$.
For a full-wave rectifier, $C = 10416\ \mu\text{F}$.

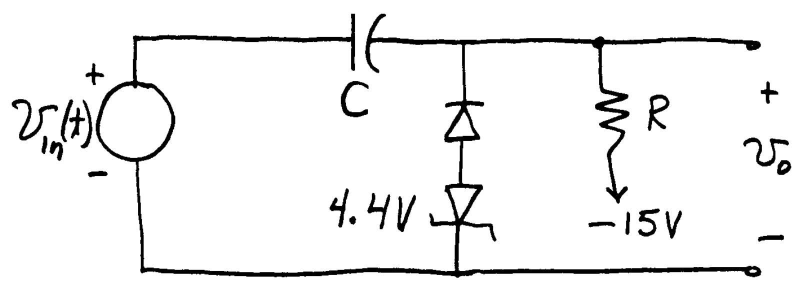
P10.70*



P10.72*

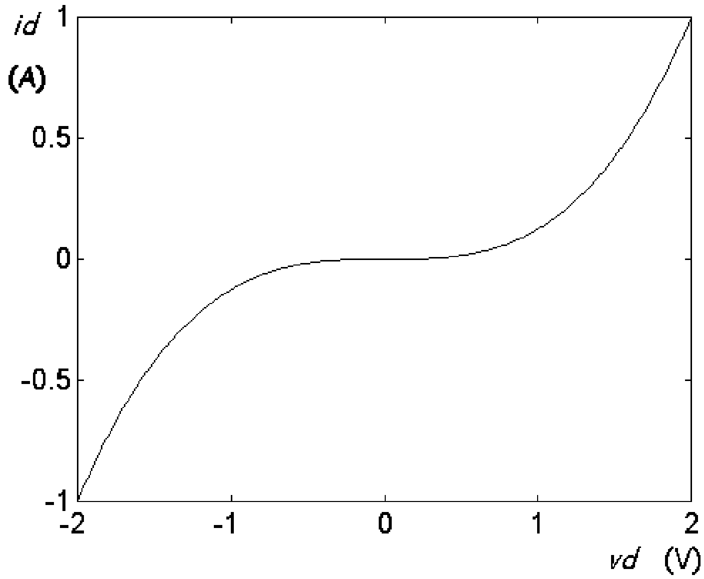


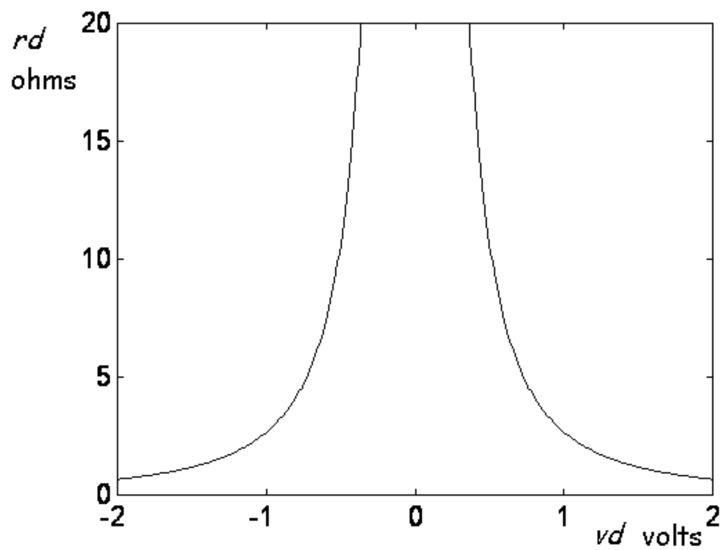
P10.75*



We must choose the time constant *RC* >> *T*, where *T* is the period of the input waveform.

P10.81*

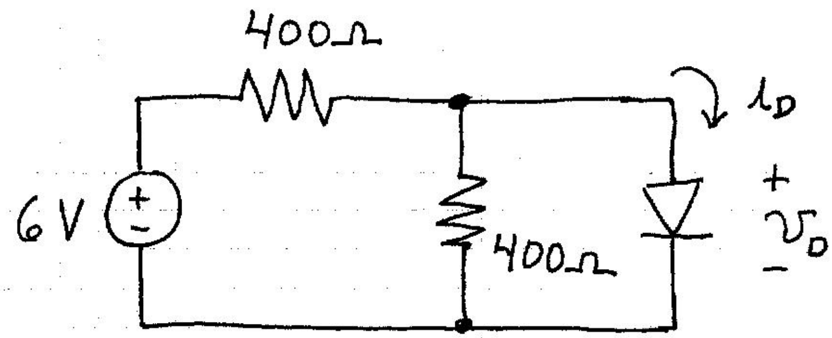




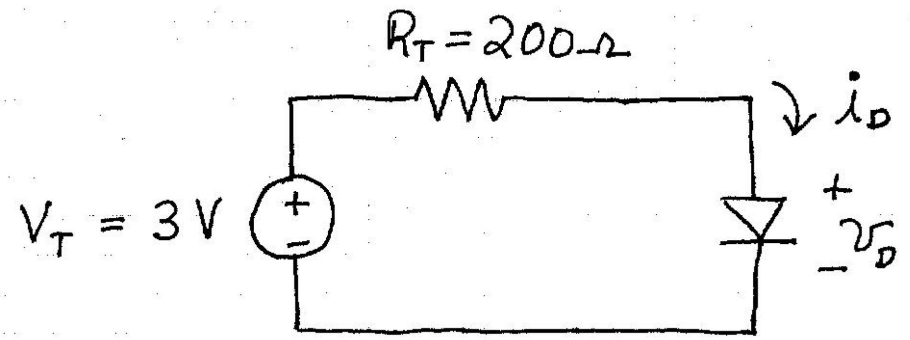
P10.85* $I_{DQ} = 100$ mA $\quad r_D = 0.202\ \Omega$

Practice Test

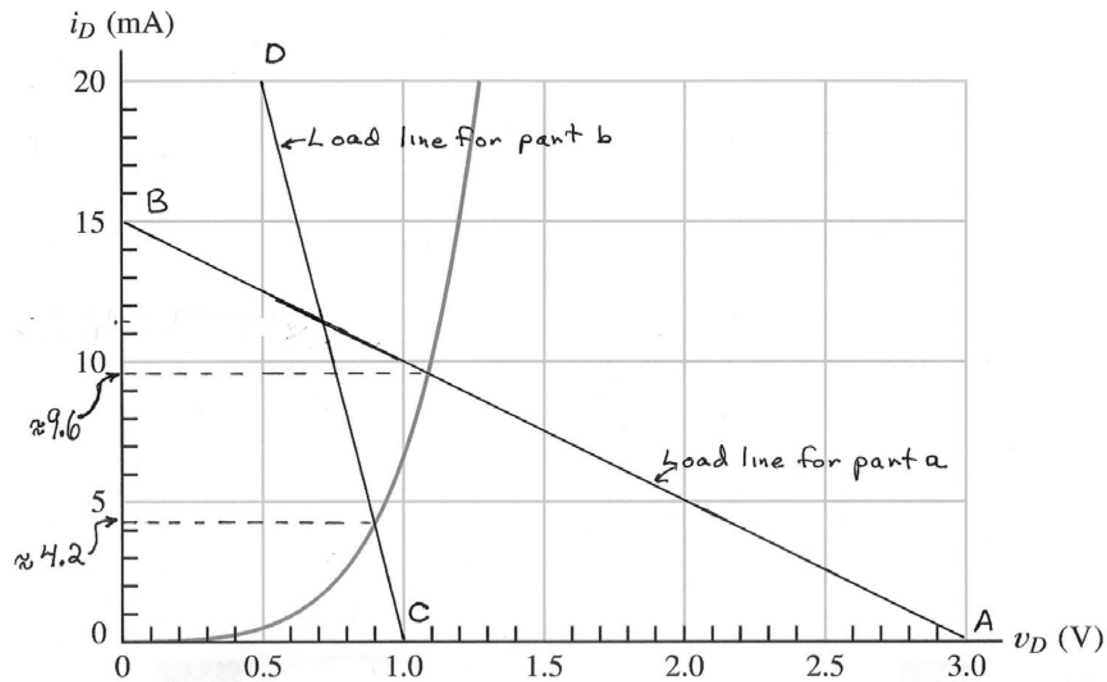
T10.1 (a) First, we redraw the circuit, grouping the linear elements to the left of the diode.



Then, we determine the Thévenin equivalent for the circuit looking back from the diode terminals.



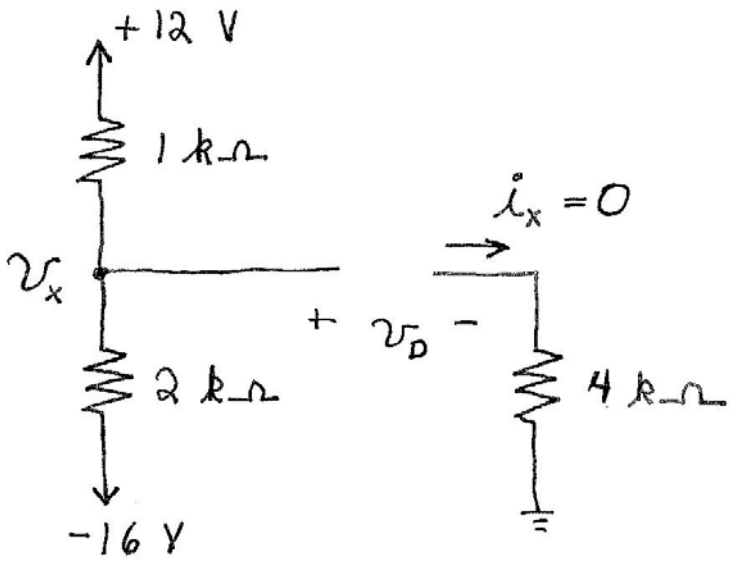
Next, we write the KVL equation for the network, which yields $V_T = R_T i_D + v_D$. Substituting the values for the Thévenin voltage and resistance, we have the load-line equation, $3 = 200 i_D + v_D$. For $i_D = 0$, we have $v_D = 3$ V which are the coordinates for Point *A* on the load line, as shown below. For $v_D = 0$, the load-line equation gives $i_D = 15$ mA which are the coordinates for Point *B* on the load line. Using these two points to plot the load line on Figure 10.8, we have



The intersection of the load line and the diode characteristic gives the current at the operating point as $i_D \cong 9.6\,\text{mA}$.

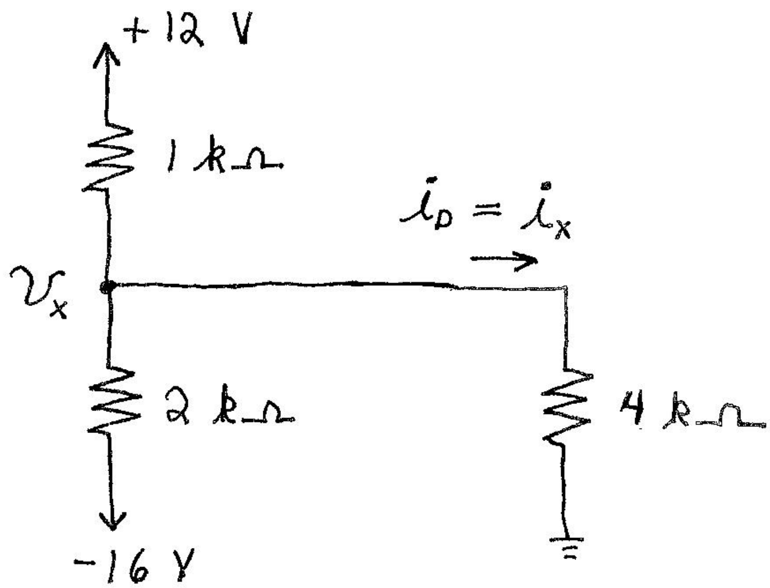
(b) First, we write the KCL equation at the top node of the network, which yields $i_D + v_D/25 = 40\,\text{mA}$. For $i_D = 0$, we have $v_D = 1\,\text{V}$ which are the coordinates for Point C on the load line shown above. For $v_D = 0$, the load-line equation gives $i_D = 40\,\text{mA}$ which plots off the vertical scale. Therefore, we substitute $i_D = 20\,\text{mA}$, and the KCL equation then yields $v_D = 0.5\,\text{V}$. These values are shown as point D. Using Points C and D we plot the load line on Figure 10.8 as shown above. The intersection of the load line and the diode characteristic gives the current at the operating point as $i_D \cong 4.2\,\text{mA}$.

T10.2 If we assume that the diode is off (i.e., an open circuit), the circuit becomes



Writing a KCL equation with resistances in kΩ, currents in mA, and voltages in V, we have $\frac{v_x - 12}{1} + \frac{v_x - (-16)}{2} = 0$. Solving, we find that $v_x = 2.667$ V. However, the voltage across the diode is $v_D = v_x$, which must be negative for the diode to be off. Therefore, the diode must be on.

With the diode assumed to be on (i.e. a short circuit) the circuit becomes

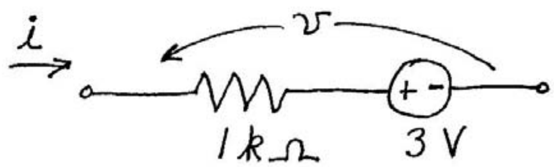


Writing a KCL equation with resistances in kΩ, currents in mA and voltages in V, we have $\frac{v_x - 12}{1} + \frac{v_x - (-16)}{2} + \frac{v_x}{4} = 0$. Solving, we find that

$v_x = 2.286$ V. Then, the current through the diode is

$i_D = i_x = \frac{v_x}{4} = 0.571$ mA. Of course, a positive value for i_D is consistent with the assumption that the diode is on.

T10.3 We know that the line passes through the points (5 V, 2 mA) and (10 V, 7 mA). The slope of the line is $-1/R = -\Delta i/\Delta v = (-5\text{ mA})/(5\text{ V})$, and we have $R = 1$ kΩ. Furthermore, the intercept on the voltage axis is at $v = 3$ V. Thus, the equivalent circuit for the device is



T10.4 The circuit diagram is:

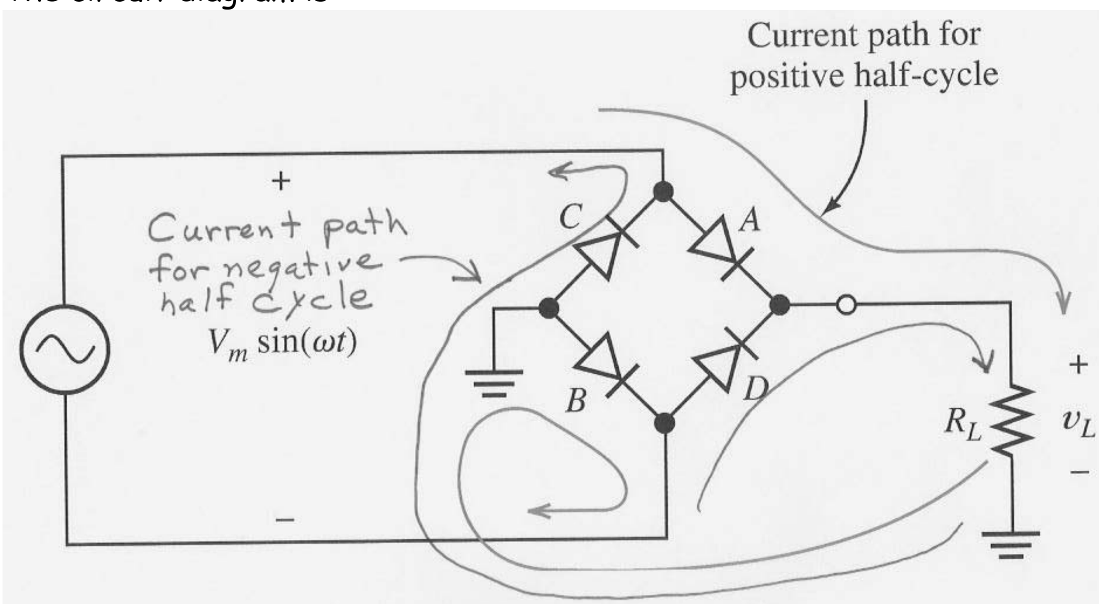
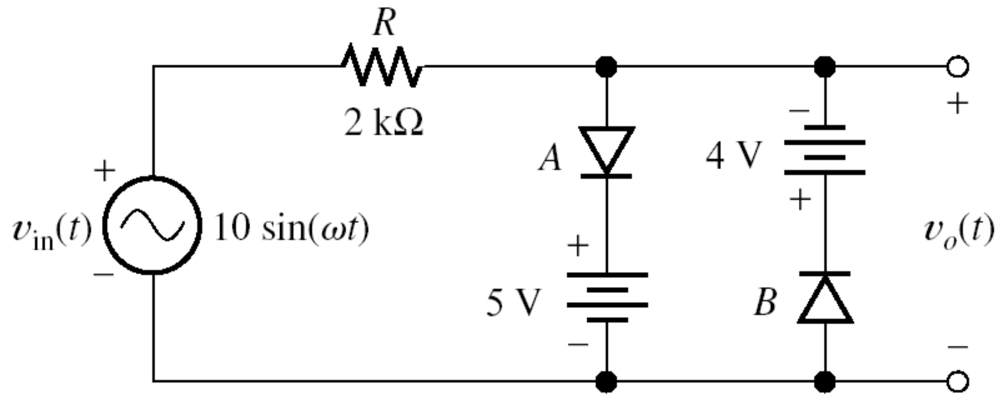


Figure 10.28 Diode-bridge full-wave rectifier.

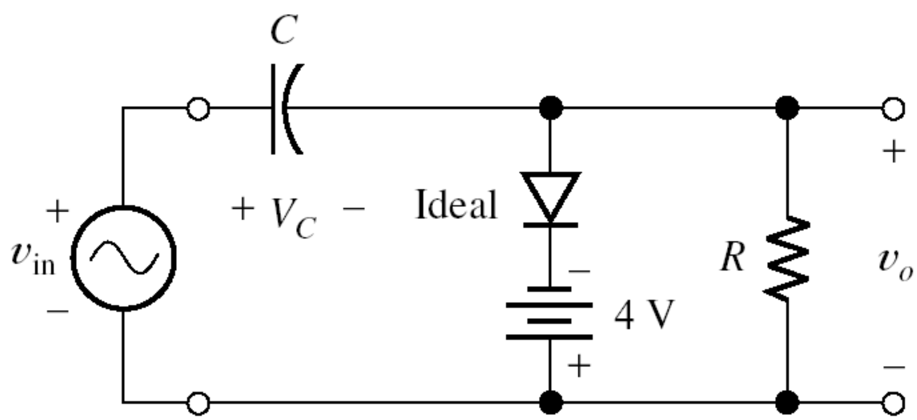
Your diagram may be correct even if it is laid out differently. Check to see that you have four diodes and that current flows from the source through a diode in the forward direction then through the load and finally through a second diode in the forward direction back to the opposite end of the source. On the opposite half cycle, the path should be through the other two diodes and through the load in the same direction as before. Notice in the diagram that current flows downward through the load on both half cycles.

T10.5 An acceptable circuit diagram is:



Your diagram may be somewhat different in appearance. For example, the 4-V source and diode *B* can be interchanged as long as the source polarity and direction of the diode don't change; similarly for the 5-V source and diode A. The parallel branches can be interchanged in position. The problem does not give enough information to properly select the value of the resistance, however, any value from about 1 kΩ to 1 MΩ is acceptable.

T10.6 An acceptable circuit diagram is:



The time constant *RC* should be much longer than the period of the source voltage. Thus, we should select component values so that $RC >> 0.1$ s.

T10.7 We have

$$V_T = \frac{kT}{q} = \frac{1.38 \times 10^{-23} \times 300}{1.60 \times 10^{-19}} = 25.88 \text{ mV}$$

$$r_d = \frac{nV_T}{I_{DQ}} = \frac{2 \times 25.88 \times 10^{-3}}{5 \times 10^{-3}} = 10.35\,\Omega$$

The small-signal equivalent circuit for the diode is a 10.35 Ω resistance.