Diode circuits-2 (`EC_diode_2.sqproj`)

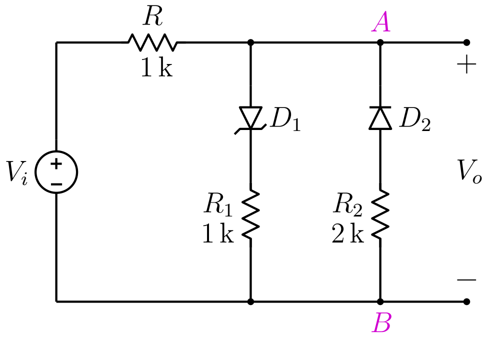

Figure 1: Diode circuit example.

Question: For the diode circuit shown in Fig. 1, plot V_o versus V_i for $-5\,\text{V} < V_i < 5\,\text{V}$. Assume $V_{\text{on}} = 0.7\,\text{V}$ for D_1 and D_2 and $V_Z = 3\,\text{V}$ for D_1.

Solution:

We note that the following conditions are required for D_1 or D_2 to conduct[1].

(i) D_1 conducting in the forward direction: $V_{AB} > V_{\text{on}}^{D1} = 0.7\,\text{V}$.

(ii) D_2 conducting in the forward direction and D_1 off: $V_{BA} > V_{\text{on}}^{D2} = 0.7\,\text{V}$ and $V_{BA} < V_Z = 3\,\text{V}$, i.e., $-3\,\text{V} < V_{AB} < -0.7\,\text{V}$.

(iii) D_2 conducting in the forward direction and D_1 conducting in the reverse direction: $V_{BA} > V_{\text{on}}^{D2} = 0.7\,\text{V}$ and $V_{BA} > V_Z = 3\,\text{V}$ which means $V_{BA} > 3\,\text{V} \rightarrow V_{AB} < -3\,\text{V}$.

Let us now use the above conditions and analyse the various possibilities.

1. For $-0.7\,\text{V} < V_{AB} < -0.7\,\text{V}$, none of the diodes can conduct, the current through R is zero, and we have $V_i = V_{AB} = 0\,\text{V}$. The slope $\dfrac{dV_o}{dV_i} = 1$ in this region.
2. For D_1 to be conducting in the forward direction, we require $V_{AB} > 0.7\,\text{V}$ which means that D_2 must be off. D_1 *just* starts conducting when the current I_1 in Fig. 2 (b) is small (zero), and therefore the voltage drop across R is zero. In other words, D_1 starts conducting when $V_i = 0.7\,\text{V}$.

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[1] We assume that D_2 can only conduct in the forward direction, i.e., it has a large breakdown voltage.

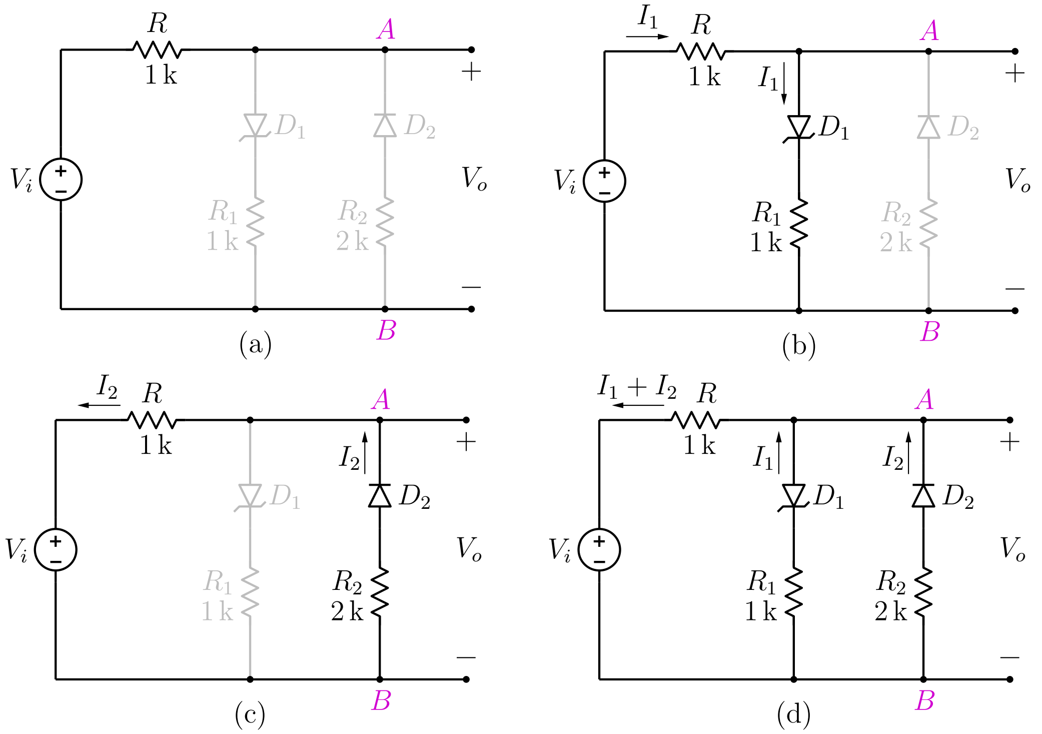
3. When D_2 conducts in the forward direction and D_1 not conducting (see Fig. 2 (c)), the current through R is the same as I_{D2}. The condition for D_2 to *just* start conducting is by KVL, $V_i + I_2 R_2 + V_{\text{on}}^{D2} + I_2 R = 0$, with $I_2 \to 0$, giving $V_i = -V_{\text{on}}^{D2} = -0.7\,\text{V}$.

4. When V_i is increased in the negative direction, the current I_2 in Fig. 2 (c) starts increasing, and at some point, V_{BA} becomes equal to V_Z of D_1. This condition gives us the break point between the situations shown in Figs. 2 (c) and 2 (d). KVL gives $V_i + I_2 R_2 + V_{\text{on}}^{D2} + (I_1 + I_2)R = 0$, with $I_1 \approx 0$ at the break point. Solving for I_2 and then using $I_2 R_2 + V_{\text{on}}^{D2} = V_Z$ gives

$$V_{\text{on}}^{D2} + \frac{-V_i - V_{\text{on}}^{D2}}{R_2 + R} \times R_2 = V_Z, \tag{1}$$

   from which the break point V_i can be obtained. Substitution of numerical values gives $V_i = -4.15\,\text{V}$.

The break points are summarised in Fig. 3.



(a) (b) (c) (d)

Figure 2: Diode circuit of Fig. 1 under different conditions: (a) D_1 off, D_2 off, (b) D_1 conducting in the forward direction, D_2 off, (c) D_1 off, D_2 conducting in the forward direction, (d) D_1 conducting in the reverse direction, D_2 conducting in the forward direction.

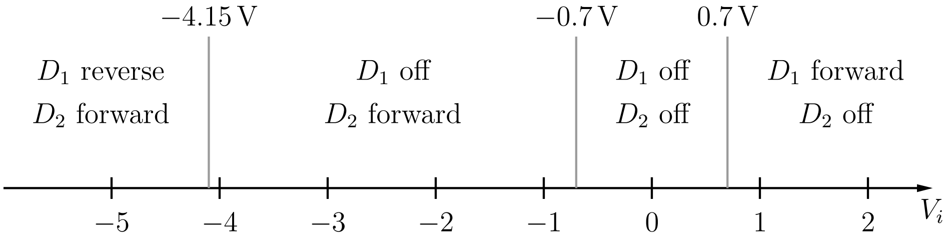


Figure 3: Break points in the V_o versus V_i relationship for the circuit of Fig. 1.

Next, we compute the slope $\dfrac{dV_o}{dV_i}$ in each of the four regions shown in Fig. 3. For this purpose, we replace the diode with an open circuit when it is off, with a voltage source V_{on} when it is conducting in the forward direction, and with a voltage source V_Z when it is conducting in the reverse direction, as shown in Figs. 4 (a)-(d).

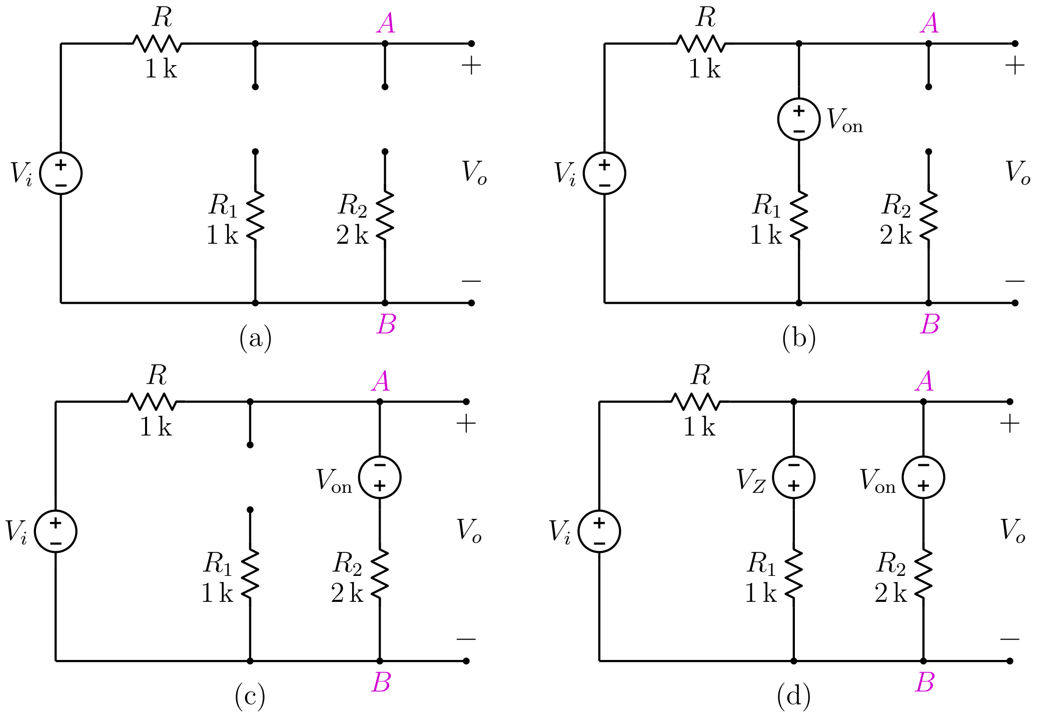


Figure 4: Diode circuit of Fig. 1 under different conditions, with diodes replaced by equivalent circuits, (a) D_1 off, D_2 off, (b) D_1 conducting in the forward direction, D_2 off, (c) D_1 off, D_2 conducting in the forward direction, (d) D_1 conducting in the reverse direction, D_2 conducting in the forward direction.

We can use KVL to obtain V_o in terms of V_i in each of these cases and then differentiate to get $\dfrac{dV_o}{dV_i}$. However, there is a simpler way to arrive at the same result. Since we are only interested in the effect of V_i on V_o in each of the circuits in Figs. 4 (a)-(d) – which are linear – we simply deactivate the voltage source(s) representing the diode(s), as shown in Figs. 5 (a)-(d), and obtain V_o in each case.

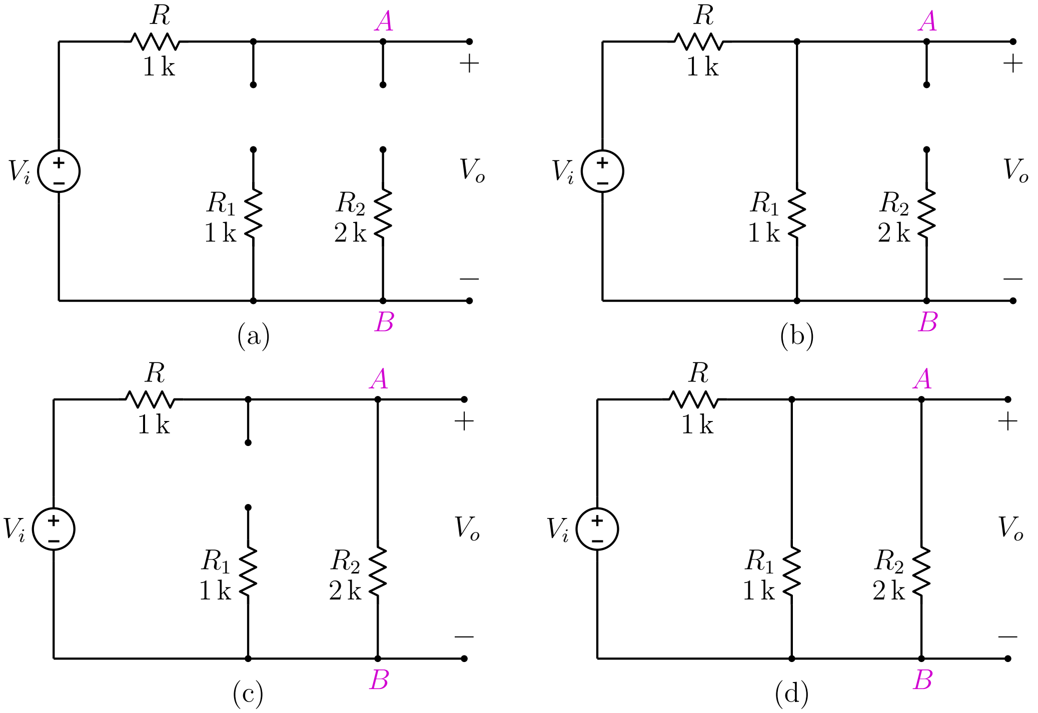


Figure 5: Simplification of circuits in Figs. 4 (a)-(d) for computation of $\dfrac{dV_o}{dV_i}$: (a) D_1 off, D_2 off, (b) D_1 conducting in the forward direction, D_2 off, (c) D_1 off, D_2 conducting in the forward direction, (d) D_1 conducting in the reverse direction, D_2 conducting in the forward direction.

Using this procedure, we get the following values for $\dfrac{dV_o}{dV_i}$.

(i) $-0.7\,\text{V} < V_i < 0.7\,\text{V}$: $V_o = V_i \rightarrow \dfrac{dV_o}{dV_i} = 1$.

(ii) $V_i > 0.7\,\text{V}$: $V_o = \dfrac{R_1}{R + R_1} \times V_i \rightarrow \dfrac{dV_o}{dV_i} = \dfrac{R_1}{R + R_1}$.

(iii) $-4.15\,\text{V} < V_i < -0.7\,\text{V}$: $V_o = \dfrac{R_2}{R + R_2} \times V_i \rightarrow \dfrac{dV_o}{dV_i} = \dfrac{R_2}{R + R_2}$.

(iv) $V_i < -4.15\,\text{V}$: $V_o = \dfrac{(R_1 \parallel R_2)}{R + (R_1 \parallel R_2)} \times V_i \rightarrow \dfrac{dV_o}{dV_i} = \dfrac{(R_1 \parallel R_2)}{R + (R_1 \parallel R_2)}$.

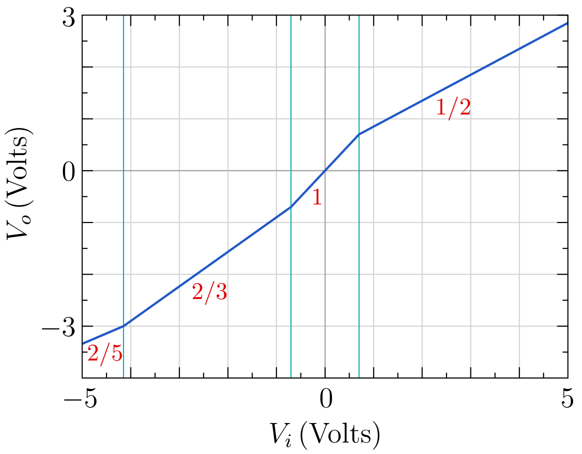


Figure 6: V_o versus V_i plot for the diode circuit of Fig. 1. Slopes are marked in red.

Finally, putting together all our observations, we obtain the V_o versus V_i plot shown in Fig. 6.

SequelApp Exercises: Answer the following, and verify using SequelApp.

1. How will the V_o versus V_i curve be affected with the following changes (keeping all other component values the same as in Fig. 1)?

   (i) R_1 is changed 0.5 k.

   (ii) R_2 is changed 0.5 k.

2. If $V_i(t) = V_m \sin \omega t$, find the minimum and maximum values of $V_o(t)$ for two cases: (a) $V_m = 3\,\text{V}$, (b) $V_m = 5\,\text{V}$.