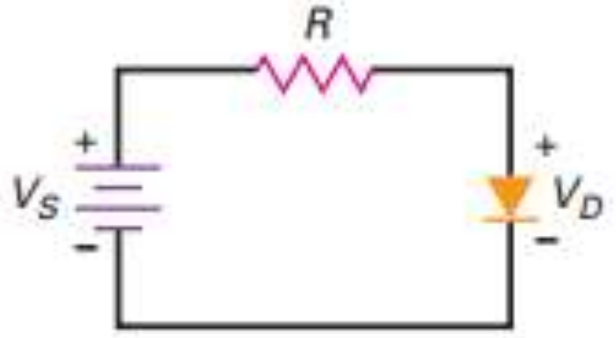
ECE312 | Electronic Circuits

Lecture 1| Diode Circuits - Part (1)

Basic Diode Circuit

- In this circuit, the diode is forward biased. How do we know?



- The forward region
- Knee voltage

$$V_K \approx 0.7\ \text{V}$$

- Bulk resistance

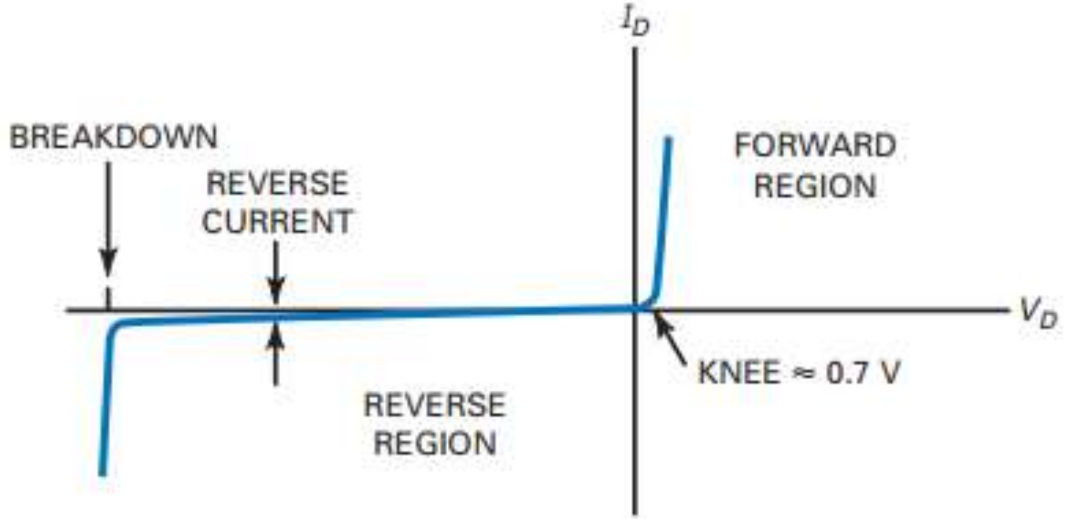
$$R_B = R_P + R_N$$

- Maximum DC forward current
  - Power dissipation

$$P_D = V_D I_D$$

  - Power rating

$$P_{\max} = V_{\max} I_{\max}$$



Basic Diode Circuit

Example 1: Is the diode of Fig. 1a forward biased or reverse biased?

Solution:

First, we find Thevenin circuit as in Fig. 1b

$$V_{Th} = V_s \frac{R_2}{R_1 + R_2} \qquad R_{Th} = \frac{R_1 R_2}{R_1 + R_2}$$

Now, in this circuit, you can see that the dc source is trying to push current in the easy direction of flow. Therefore the diode is forward biased.

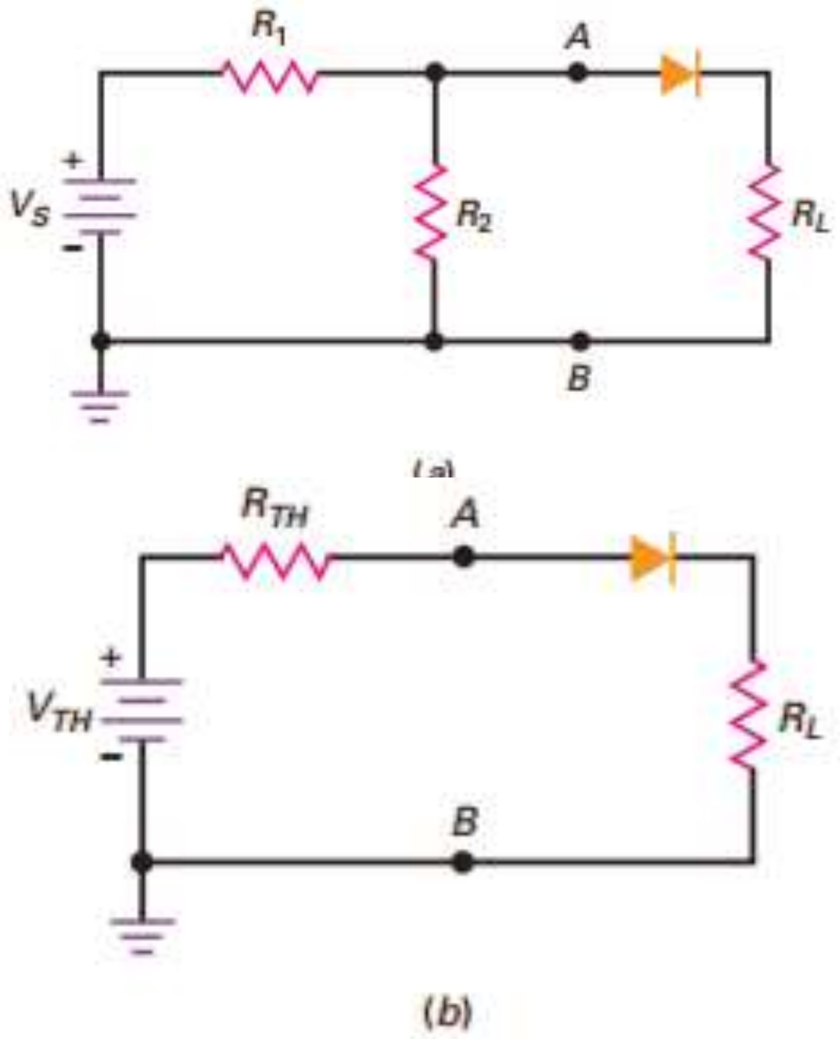


Figure 1

Basic Diode Circuit

Practice Problem 1:

Are the diodes of Fig. 2 forward biased or reverse biased?

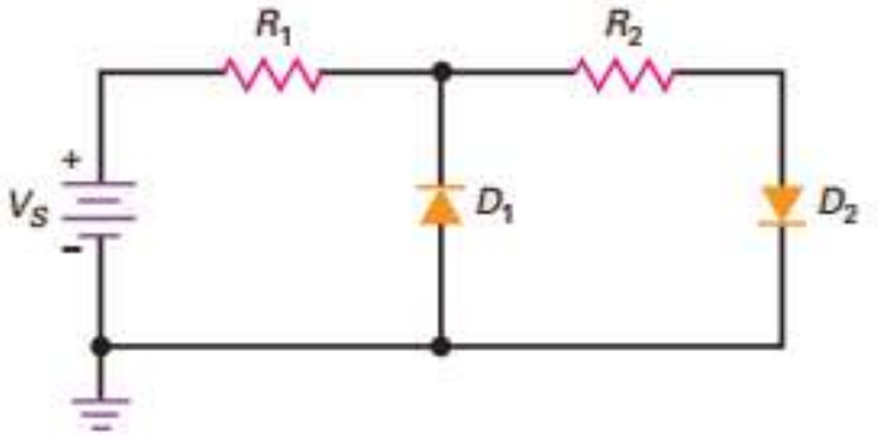


Figure 2

Basic Diode Circuit

Example 2: A diode has a power rating of 5 W. If the diode voltage is 1.2 V and the diode current is 1.75 A, what is the power dissipation? Will the diode be destroyed?

Solution:

$$P_D = V_D I_D = (1.2)(1.75) = 2.1\ \mathrm{W}$$

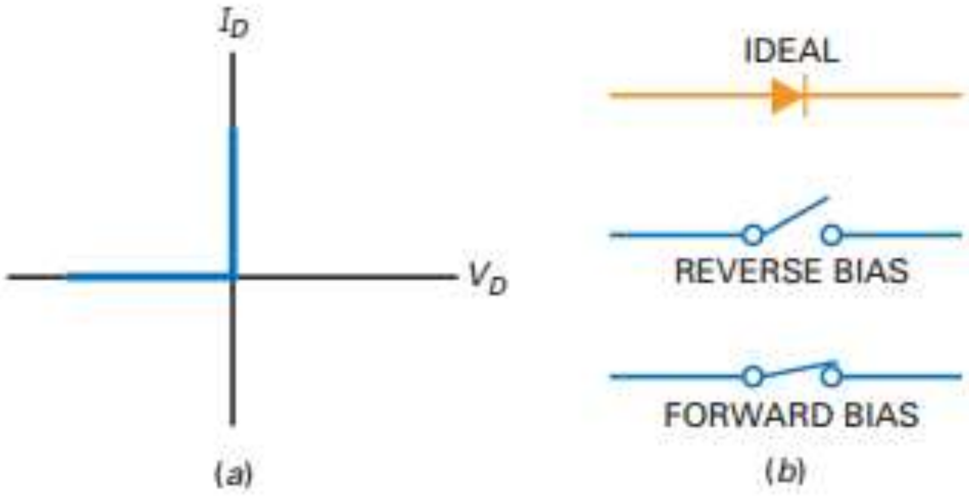
This is less than the power rating, so the diode will not be destroyed.

Practice Problem 2:

Referring to Example 2, what is the diode's power dissipation if the diode voltage 1.1 V and the diode current is 2 A.

Diode Approximations

- **The First Approximation**: the simplest approximation, called an ideal diode.



Diode Approximations

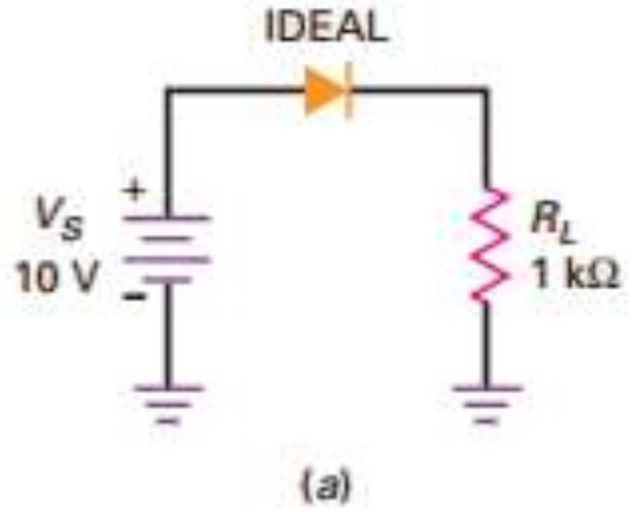


Figure 3.

Example 2:

Use the ideal diode to calculate the load voltage and load current in Fig. 3

Solution:

You can see that all of the source voltage appears across the load resistor:

$$V_L = 10\text{ V}$$

with ohm's law, the load current is:

$$I_L = \frac{10}{1000} = 10\text{ mA}$$

Diode Approximations

Example 3:

Calculate the load voltage and load current in Fig. 3b using an ideal diode.

Solution:

Using voltage division, the Thevenin's voltage is

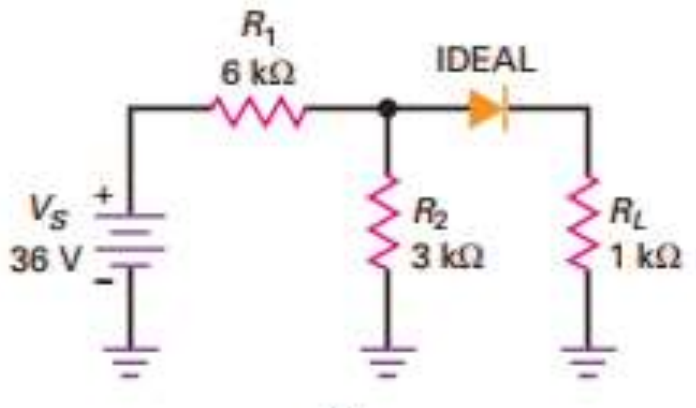
$$V_{Th} = \frac{(36)(3)}{(3+6)} = \frac{36\times 3}{9} = 12\ \text{V}$$

The Thevenin's resistance is

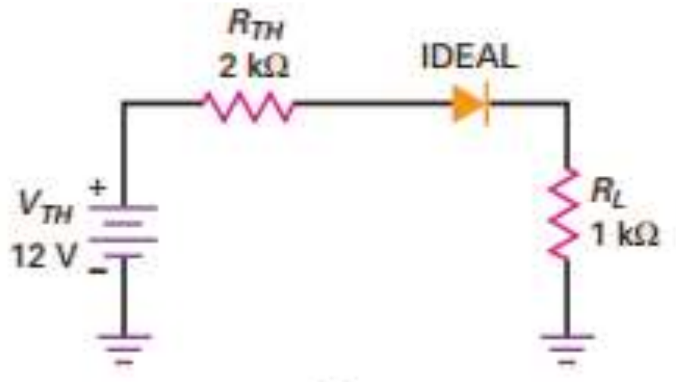
$$R_{Th} = \frac{3\times 6}{3+6} = 2\ \text{k}\Omega$$

with Ohm's law, the load current is: $I_L = \dfrac{12}{2000+1000} = \dfrac{12}{3000} = 4\ \text{mA}$

and the load voltage is: $V_L = (4\,\text{mA})(1\text{k}\Omega) = 4\ \text{V}$



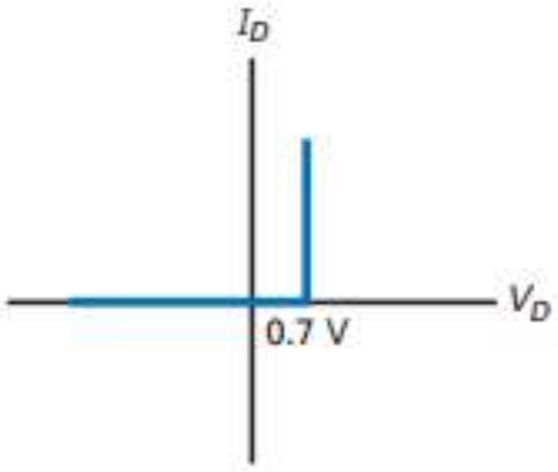
(b)



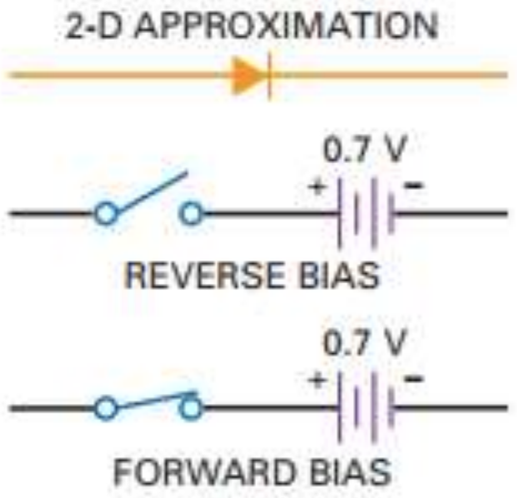
(c)

Diode Approximations

- The Second Approximation:
- We think of the diode as a switch in series with a barrier potential of 0.7 V.
  - If the Thevenin voltage facing the diode is greater than 0.7 V, the switch will close.
  - When conducting, then the diode voltage is 0.7 V for any forward current.
- On the other hand, if the Thevenin voltage is less than 0.7 V, the switch will open. In this case, there is no current through the diode.



(a)



(b)

Diode Approximations

Example 4:

Use the second approximation to calculate the load voltage, load current, and diode power in Fig. 4.

Solution:

Since the diode is forward biased, it is equivalent to a battery of 0.7 V. This means that the load voltage equals the source voltage minus the diode drop:

$$V_L = 10 - 0.7 = 9.3\text{ V}$$

With Ohm’s law, the load current is:

$$I_L = \frac{9.3}{1000} = 9.3\text{ mA}$$

The diode power is:

$$P_D = (0.7)(9.3) = 6.51\text{ mW}$$

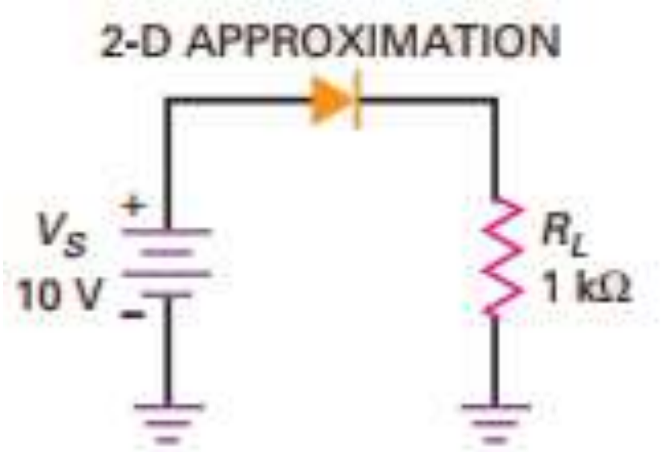


Figure 4.

Diode Approximations

Example 5:

Calculate the load voltage, load current, diode power in Fig. 5a using the second approximation.

Solution:

The Thevenin's version of Fig. 4a circuit is in Fig. 5b, hence, since the voltage is 0.7 V, the load current is:

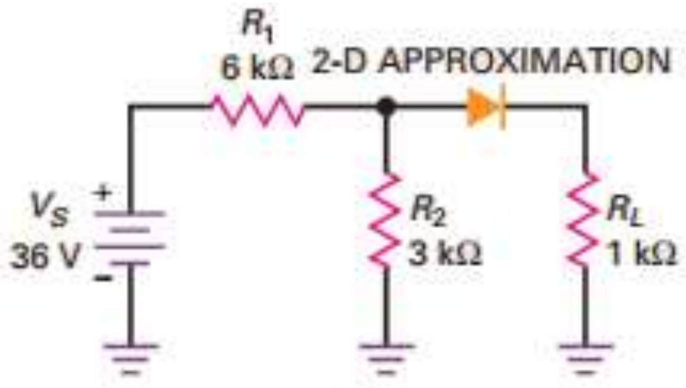
$$I_L = \frac{12 - 0.7}{3000} = 3.77\ \mathrm{mA}$$

the load voltage is:

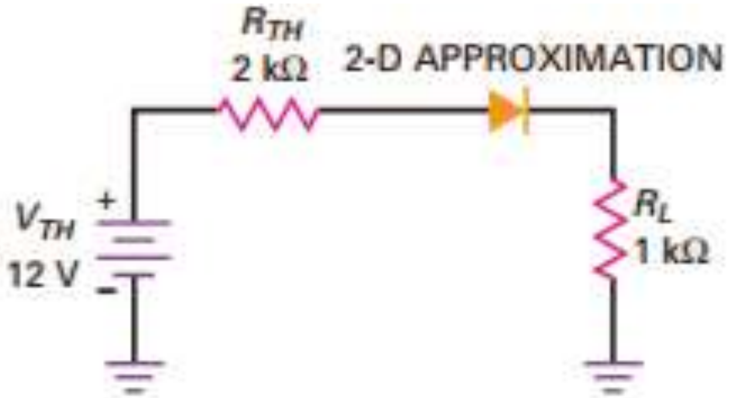
$$V_L = (3.77\,\mathrm{mA})(1\mathrm{k}\Omega) = 3.77\ \mathrm{V}$$

and the diode power is:

$$P_D = (0.7)(3.77 \times 10^{-3}) = 2.64\ \mathrm{mW}$$



(a)



(b)

Diode Approximations

The Third Approximation:

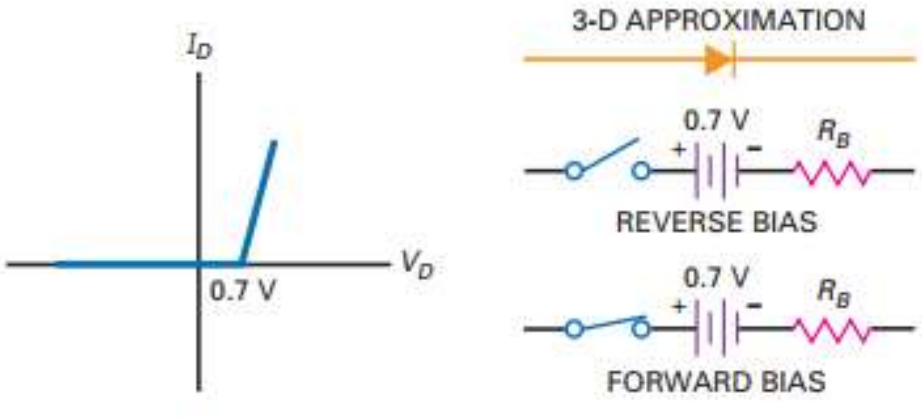
- In the third approximation of a diode, we include the bulk resistance $\boldsymbol{R_B}$.

- The equivalent circuit for the third approximation is a switch in series with a barrier potential of 0.7 V and a resistance of $\boldsymbol{R_B}$.
- During conduction, the total voltage across the diode is:

$$V_D = 0.7 + I_D R_B$$

- A useful guideline for ignoring bulk resistance is this definition:

$$R_B < 0.01 R_{Th}$$



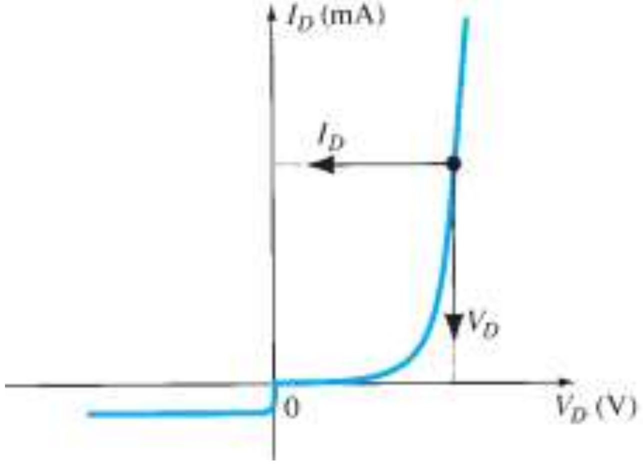
(a) (b)

- When this condition is satisfied, the error is less than 1 percent.

Resistance Levels -DC or Static Resistance

- The resistance of the diode at the operating point can be found simply by finding the corresponding levels of V_D and $\mathbf{I}_D$ as shown in Fig. and applying the following equation:

$$R_D = \frac{V_D}{I_D}$$



- The **dc resistance levels** at the knee and below will be greater than the resistance levels obtained for the vertical rise section of the characteristics.
- The **resistance levels in the reverse-bias region** will naturally be **quite high**.
- Typically, the dc resistance of a diode in the active (most utilized) will range from about 10 Ω to 80 Ω.

In general, therefore, the higher the current through a diode, the lower is the dc resistance level.

Resistance Levels -DC or Static Resistance

Example : Determine the dc resistance levels for the diode of Fig. at (a) I_D =2mA (low level), (b) I_D = 20 mA (high level) and (c) V_D = -10 V (reverse biased)

Solution:

a. At $I_D = 2$ mA, $V_D = 0.5$ V (from the curve) and

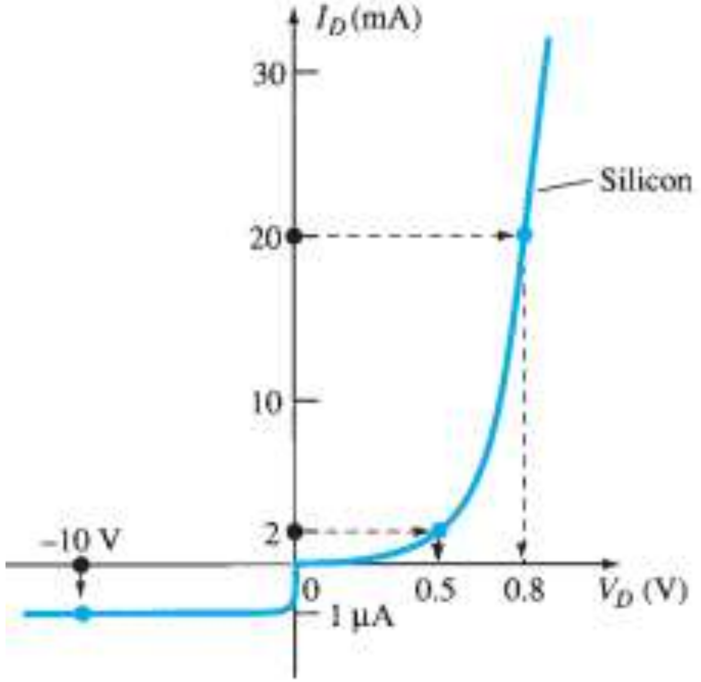
$$R_D = \frac{V_D}{I_D} = \frac{0.5\text{ V}}{2\text{ mA}} = \mathbf{250\ \Omega}$$

b. At $I_D = 20$ mA, $V_D = 0.8$ V (from the curve) and

$$R_D = \frac{V_D}{I_D} = \frac{0.8\text{ V}}{20\text{ mA}} = \mathbf{40\ \Omega}$$

c. At $V_D = -10$ V, $I_D = -I_s = -1\ \mu$A (from the curve) and

$$R_D = \frac{V_D}{I_D} = \frac{10\text{ V}}{1\ \mu\text{A}} = \mathbf{10\ M\Omega}$$

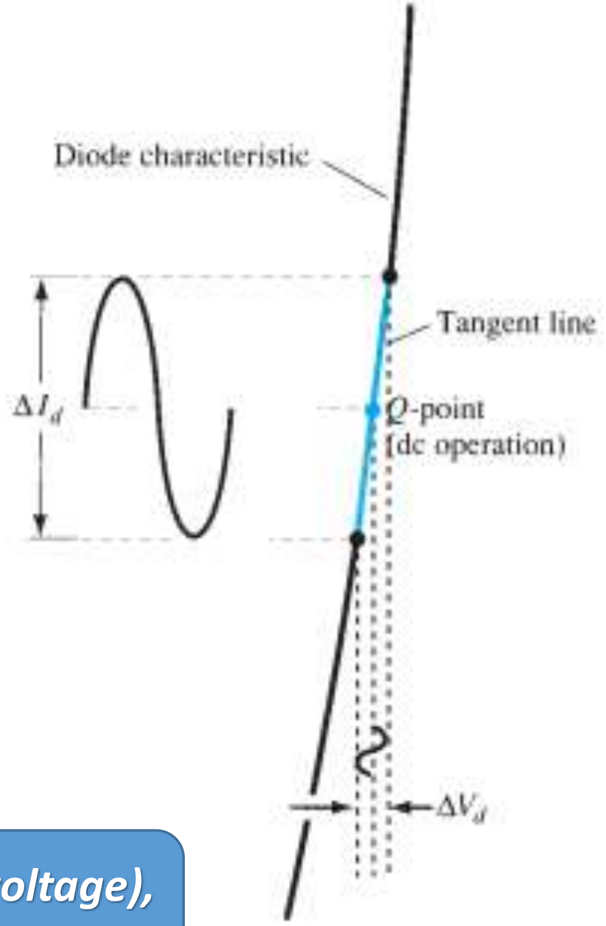


clearly supporting some of the earlier comments regarding the dc resistance levels of a diode.

Resistance Levels -AC or Dynamic Resistance

- the dc resistance of a diode is independent of the shape of the characteristic in the region surrounding the point of interest.
- The varying input will move the instantaneous **operating point** up and down a region of the characteristics and thus defines a specific change in current and voltage as shown in Fig.
- The designation **Q-point** is derived from the word **quiescent**, which means "**still** or **unvarying**."
  the **ac or dynamic resistance** for this region of the diode characteristics and applying the following equation:

$$r_d = \frac{\Delta V_d}{\Delta I_d}$$



In general, therefore, the lower the Q-point of operation (smaller current or lower voltage), the higher is the ac resistance.

Resistance Levels -AC or Dynamic Resistance

Example: For the characteristics of Fig. a. Determine the ac resistance at I_D = 2 mA, b. Determine the ac resistance at I_D = 25 mA and c. Compare the results of parts (a) and (b) to the dc resistances at each current level

Solution:

a. For $I_D = 2$ mA, the tangent line at $I_D = 2$ mA was drawn as shown in Fig. 1.27 and a swing of 2 mA above and below the specified diode current was chosen. At $I_D = 4$ mA, $V_D = 0.76$ V, and at $I_D = 0$ mA, $V_D = 0.65$ V. The resulting changes in current and voltage are, respectively,

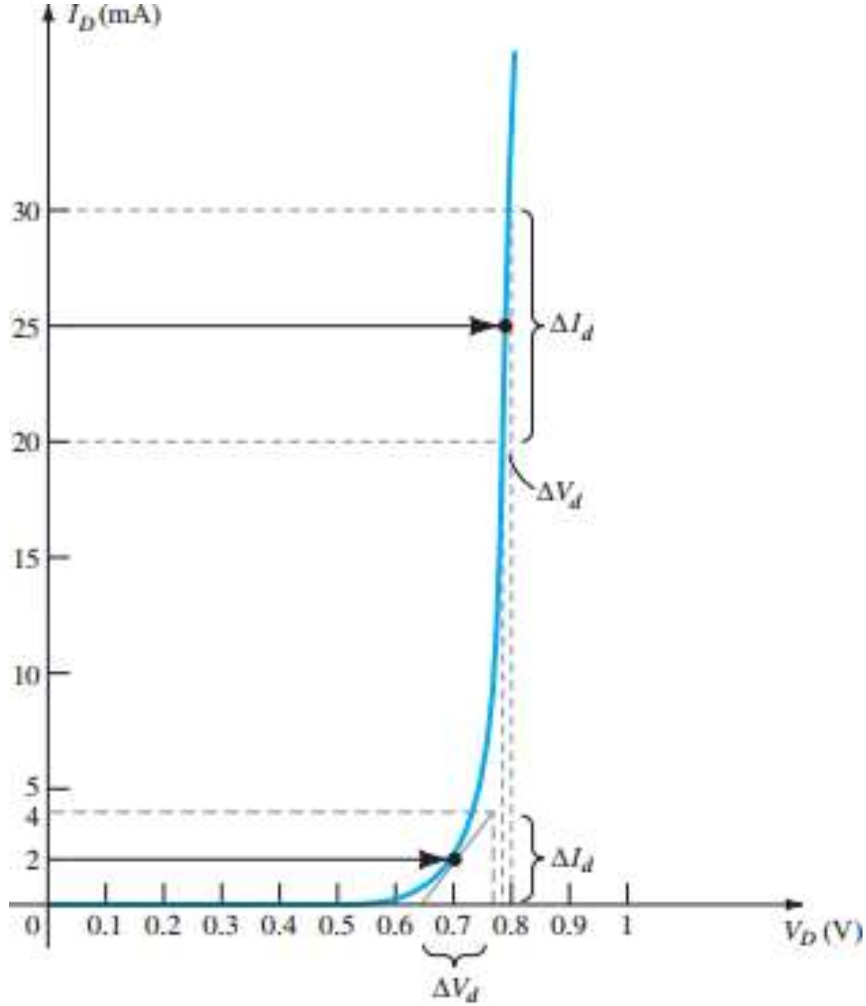
$$\Delta I_d = 4\text{ mA} - 0\text{ mA} = 4\text{ mA}$$

and

$$\Delta V_d = 0.76\text{ V} - 0.65\text{ V} = 0.11\text{ V}$$

and the ac resistance is

$$r_d = \frac{\Delta V_d}{\Delta I_d} = \frac{0.11\text{ V}}{4\text{ mA}} = \mathbf{27.5\ \Omega}$$



Resistance Levels -AC or Dynamic Resistance

b. For $I_D = 25\ \text{mA}$, the tangent line at $I_D = 25\ \text{mA}$ was drawn in Fig 1.27 and a swing of 5 mA above and below the specified diode current was chosen. At $I_D = 30\ \text{mA}, V_D = 0{,}8\ \text{V}$ and at $I_D = 20\ \text{mA}, V_D = 0.78\ \text{V}$ The resulting changes in current and voltage are respectively,

$$\Delta I_D = 30 - 20 = 10\ \text{mA},$$
$$\Delta V_D = 0.8 - 0.78 = 0.02\ \text{V}$$

and the ac resistance is

$$r_d = \frac{\Delta V_D}{\Delta I_D} = \frac{0.02\ \text{V}}{10\ \text{mA}} = 2\,\Omega$$

c. For $I_D = 2\ \text{mA}, V_D = 0.7\ \text{V}$ and

$$R_D = \frac{V_D}{I_D} = \frac{0.7\ \text{V}}{2\ \text{mA}} = 350\,\Omega$$

which far exceeds the r_d of 27.5 Ω

For $I_D = 25\ \text{mA}, V_D = 0.79\ \text{V}$ and

$$R_D = \frac{V_D}{I_D} = \frac{0.79\ \text{V}}{25\ \text{mA}} = 31.62\ \Omega$$

which far exceeds the r_d of 2 Ω

Resistance Levels - Average AC Resistance

- The **average ac resistance** is, by definition, the resistance determined by a **straight line** drawn between the two intersections established by the **maximum** and **minimum** values of input voltage. In equation form

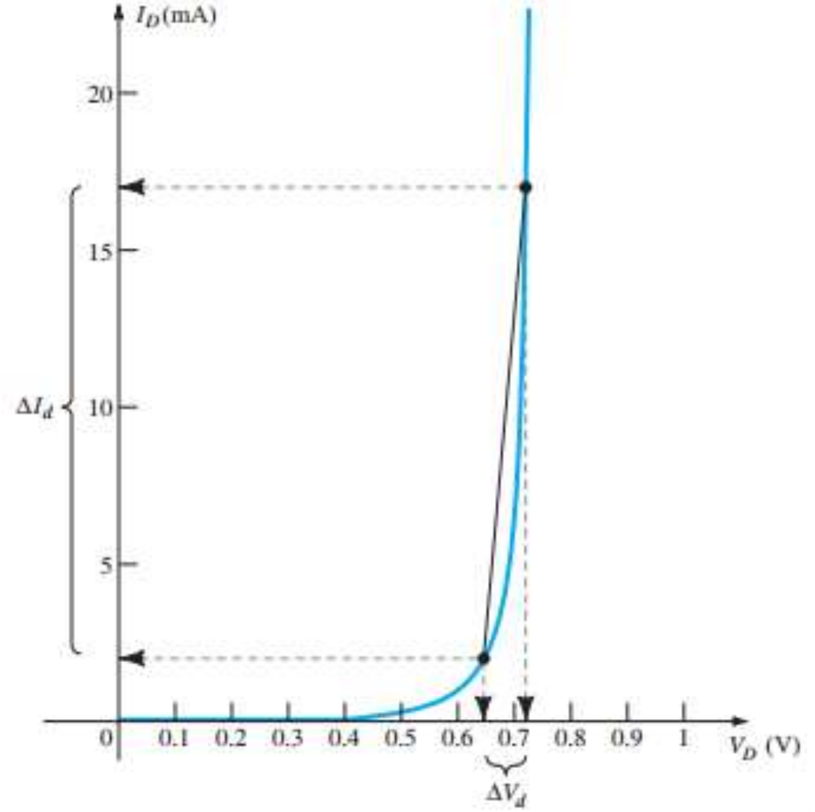
$$r_{av} = \left.\frac{\Delta V_d}{\Delta I_d}\right|_{pt. to\ pt.}$$

- For the situation indicated by Fig.

$$\Delta I_d = 17\text{ mA} - 2\text{ mA} = 15\text{ mA}$$

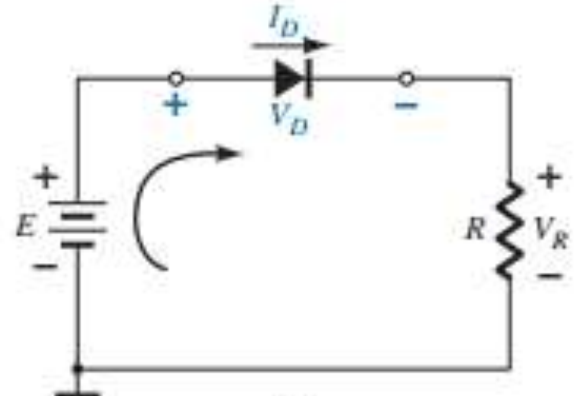
$$\Delta V_d = 0.725\text{ V} - 0.65\text{ V} = 0.075\text{ V}$$

$$r_{av} = \frac{\Delta V_d}{\Delta I_d} = \frac{0.075\text{ V}}{15\text{ mA}} = 5\ \Omega$$



As with the dc and ac resistance levels, the lower the level of currents used to determine the average resistance, the higher is the resistance level.

Diode Circuit - Load-Line analysis



(a)

- The intersection of the two curves will define the solution for the network and define the *current* and *voltage levels* for the network.
- The intersections of the *load line* on the characteristics can be determined by first *applying Kirchhoff's voltage law* which results in

$$-E + V_D + V_R = 0$$

or

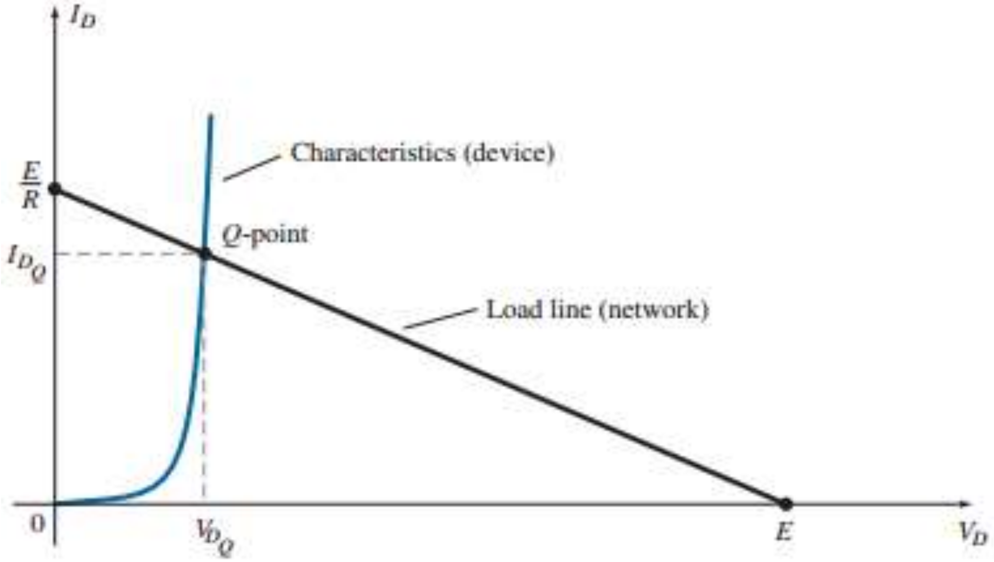
$$E = V_D + I_D R$$

- If we set V_D = 0 V in equation above and solve for I_D, we have the magnitude of I_D on the vertical axis. Therefore, with V_D = 0 V, the equation becomes

$$I_D = \frac{E}{R}\bigg|_{V_D = 0\text{ V}}$$

- If we set I_D = 0 A in equation above and solve for V_D, we have the magnitude of V_D on the horizontal axis. Therefore, with I_D = 0 A, the equation becomes

$$V_D = E\big|_{I_D = 0\text{ A}}$$



Diode Circuit - Load-Line analysis

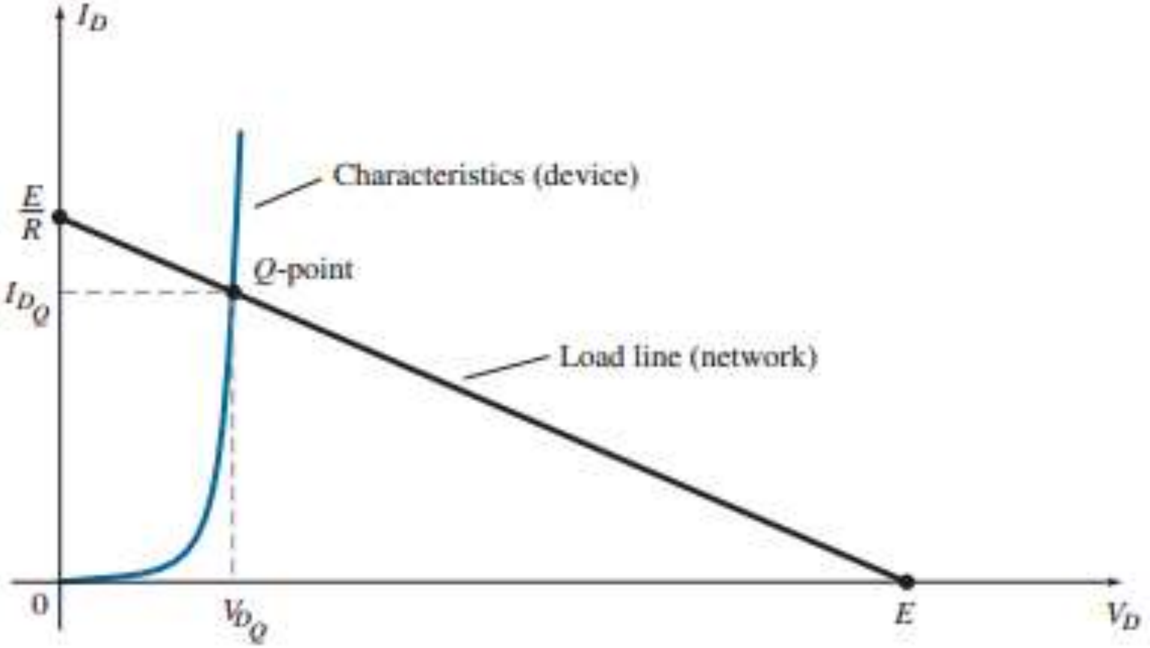
- The *point of intersection* between the two is the *point of operation* for this circuit or is usually called the *quiescent point* (abbreviated "Q-point") to reflect its "still, unmoving" qualities as defined by a dc network.
- The solution obtained at the intersection of the two curves is the same as would be obtained by a simultaneous mathematical solution of

$$I_D = \frac{E}{R} - \frac{V_D}{R}$$

- and

$$I_D = I_s\left(e^{V_D/nV_T} - 1\right)$$

- The load-line analysis described above provides *a solution with a minimum of effort* and a "pictorial" description of why the levels of solution for V_{DQ} and I_{DQ} were obtained.



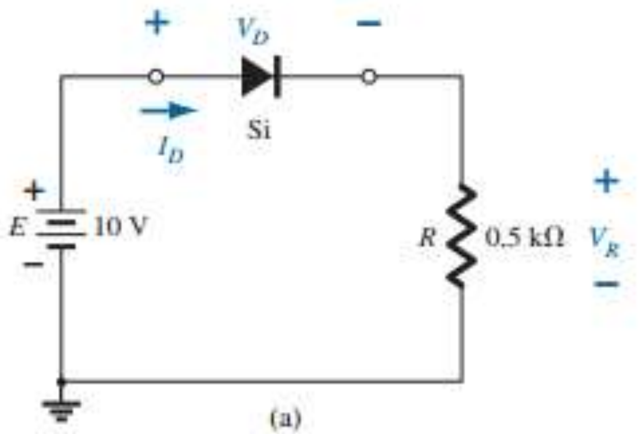
Diode Circuit - Load-Line analysis

Example 6: For the series diode configuration of Fig. 6a, employing the diode characteristics of Fig. 6b, determine (a) V_{D_Q} and I_{D_Q} (b) V_R

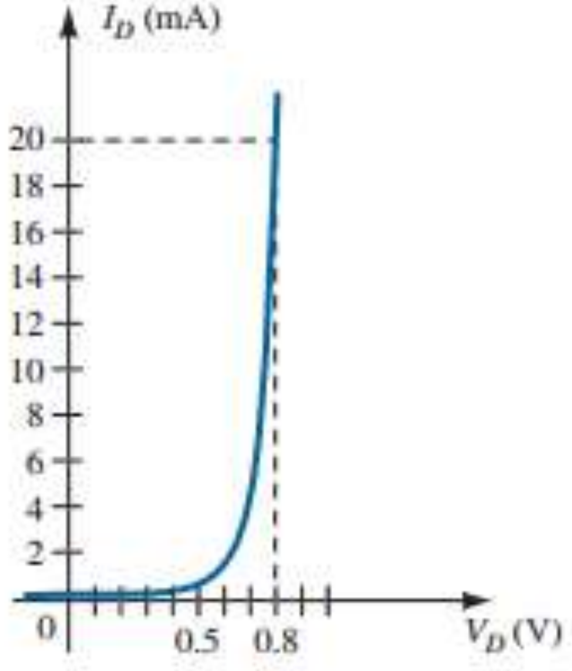
Solution:

$$I_D = \frac{E}{R}\bigg|_{V_D=0\text{ V}} = \frac{10}{500} = 20\text{ mA},$$

$$V_D = E\big|_{I_D=0\text{ A}} = 10\text{ V}$$



(a)



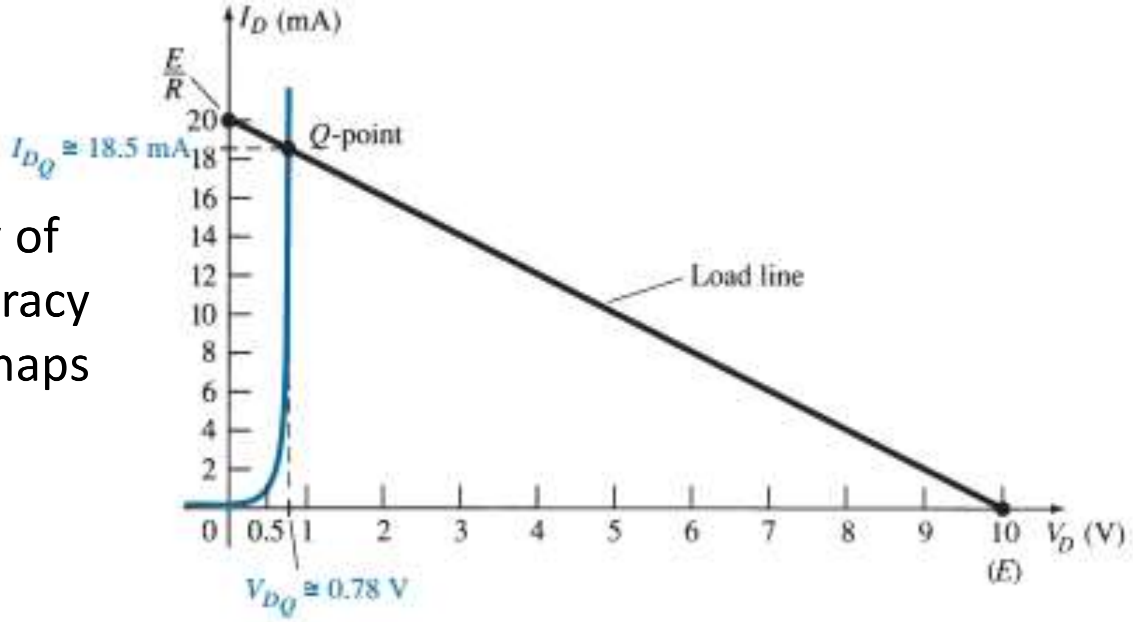
(b)

Diode Circuit - Load-Line analysis

The resulting load line appears in Fig. 6. The intersection between the load line and the characteristic curve defines the *Q*-point as

$$V_{D_Q} \cong 0.78\ \text{V}$$

$$I_{D_Q} \cong 18.5\ \text{mA}$$



The level of V_D is certainly an estimate, and the accuracy of I_D is limited by the chosen scale. A higher degree of accuracy would require a plot that would be much larger and perhaps unwieldy

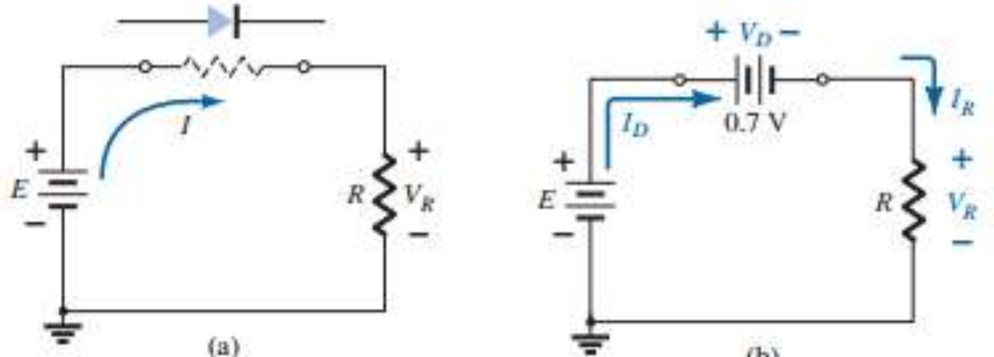
$$V_R = E - V_{D_Q} = 10 - 0.78 = 9.22\ \text{V}$$

Using the *Q*-point values, the dc resistance is

$$R_D = \frac{V_{D_Q}}{I_{D_Q}} = \frac{0.78\ \text{V}}{18.5\ \text{mA}} = 42.16\ \Omega$$

Diode Circuit - series diode Configurations

- For all the analysis to follow in this course it is assumed that *the forward resistance of the diode is usually so small compared to the other series elements of the network that it can be ignored*.
- In general, a diode is in the "**on**" state if the current established by the applied sources is such that its direction matches that of the arrow in the diode symbol, and
  - $V_D \geq 0.7\ \mathrm{V}$ for silicon
  - $V_D \geq 0.3\ \mathrm{V}$ for germanium
  - $V_D \geq 1.2\ \mathrm{V}$ for gallium arsenide.
- In the series circuit, the *state of the diode is first determined* by mentally replacing the diode with a resistive element as shown in Fig. 7a. The resulting direction of ***I*** is a match with the arrow in the diode symbol, and since *E* > V_K, the diode is in the "on" state. The network is then redrawn as shown in Fig. 7b with the appropriate equivalent model for the forward-biased silicon diode.



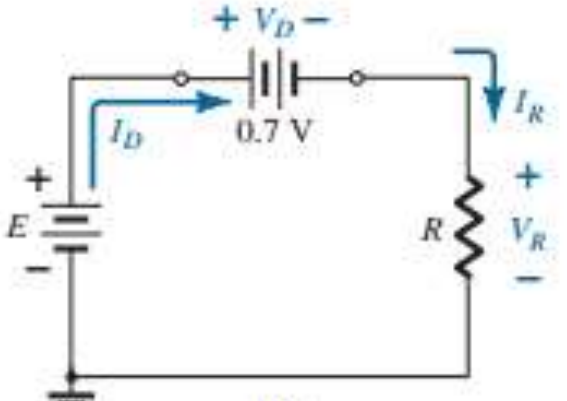
Diode Circuit - series diode Configurations

- The resulting voltage and current levels are the following:

$$V_D = V_k$$

$$V_R = E - V_k$$

$$I_D = I_R = \frac{V_R}{R}$$



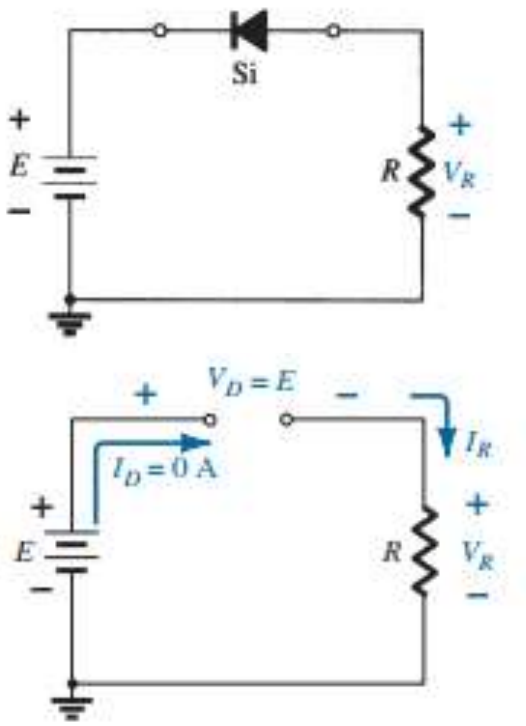
(b)

Diode Circuit - series diode Configurations

- The diode is in the "**off**" state, resulting in the equivalent circuit due to the ***open circuit***, the diode current is 0 A and the voltage across the resistor R is the following:

$$V_R = I_R R = I_D R = (0) R = 0\ \text{V}$$

- The fact that $V_R = 0\ \text{V}$ will establish E volts across the open circuit as defined by Kirchhoff's voltage law.



Diode Circuit - series diode Configurations

Example :

Determine V_o and I_D for the series circuit of Fig. 8.

Solution:

the resulting current has the same direction as the arrowheads of the symbols of both diodes, and the network

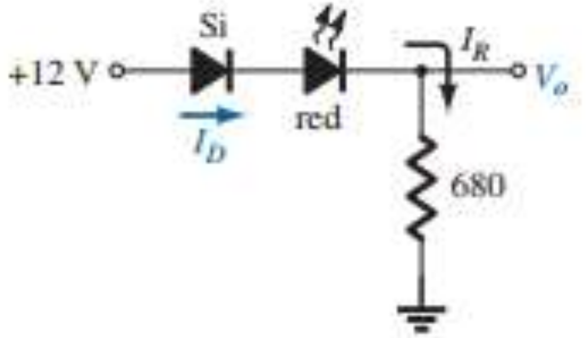
$$E = 12 > (0.7 + 1.8) = 2.5$$

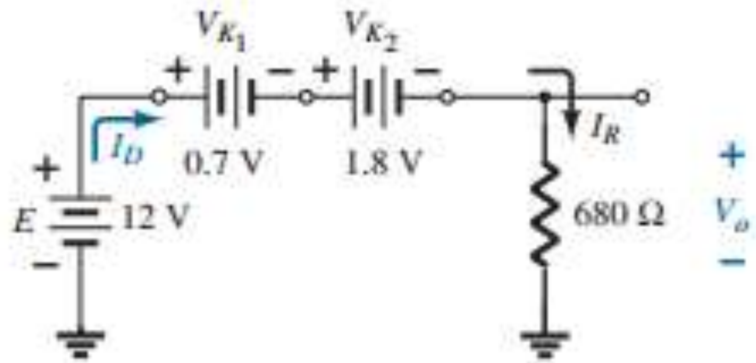
The resulting voltage is

$$V_o = E - V_{K_1} - V_{K_2} = 12 - 2.5 = 9.5\text{ V}$$

and

$$I_D = I_R = \frac{V_R}{R} = \frac{V_R}{R} = \frac{9.5\text{ V}}{680\ \Omega} = 13.97\text{ mA}$$

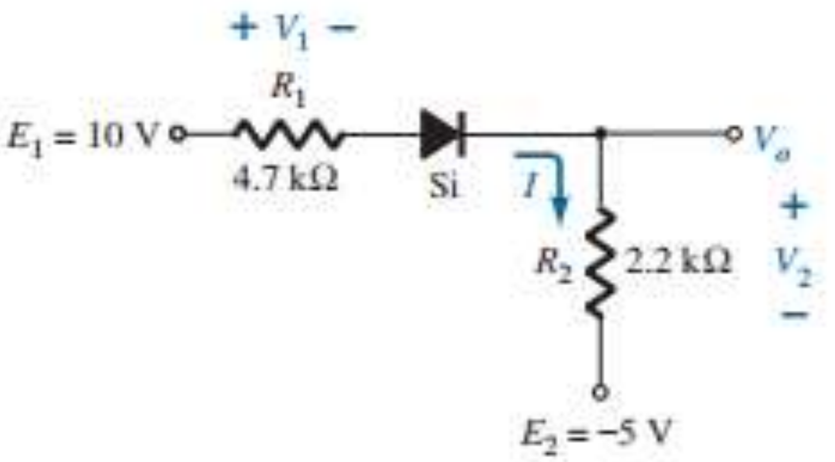




Diode Circuit - series diode Configurations

Example:

Determine I, V_1, V_2, and V_o for the series dc configuration of Fig. 9.



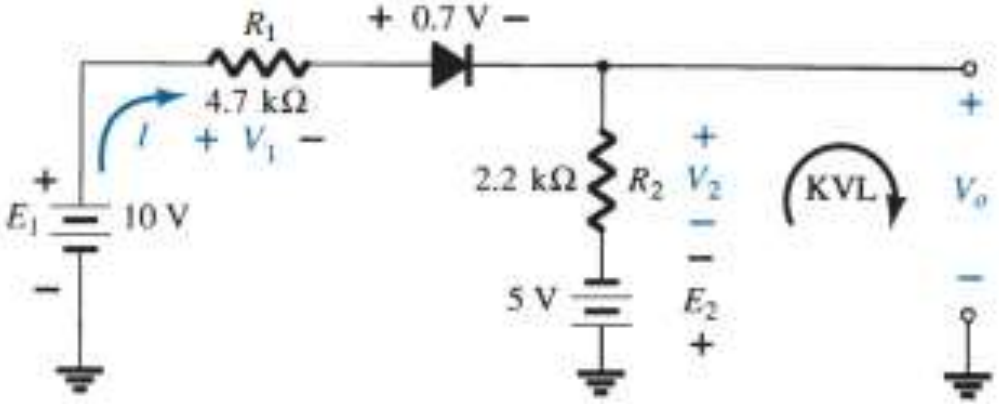
Diode Circuit - series diode Configurations

Solution:

By using KVL, the resulting current through the circuit is

$$-E_1 + 4700I + 0.7 + 2200I - E_2 = 0$$

$$I = \frac{E_1 + E_2 - 0.7}{(4700 + 2200)} = \frac{10 + 5 - 0.7}{6900} = \frac{14.3}{6900} \cong 2.07\text{ mA}$$



and the voltages are

$$V_1 = IR_1 = (2.07\text{ mA})(4.7\text{ k}\Omega) = 9.73\text{ V}$$

$$V_2 = IR_2 = (2.07\text{ mA})(2.2\text{ k}\Omega) = 4.55\text{ V}$$

Applying Kirchhoff's voltage law to the output section in the clockwise direction results in

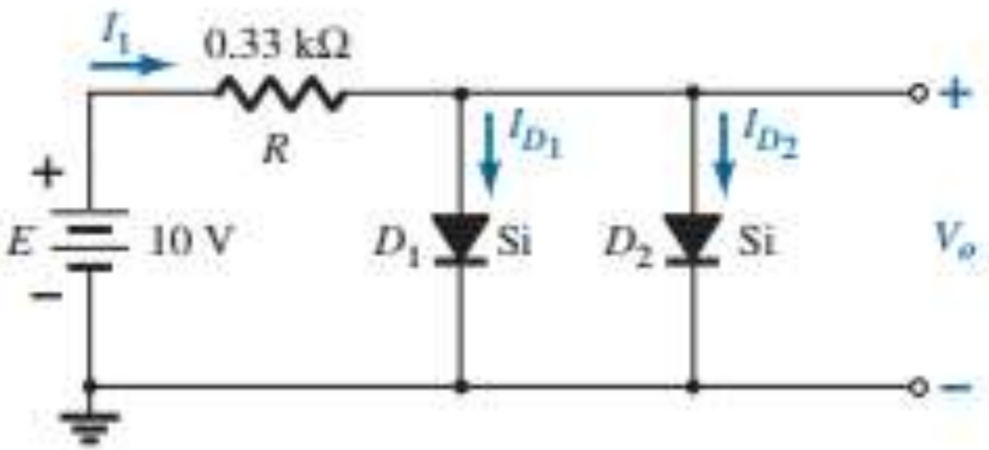
$$E_2 - V_2 + V_o = 0$$

$$V_o = -E_2 + V_2 = -5 + 4.55 = -0.45\text{ V}$$

Diode Circuit - parallel and series–parallel configurations

Example:

Determine V_o, I_1, I_{D1}, and I_{D2} for the parallel diode configuration of Fig. 10

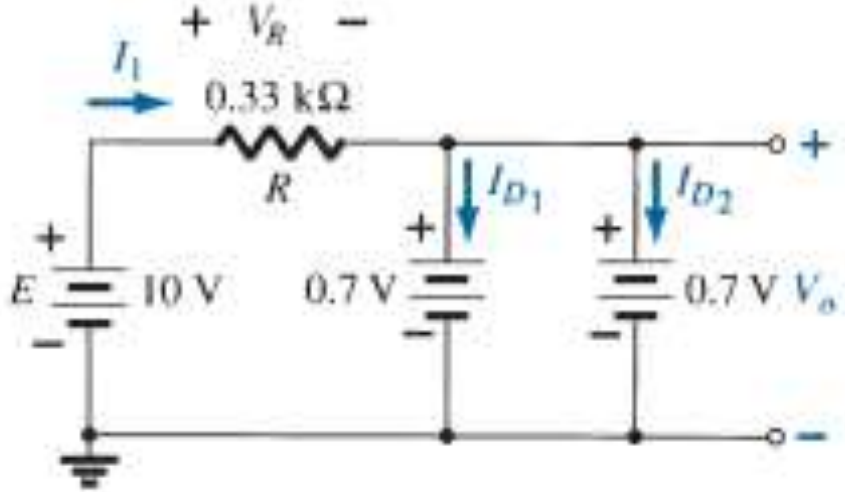


Diode Circuit - parallel and series–parallel configurations

Solution:

The voltage across parallel elements is always the same and

$$V_o = 0.7\ \text{V}$$



The current is

$$I_1 = \frac{V_R}{R} = \frac{E - V_D}{R} = \frac{10 - 0.7}{330} = 28.18\ \text{mA}$$

Assuming diodes of similar characteristics, we have

$$I_{D_1} = I_{D_2} = \frac{I_1}{2} = \frac{28.18}{2} = 14.09\ \text{mA}$$

This example demonstrates *one reason for placing diodes in parallel*. If the current rating of the diodes of Fig. 10 is only 20 mA, a current of 28.18 mA would *damage the device if it appeared alone* in Fig. 10. By placing two in parallel, we *limit the current to a safe value* of 14.09 mA with *the same terminal voltage*.

Diode Circuit - parallel and series–parallel configurations

Example:

Determine the voltage V_o for the network of Fig. 11.

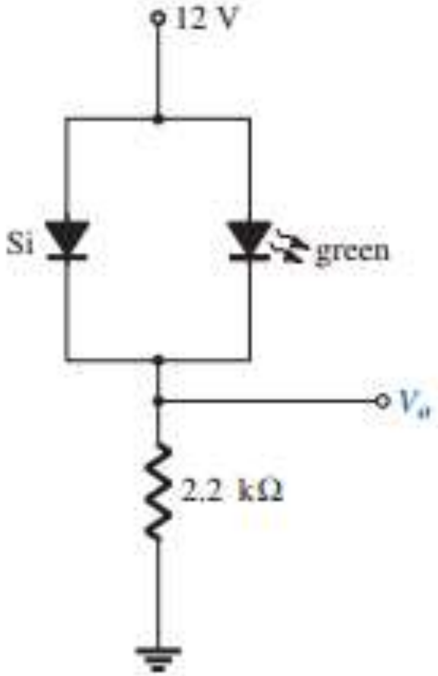


Figure 11

Diode Circuit - parallel and series–parallel configurations

Solution:

Initially, it might appear that the applied voltage will turn both diodes "on" because the applied voltage ("**pressure**") is trying to establish a conventional current through each diode that would suggest the "**on**" state. ***However, if both were on, there would be more than one voltage across the parallel diodes, violating one of the basic rules of network analysis: The voltage must be the same across parallel elements***.

The resulting action can best be explained by remembering that there is a period of build-up of the supply voltage from **0 V** to **12 V** even though it may take milliseconds or microseconds. At the instant the increasing supply voltage reaches **0.7 V** the silicon diode will turn "on" and maintain the level of **0.7 V** since the characteristic is vertical at this voltage—the current of the silicon diode will simply rise to the defined level. The result is that *the voltage across the green LED will never rise above* **0.7 V** and will remain in the equivalent open-circuit state as shown in Fig. 11b.

The result is

$$V_o = 12 - 0.7 = 11.3\text{ V}$$

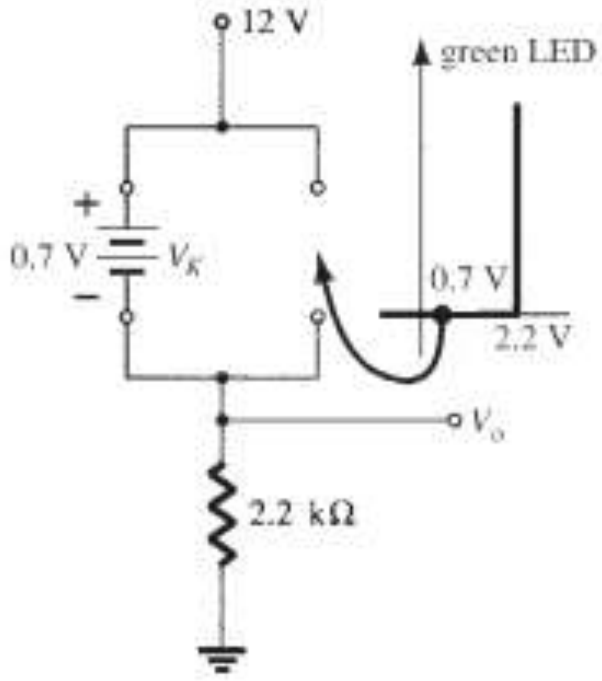


Figure 11a

Diode Circuit - parallel and series–parallel configurations

Example:

Determine the currents I_1, I_2, and I_{D2} for the network of Fig. 12

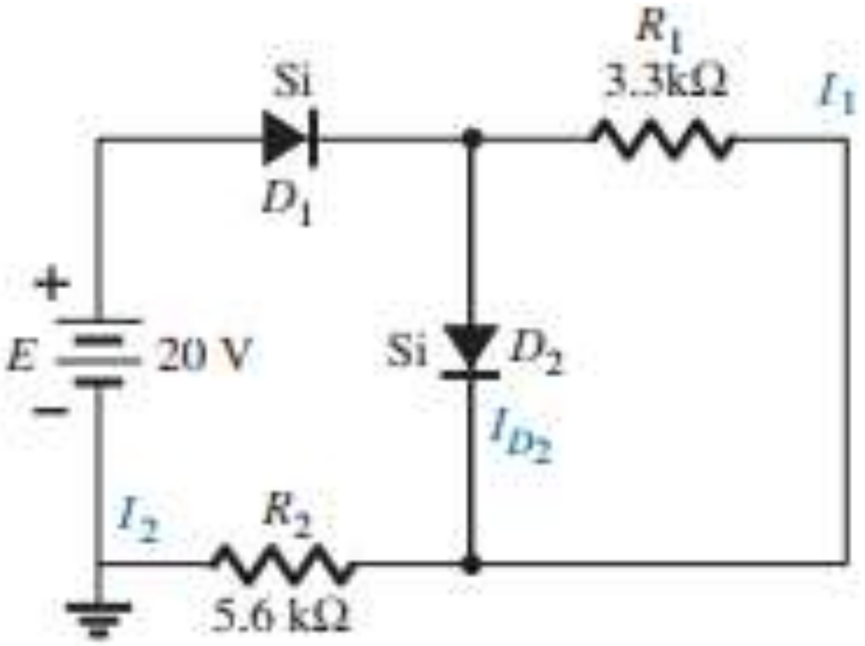


Figure 12

Diode Circuit - parallel and series–parallel configurations

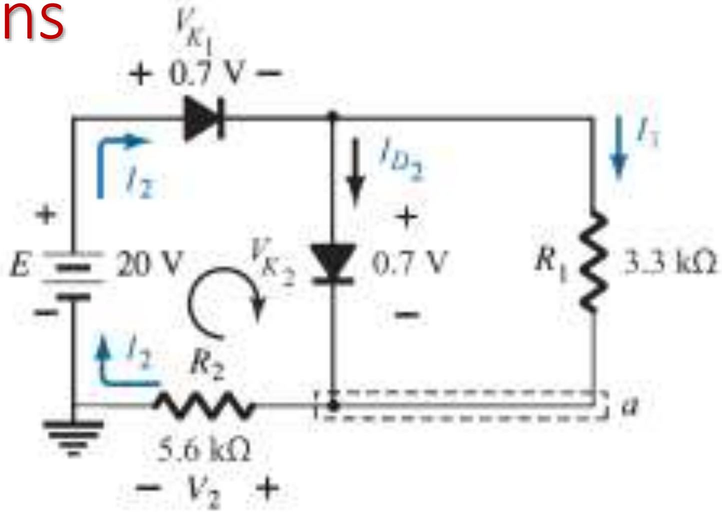


Figure 12a

Solution:

The applied voltage (pressure) is such as to turn both diodes on, as indicated by the resulting current directions in the network of Fig. 12. Note the use of the abbreviated notation for “on” diodes and that the solution is obtained through an application of techniques applied to dc series–parallel networks. We have

$$I_1 = \frac{V_{K_2}}{R_1} = \frac{0.7}{3300} = 0.212\text{ mA}$$

Applying Kirchhoff’s voltage law around the indicated loop in the clockwise direction yields

$$-E + V_{K_1} - V_{K_2} - V_2 = 0 \quad \Rightarrow \quad V_2 = E - V_{K_1} - V_{K_2} = 20 - 0.7 - .7 = 18.6\text{ V}$$

with

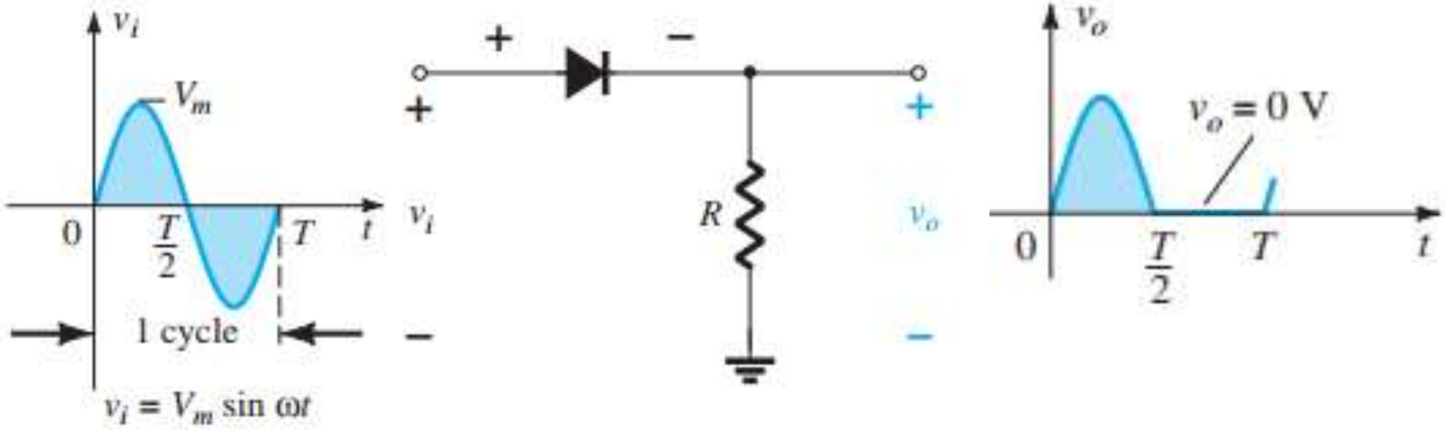
$$I_2 = \frac{V_2}{R_2} = \frac{18.6}{5600} = 3.32\text{ mA}$$

At the bottom node *a*,

$$I_{D_2} + I_1 = I_2 \quad \Rightarrow \quad I_{D_2} = I_2 - I_1 = 3.32 - 0.212 = 3.11\text{ mA}$$

Diode Circuits – Rectifiers Circuits (Half, Full, and Center tap)

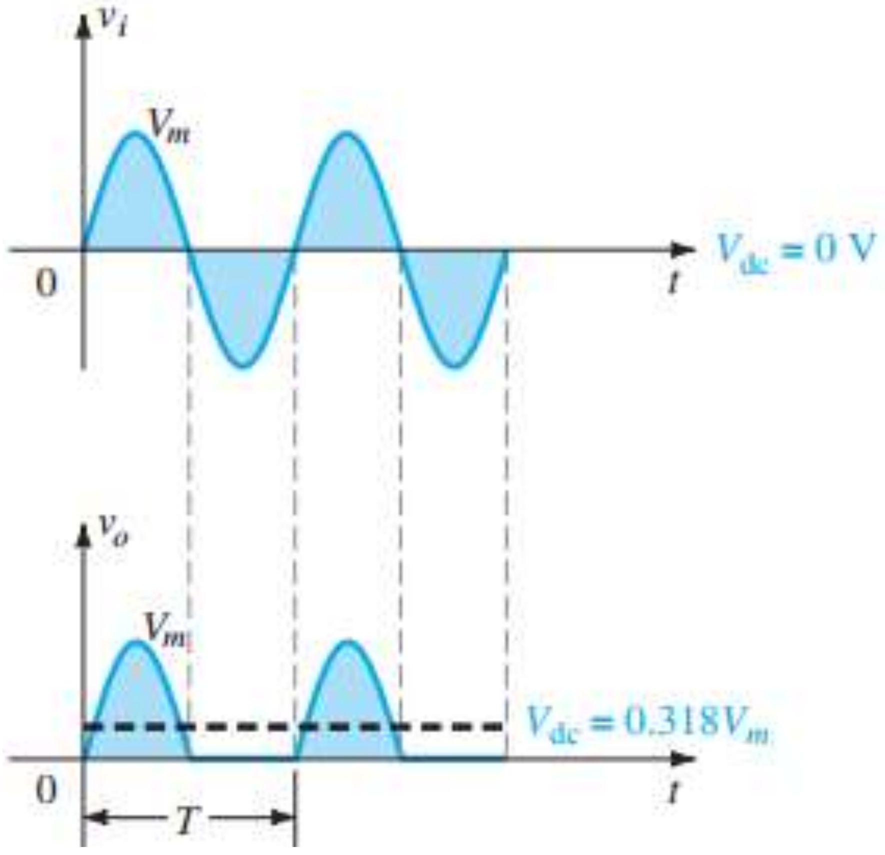
- The simplest of networks to examine with a time-varying signal appears in Fig. 2.44.
    - Over one full cycle, defined by the period T of Fig. 2.44 , the average value is zero.
    - The circuit of Fig. 2.44, called a half-wave rectifier, will generate a waveform v_o that will have an average value of particular use in the ac-to-dc conversion process.
- When employed in the rectification process, a diode is typically referred to as a ***rectifier***.
    - During the interval $t = 0 \to T/2$, in Fig. 2.44 the polarity of the applied voltage v_i is such as to establish "pressure" in the direction indicated and turn on the diode with the polarity appearing above the diode.
    - For the period $t = T/2 \to T$, the polarity of the input vi is as shown in Fig. 2.46 , and the resulting polarity across the ideal diode produces an "off" state with an open-circuit equivalent.



Diode Circuits – Rectifiers Circuits (Half, Full, and Center tap)

- The output signal vo now has a net positive area above the axis over a full period $T = 2\pi$ and an average value determined by

$$V_{\text{ave}} = V_{\text{dc}} = \frac{1}{T}\int_0^{T/2} V_m \sin t\, dt$$
$$= \frac{1}{2\pi}\int_0^{\pi} V_m \sin t\, dt = \frac{V_m}{2\pi}\int_0^{\pi} \sin t\, dt$$
$$= -\frac{V_m}{2\pi}\cos t\Big|_0^{\pi} = -\frac{V_m}{2\pi}(\cos\pi - \cos 0)$$
$$= -\frac{V_m}{2\pi}(-1-1) = \frac{V_m}{\pi} \approx 0.318 V_m$$



The process of removing one-half the input signal to establish a **dc level** is called ***half wave rectification***.

Diode Circuits – Rectifiers Circuits (Half, Full, and Center tap)

- The effect of using a silicon diode with V_K = 0.7 V is demonstrated in Fig. 2.48 for the forward-bias region.
- The applied signal must now be at least 0.7 V before the diode can turn "on." For levels of v_i less than 0.7 V, the diode is still in an open-circuit state and v_o = 0 V, as shown in the same figure.
- When conducting, the difference between v_o and v_i is a fixed level of V_K = 0.7 V and $v_o = v_i - V_K$

$$V_{dc} \cong 0.318(V_m - V_K)$$

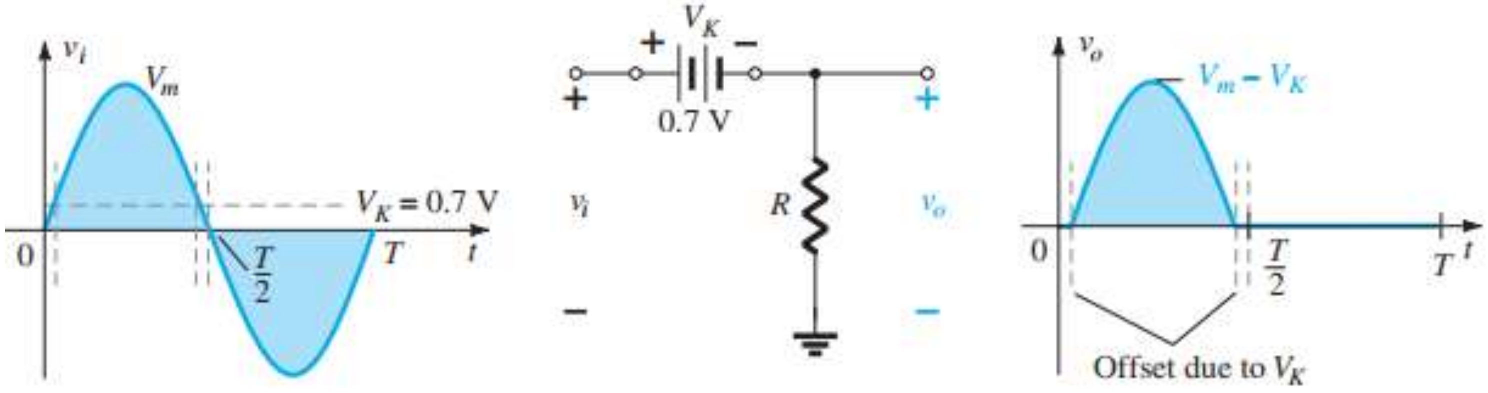


FIG. 2.48
Effect of V_K on half-wave rectified signal.

Diode Circuits – Rectifiers Circuits (Half, Full, and Center tap)

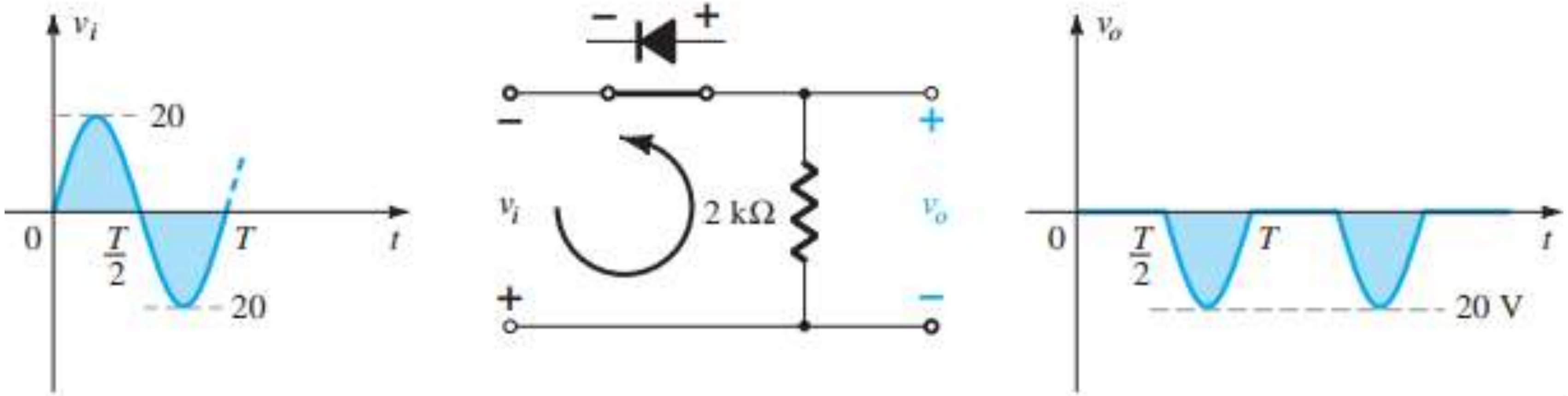
Example: Sketch the output v_o and determine the dc level of the output for the network of Fig. 2.49

Solution:

In this situation the diode will conduct during the negative part of the input as shown in Fig. 2.50 , and *vo* will appear as shown in the same figure. For the full period, the dc level is

$$V_{dc} = -0.318(V_m) = -0.318(20) = -6.36\text{ V}$$

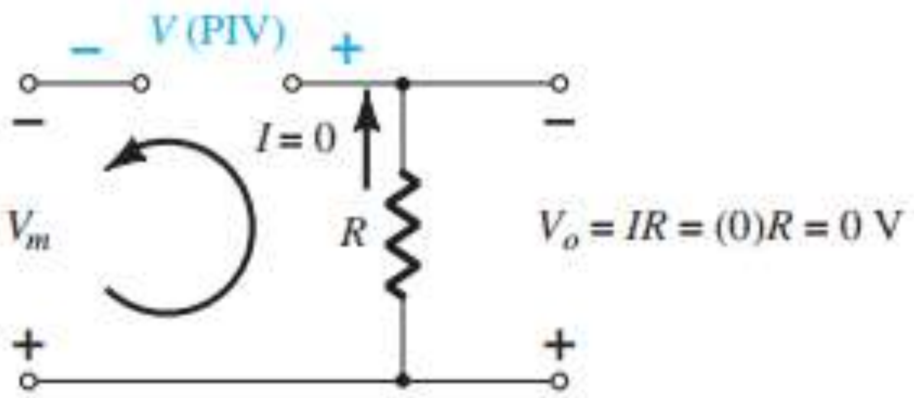
The negative sign indicates that the polarity of the output is opposite to the defined polarity of Fig. 2.49



Half Wave Rectifier Peak Inverse/reverse Voltage

- The peak inverse/reverse voltage (PIV) or (PRV) rating of the diode is of *primary importance in the design of rectification systems* and ***must not be exceeded*** in the **reverse-bias region** or the diode will enter the **Zener avalanche region**.

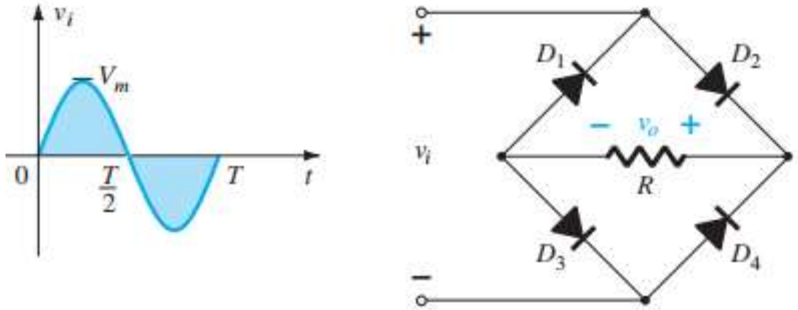
$$\text{half wave rectifier} \mid \text{PIV rating} \geq V_m$$

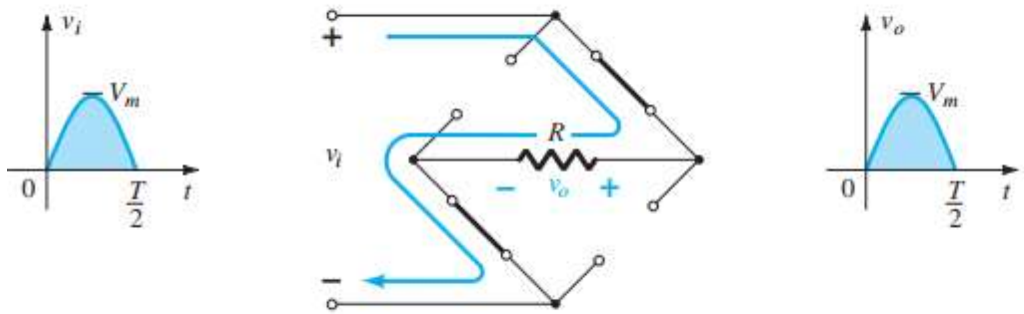


PIV rating of the diode must equal or exceed the peak value of the applied voltage.

Diode Circuits – Rectifiers Circuits (Half, Full, and Center tap)

- The dc level obtained from a sinusoidal input can be improved 100% using a process called ***full-wave rectification***.



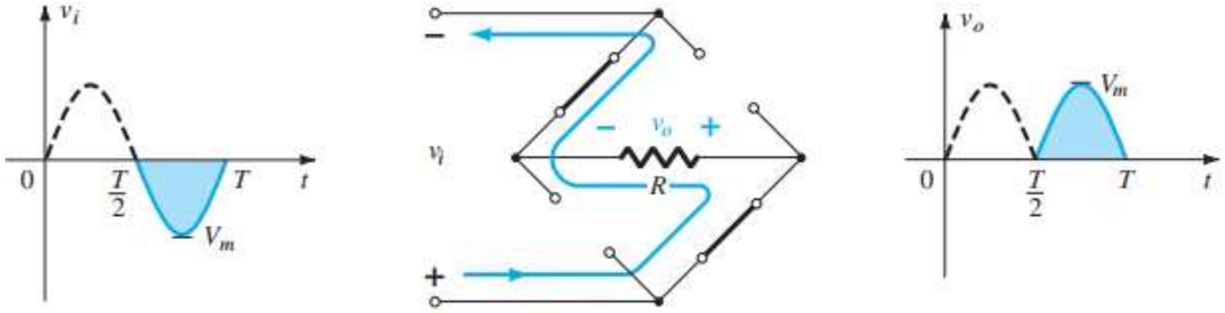


For first diode approximation, the dc level is

$$V_{dc} \cong 0.318(2V_m) \cong 0.636V_m$$

For second diode approximation, the dc level is

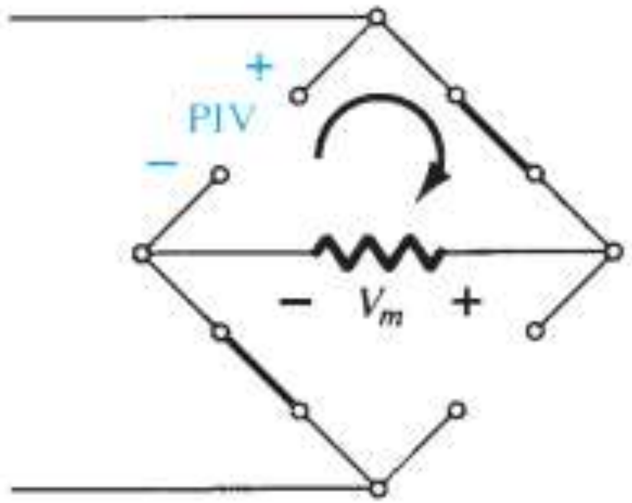
$$V_{dc} \cong 0.636(V_m - 2V_K)$$



Full Wave Rectifier Peak Inverse/reverse Voltage

- The required PIV of each diode (ideal) can be determined from Fig. 2.59 obtained at the peak of the positive region of the input signal. For the indicated loop the maximum voltage across R is V_m and the PIV rating is defined by

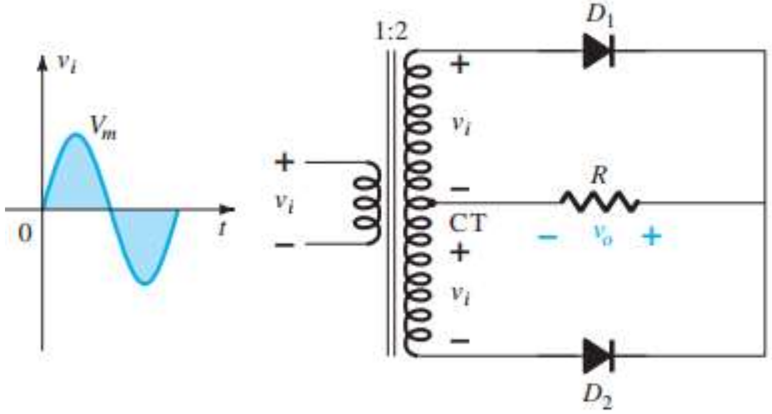
$$\text{full wave rectifier} \mid \text{PIV} \geq V_m$$



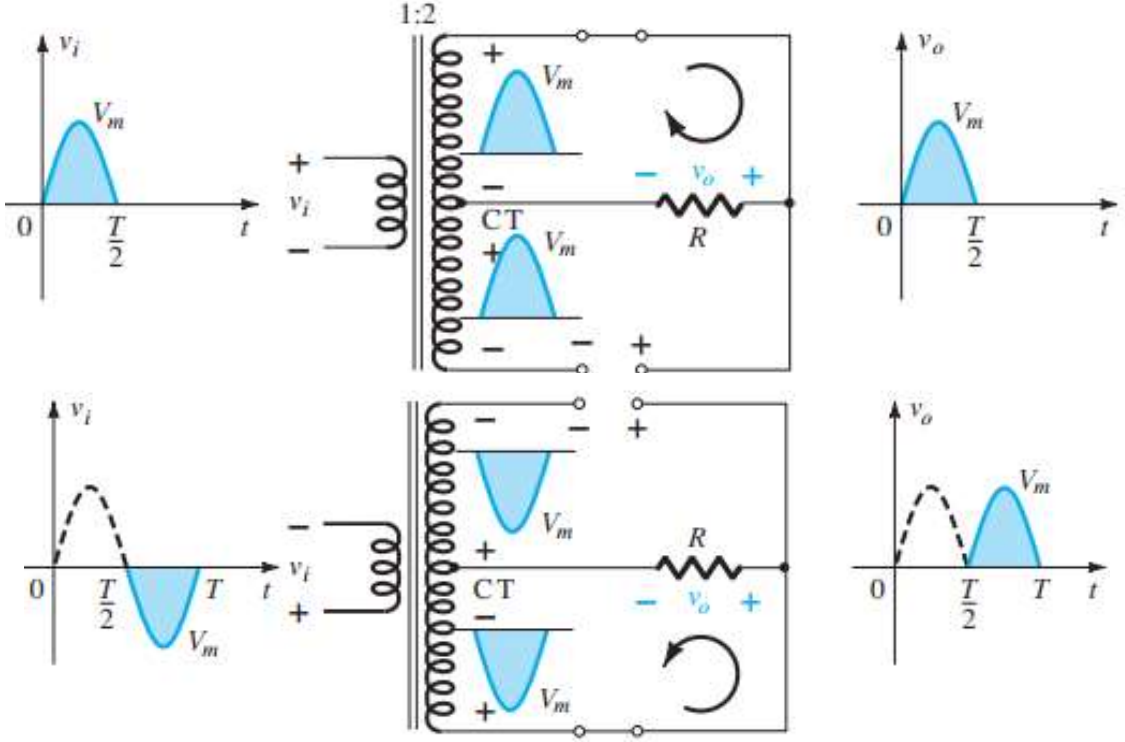
Diode Circuits – Rectifiers Circuits (Half, Full, and Center tap)

- A second popular full-wave rectifier appears in Fig. 2.60 with only two diodes but requiring a center-tapped (CT) transformer to establish the input signal across each section of the secondary of the transformer.

$$V_{dc} = 0.636V_m$$

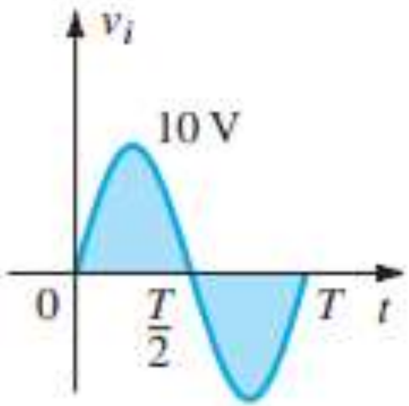


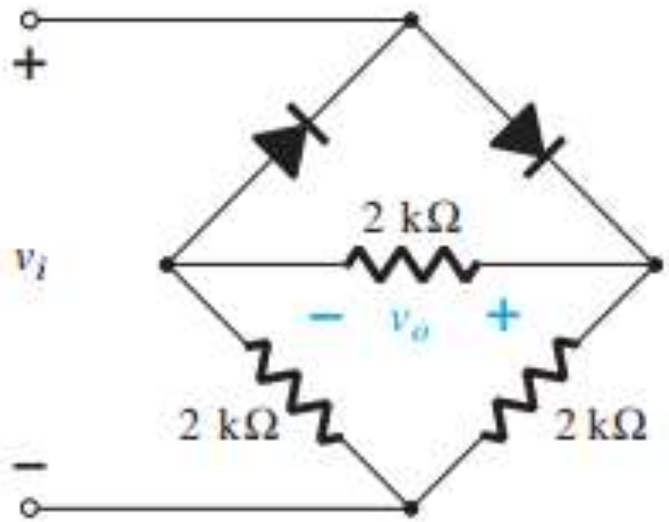
$$\text{PIV} = V_{\text{secondry}} + V_R$$
$$= V_m + V_m$$
$$\text{PIV} \geq 2V_m$$



Diode Circuits – Rectifiers Circuits (Half, Full, and Center tap)

Example : Determine the output waveform for the network of Fig. 2.64 and calculate the output dc level and the required PIV of each diode.





Diode Circuits – Rectifiers Circuits (Half, Full, and Center tap)

Solution:

Using voltage division, v_o is

$$v_o = v_i \frac{2000}{2000+2000} = \frac{1}{2} v_i = V_m$$

The dc level V_{dc} is

$$V_{\mathrm{dc}} = 0.636 V_m = 0.636(5) = 3.18 \text{ V}$$

However, the **PIV** as determined from Fig. 2.59 is equal to the maximum voltage across ***R***, which is **5 V**, or half of that required for a half-wave rectifier with the same input.