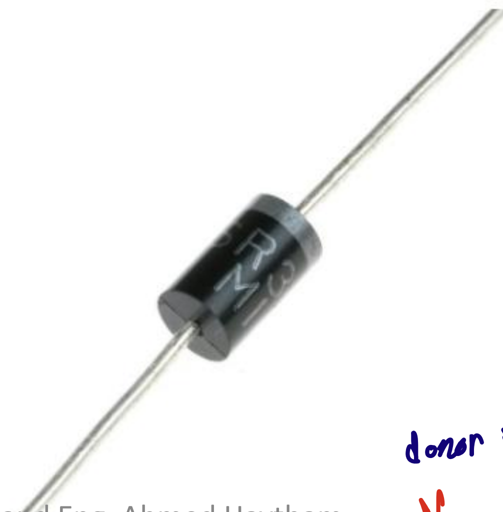
Diodes



μE

velocity μE

$-q D_p \frac{dx}{dp}$ diffusion $-q D_p \frac{dx}{dp}$

conductivity $q n \mu$

res $\rho = \frac{1}{\sigma}$

donor imp.

$N_D = \frac{\sigma}{q \mu}$

density $q n \mu E$

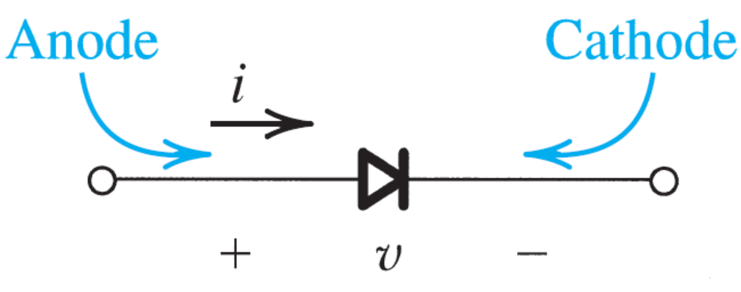
$\mu n q E$

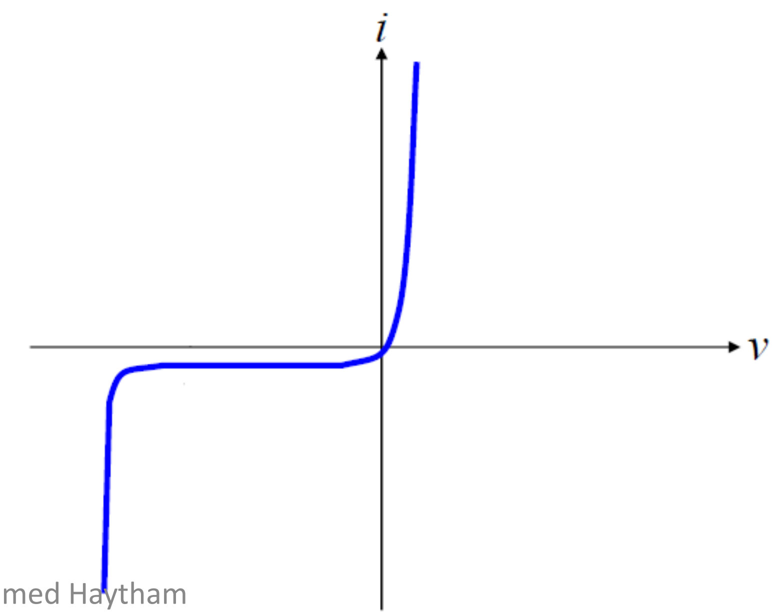
Introduction to Diodes

- The simplest and most fundamental nonlinear circuit element is the diode.

- The diode has two terminals (Anode + terminal, Cathode – terminal)

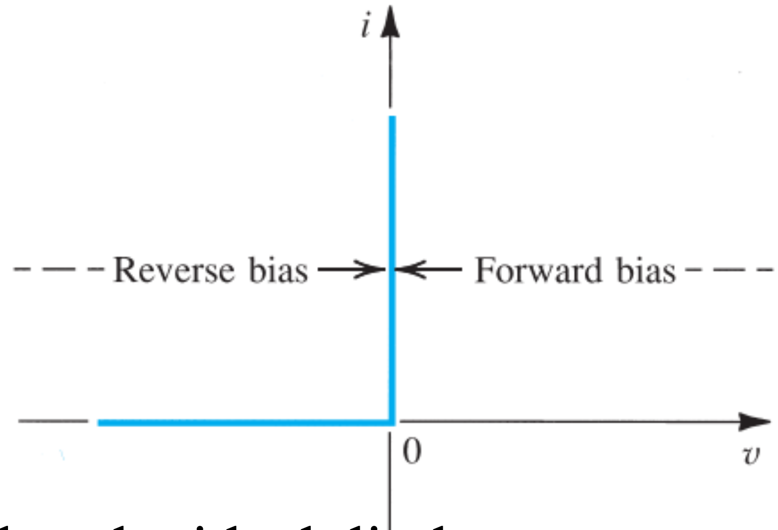
- The diode has a nonlinear *i* –*v* characteristic.





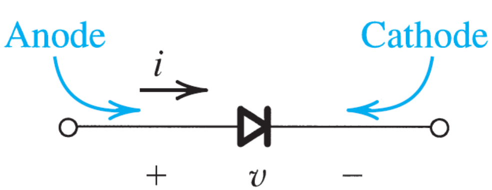
Ideal Diode

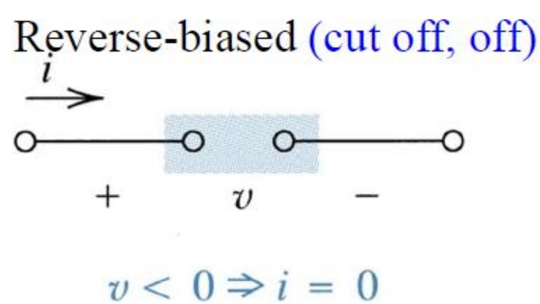
- The ideal diode has the following i-v characteristics
- If a negative voltage v is applied to the diode, no current flows and the diode behaves as an open circuit and it is said to be **reverse biased** with a **zero current** and is said to be **off**.



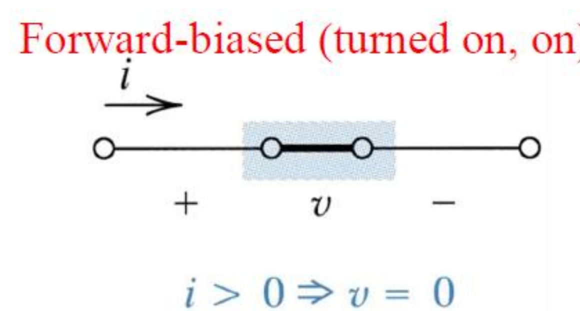
- On the other hand, if a positive current is applied to the ideal diode, **zero voltage** drop appears across the diode and works as a short circuit in the **forward biased**. Diode is said to be **on**.

ideal → no loss





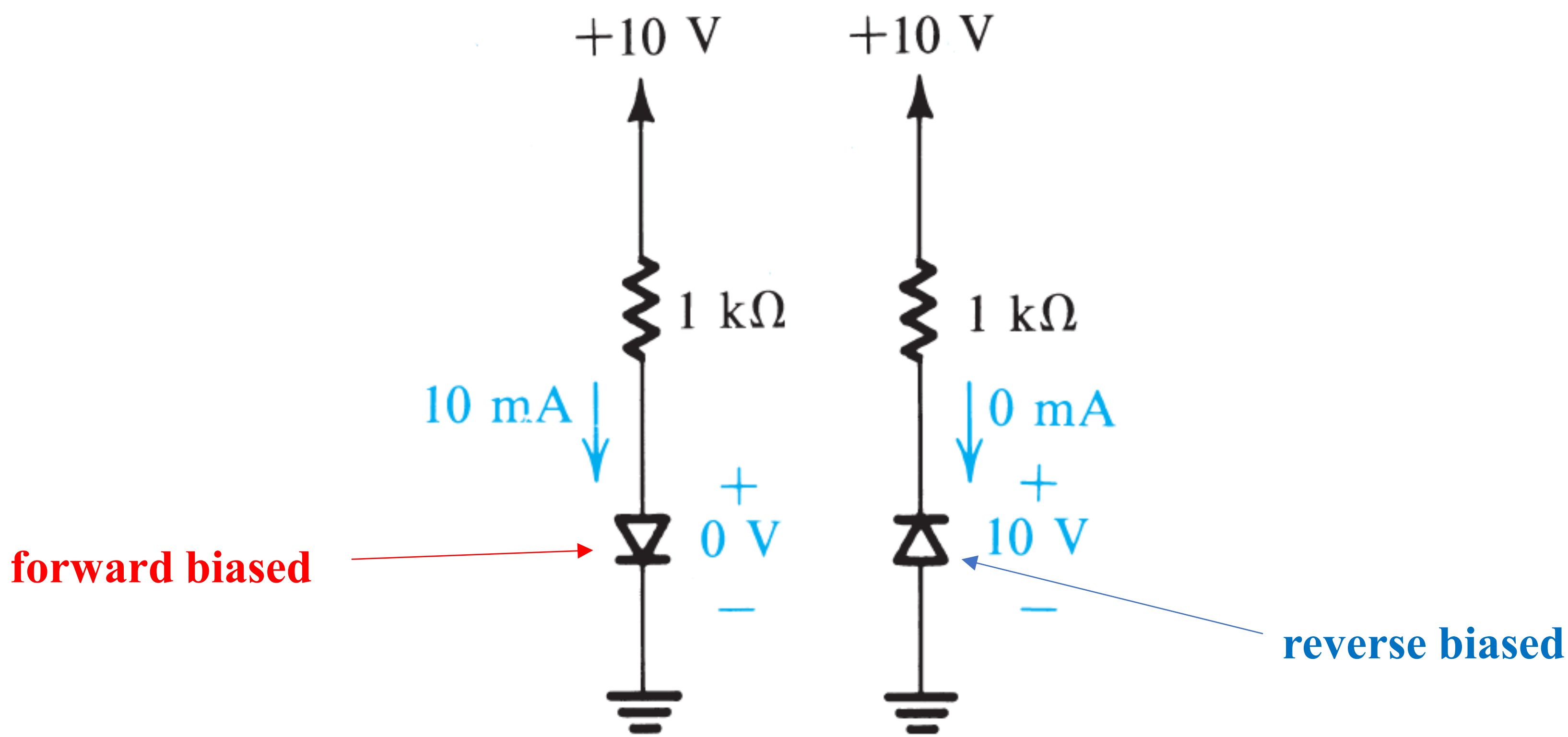
open circuit



short circuit

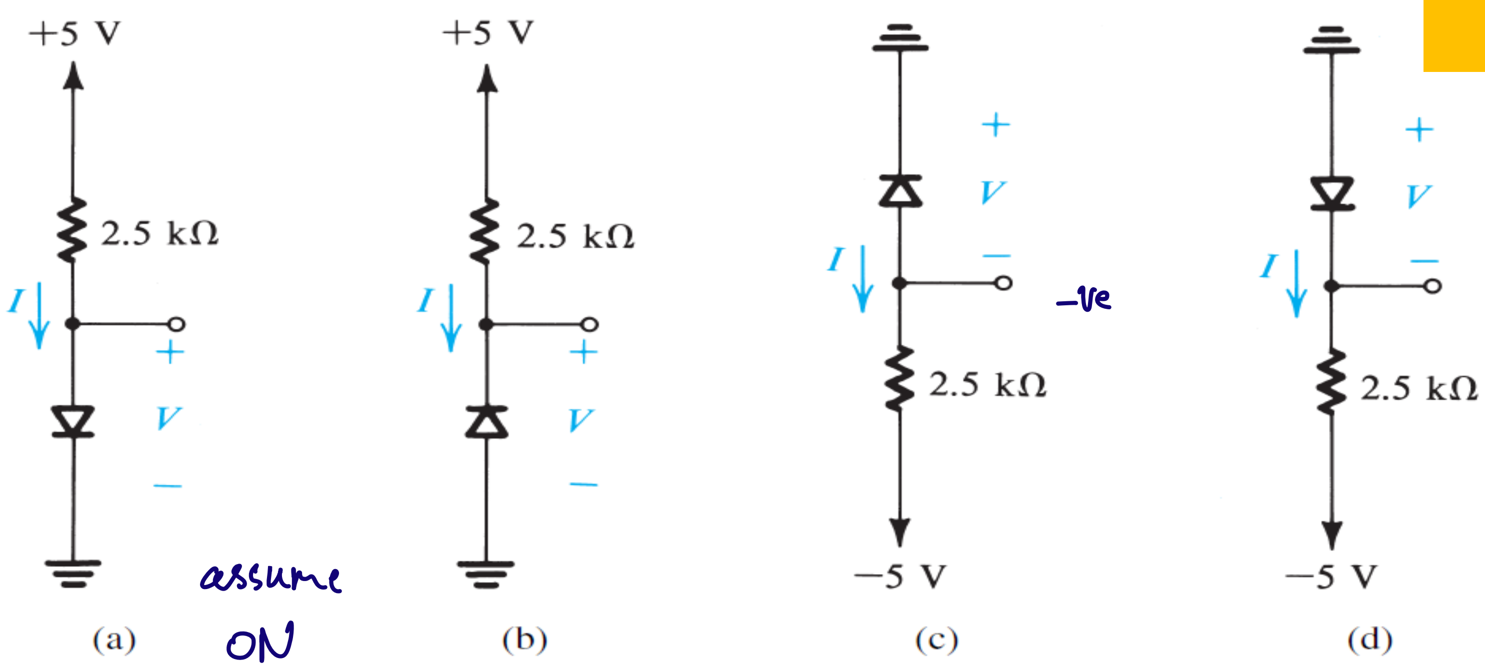
Ideal Diode

- The forward current through a conducting diode & the reverse voltage across a cutoff diode are determined by an *external circuit*



Find the values of I and V in the circuits shown

Example 1

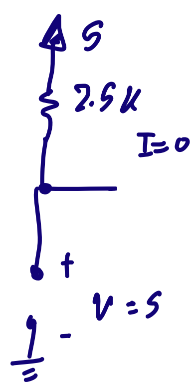


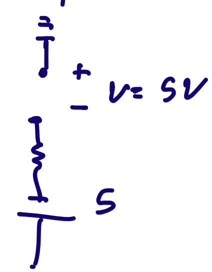
assume ON

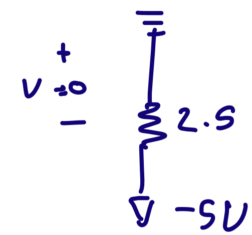
−ve

assume off

off, rev.





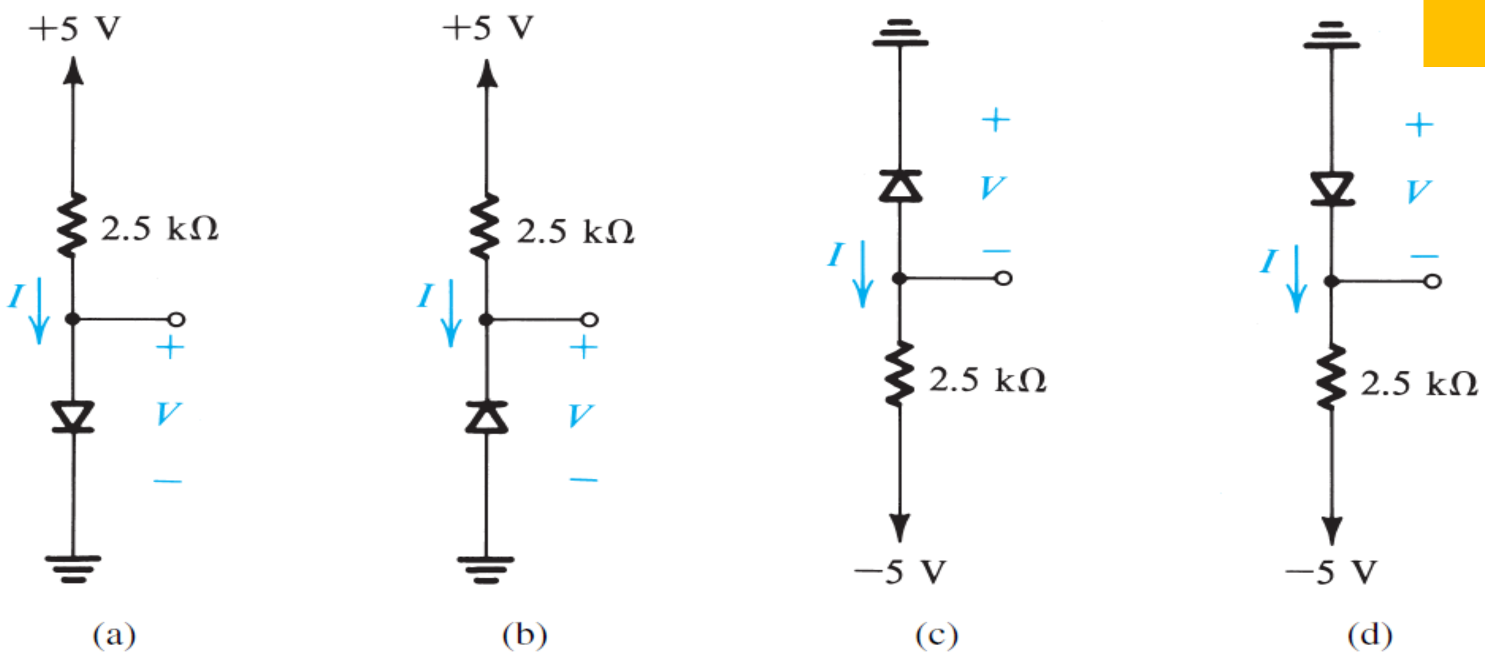


$$I = \frac{5-0}{2.5K} = 2mA$$

$$I = \frac{0-(-5)}{2.5} = 2\ mA$$

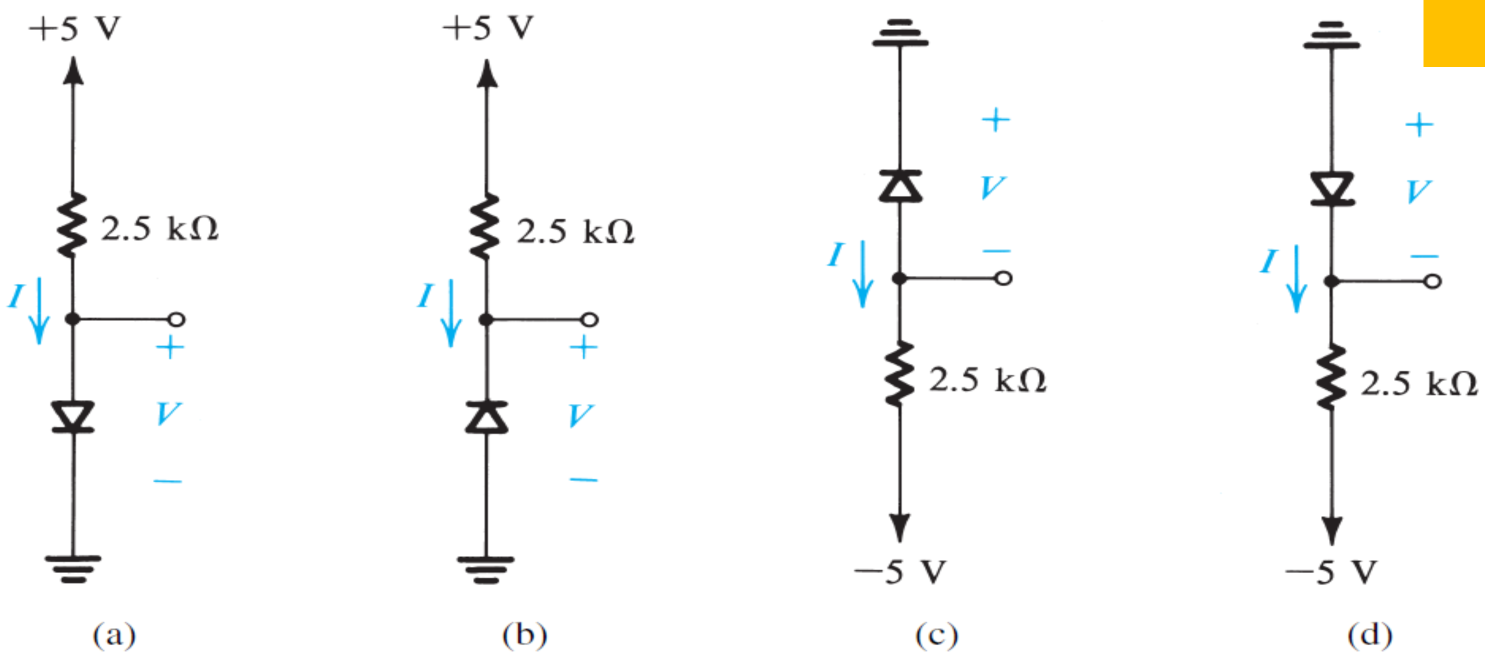
Find the values of I and V in the circuits shown

Example 1



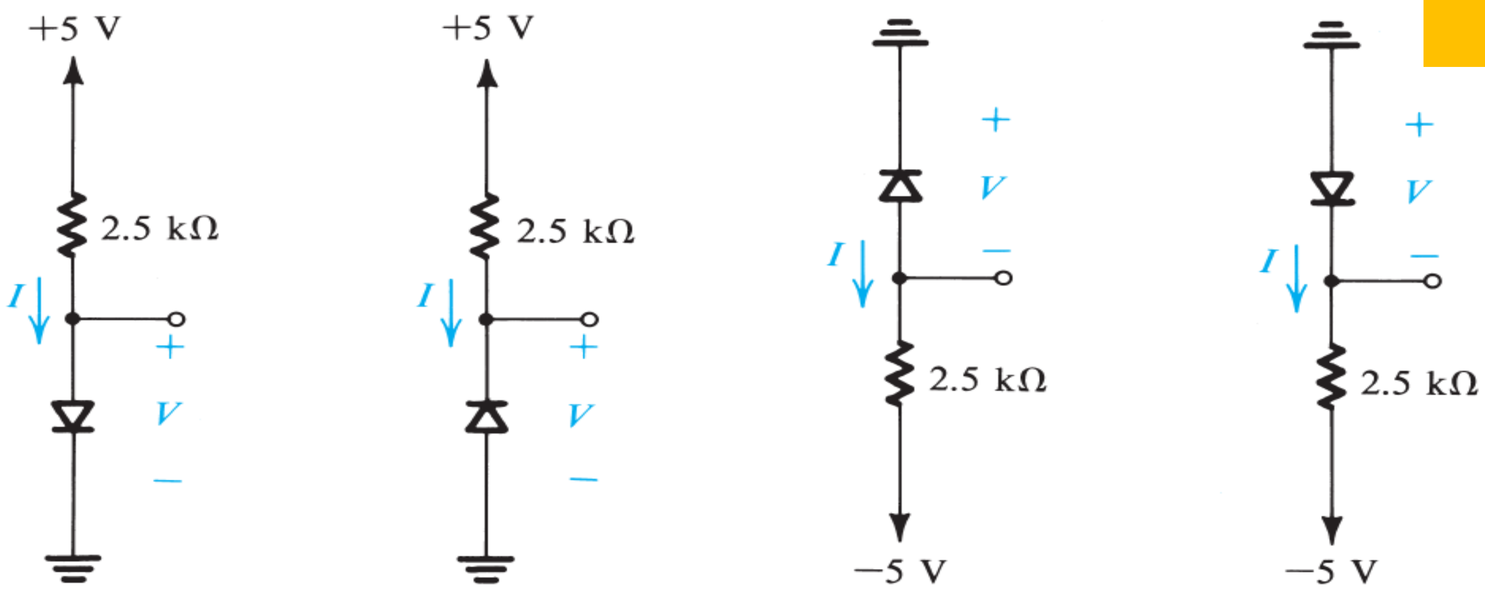
Find the values of I and V in the circuits shown

Example 1

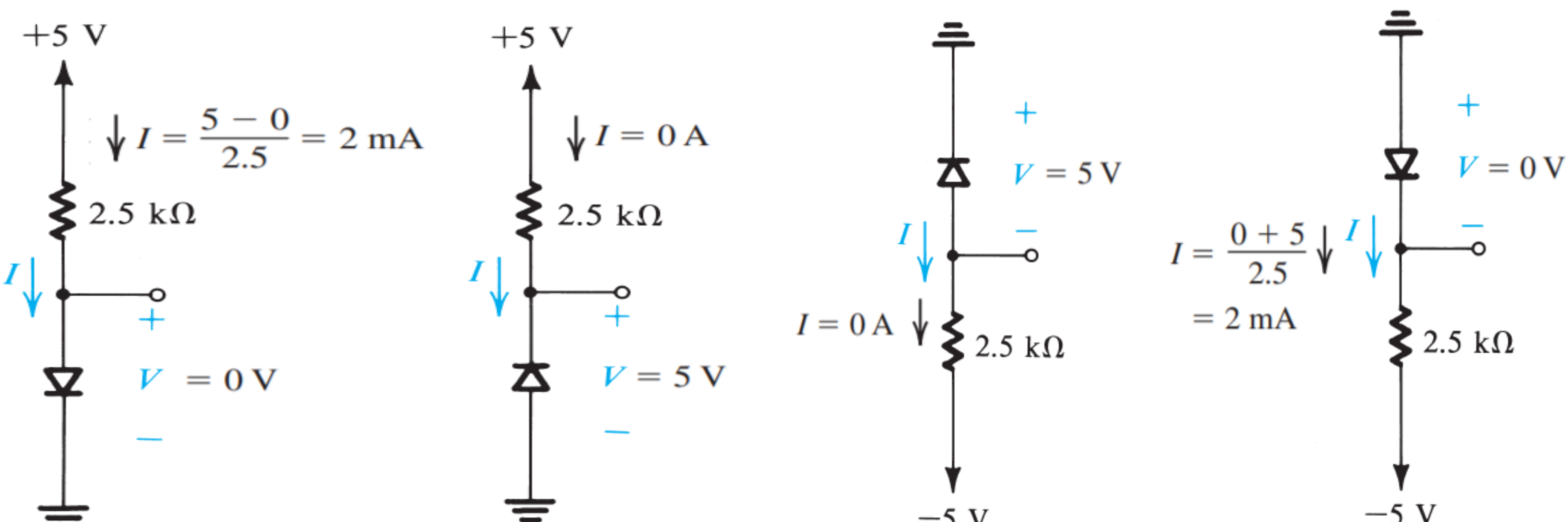


Find the values of I and V in the circuits shown

Example 1



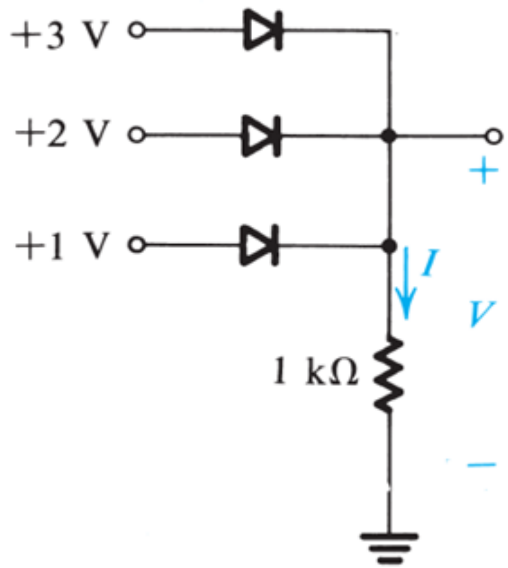
(a) (b) (c) (d)



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

Find the values of I and V in the circuits shown

Example 2



(e)

common cathod pallel diodes, cathodes connected with output

Common cathode

OR gate

$Y = A + B + C$

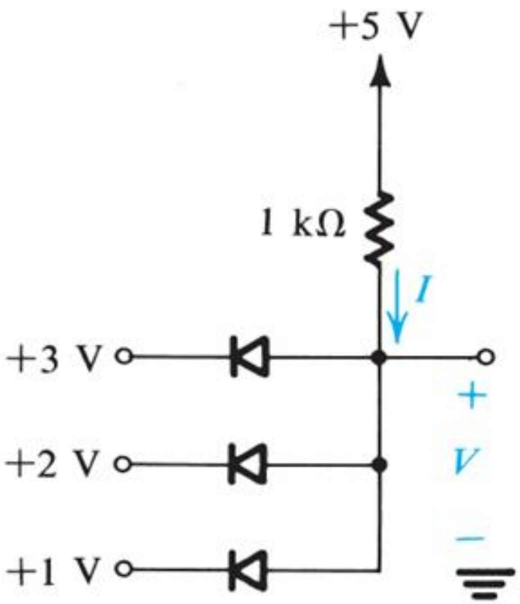
we'll have an output if at least one is on

Common anode

AND gate

$Y = A \cdot B \cdot C$

Example 2



(f)

Common anode

AND gate

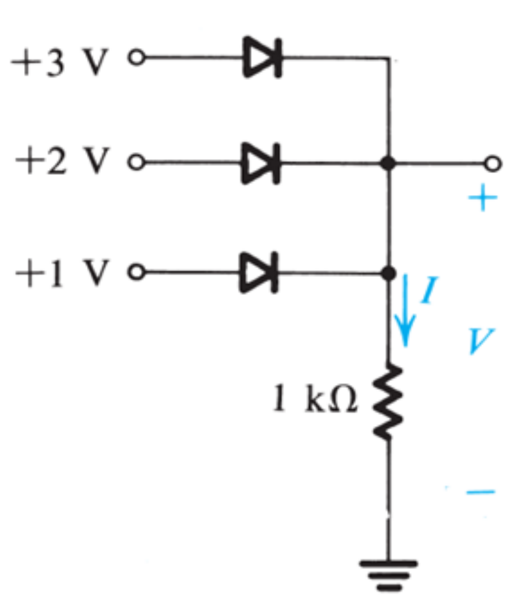
$$Y = A \cdot B \cdot C$$

common anode

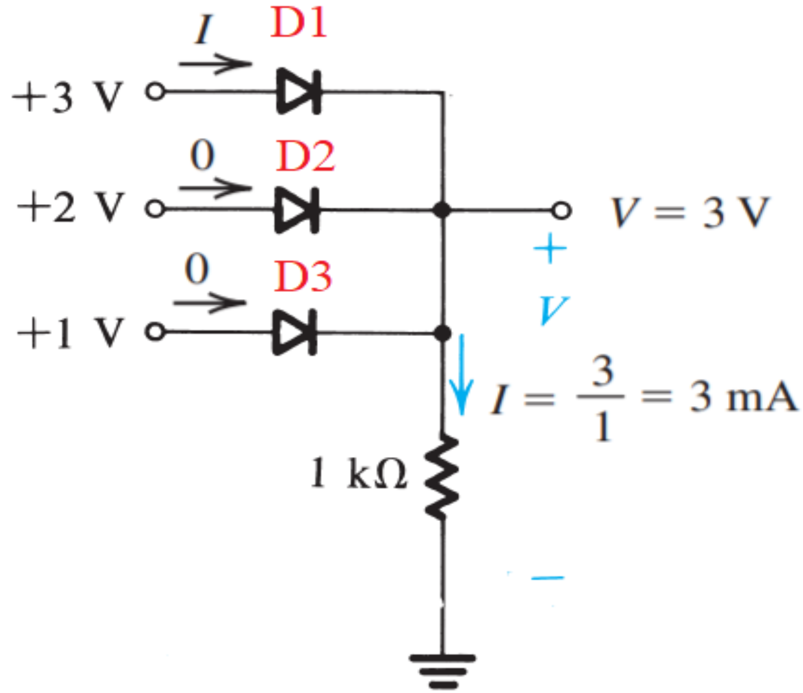
all need to work together and we'll take the ?? value

Find the values of *I* and *V* in the circuits shown

Example 2



(e)

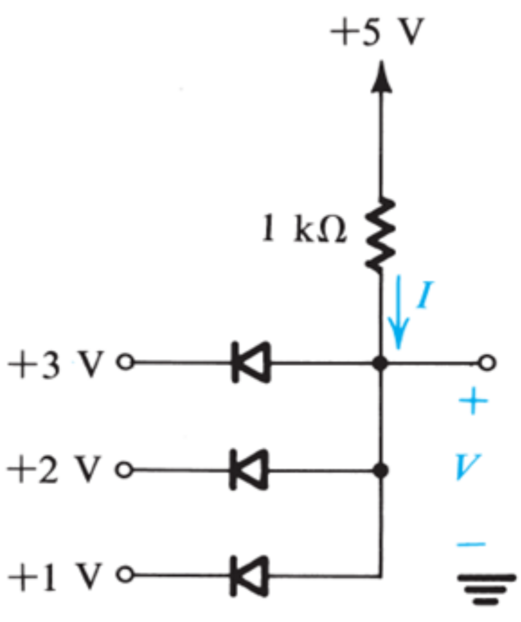


(e)

Common cathode

OR gate

Y = A + B + C

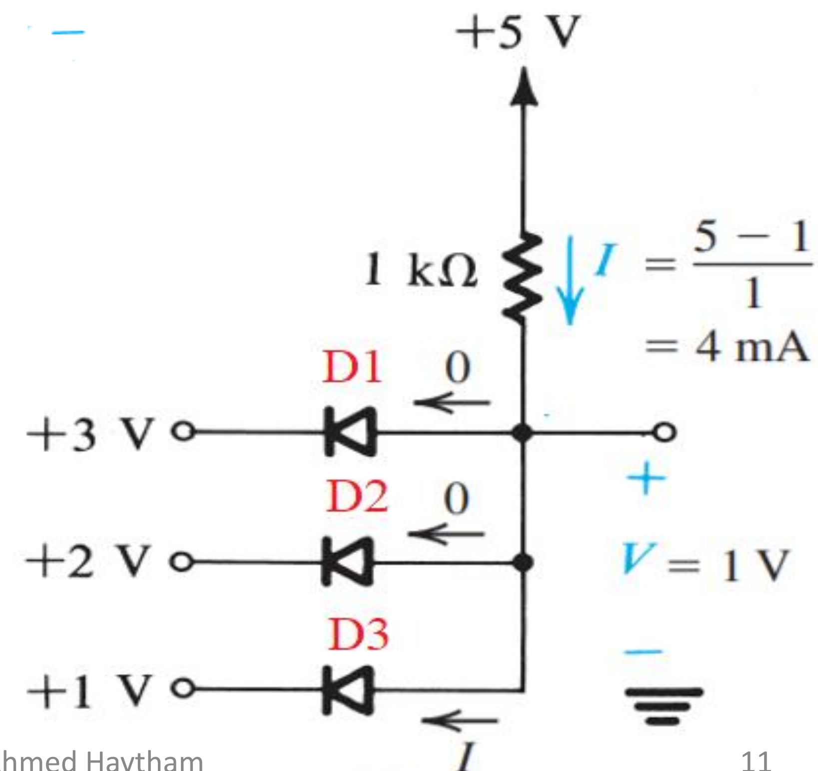


(f)

Common anode

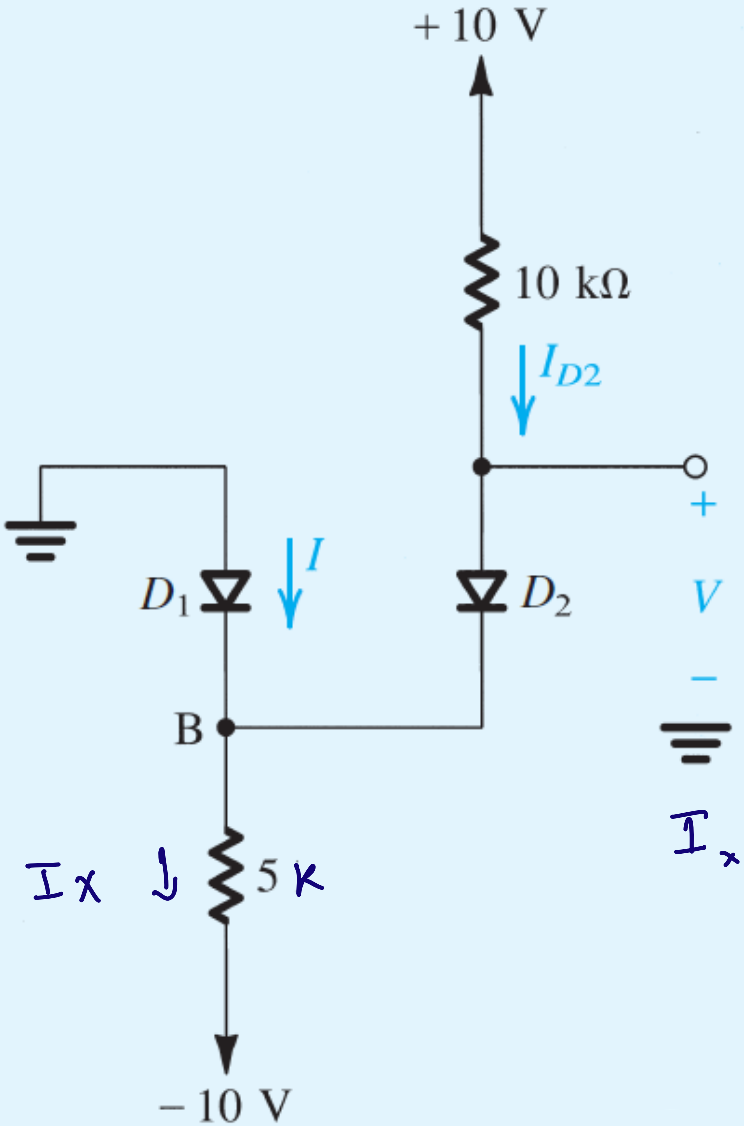
AND gate

Y = A • B • C



(f)

Assuming the diodes to be ideal, find the values of I and V in the circuits



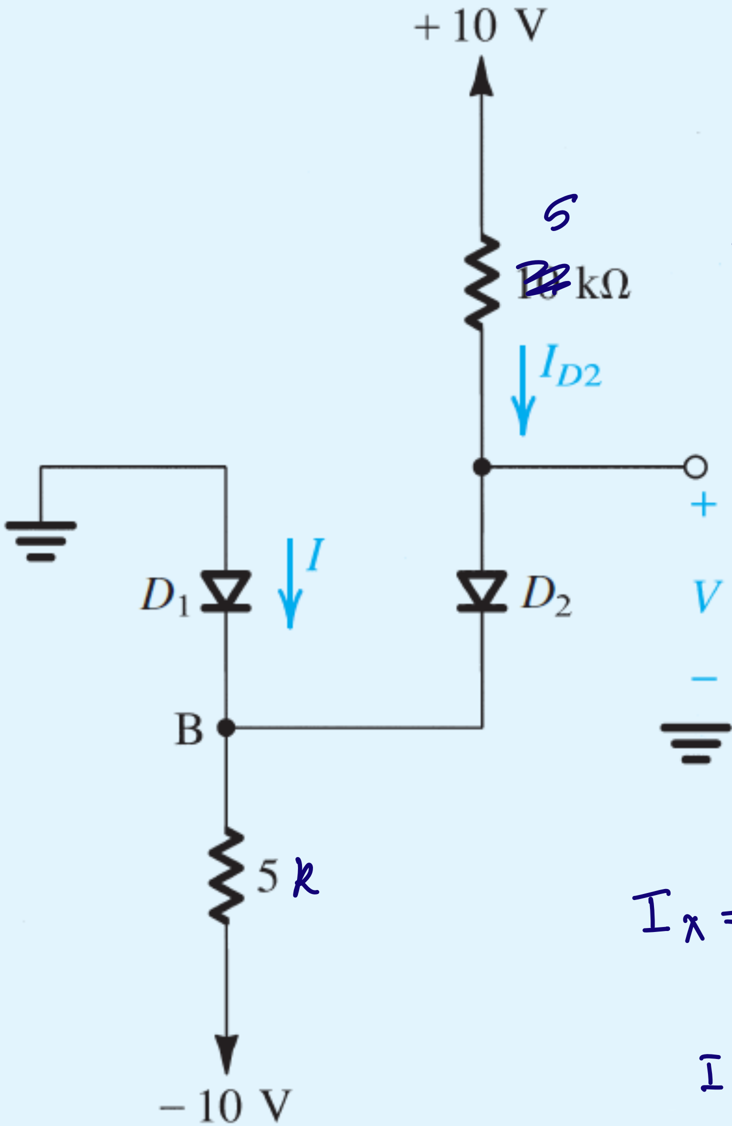
$$\frac{10}{10k} = 1m\,A$$

$$I_x = \frac{0-(-10)}{5} = I + I_{D2}$$

$$= 2mA$$

$$I = 1mA$$

Assuming the diodes to be ideal, find the values of I and V in the circuits



assume D_1, D_2 ON

$$I_{D_2} = \frac{10}{5K} = 2mA$$

$$I_x = \frac{0-(-10)}{10K} = 1mA$$

$$I_x = I + \overset{2mA}{\cancel{I_{D_2}}} = 1mA$$

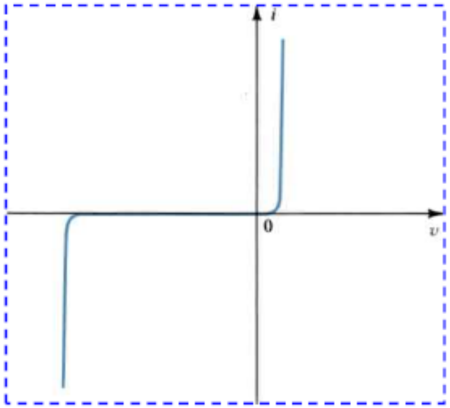
$$I = -1mA$$

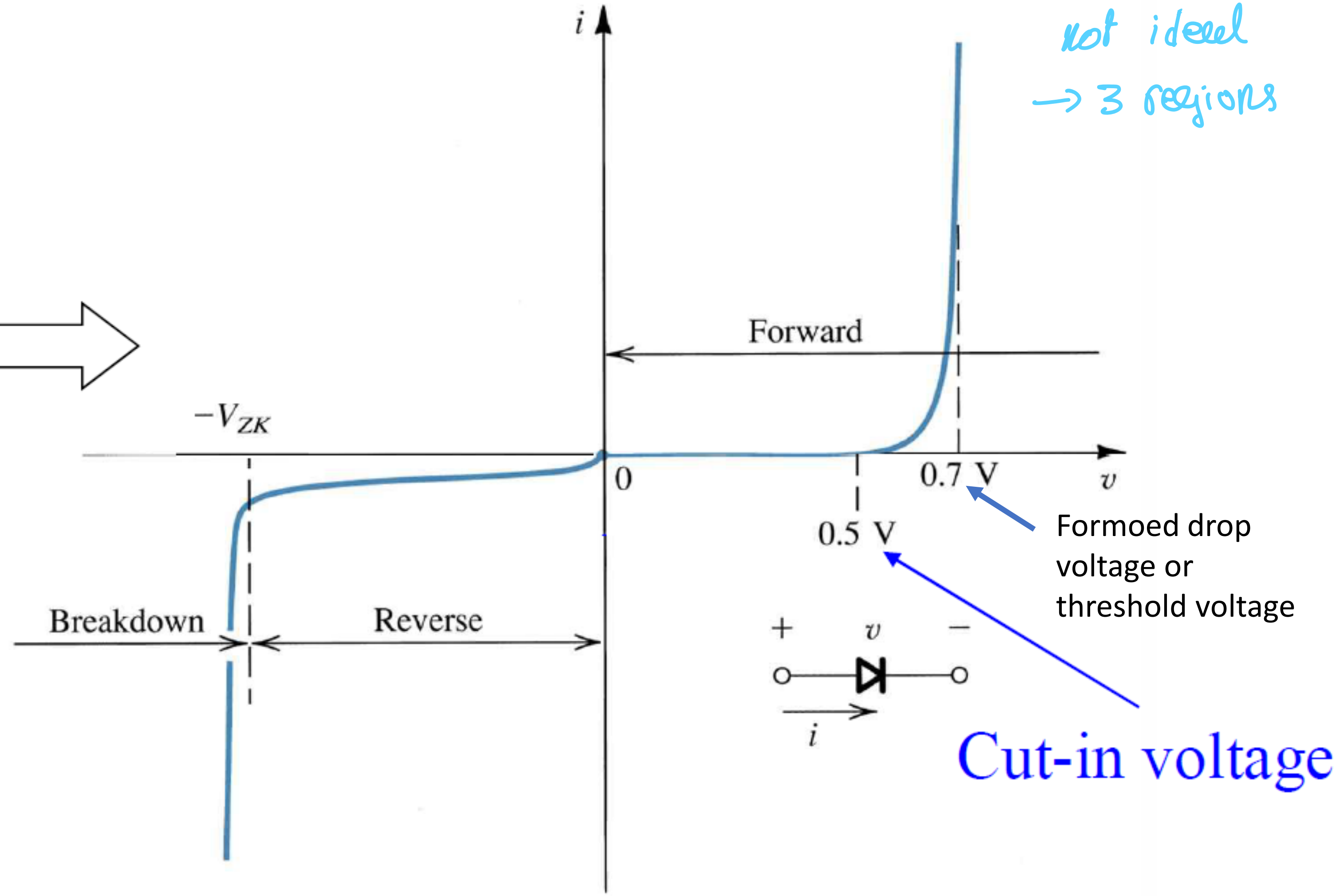
D_1 is off wrong → solve again

$13.3 - 10 = 3.3$

Terminal Characteristics of Junction Diodes

not ideal
→ 3 regions





Breakdown ($v < -V_{ZK}$)	Reverse($v < 0$)	Forward-bias ($v > 0$)

Terminal Characteristics of Junction Diodes

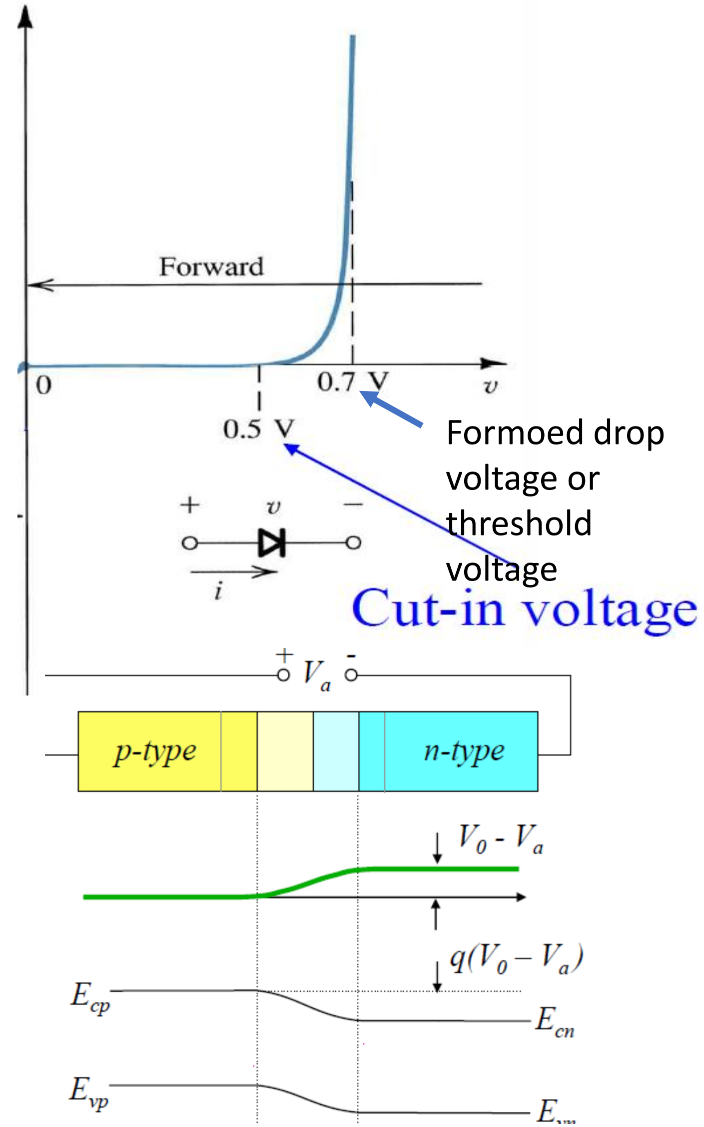
Forward Bais:

- When the voltage increases a little, there is almost no current. But at $\boxed{\text{cut-in volage}}$, the current starts to follow.
- After a certain point (called threshold voltage, around 0.7 for silicon), the diode suddenly allows a large current to pass. close to V_{bi}

  0.7 in Si
- The graph rises sharply upward on the right side after this voltage

Why?

The applied voltage close or grater than build in voltage Vo



$T(n) = 2T(n/2) + n \quad n > 1$

$T(1) = 1 \quad O(n \log n)$ using subs.

$$I = I_S\left(e^{V/nV_T} - 1\right) \Rightarrow \begin{array}{l} I \approx I_S e^{V/nV_T} \text{ when } i >> I_S \\ v = nV_T \ln\left(I/I_S\right) \end{array}$$

- I_S : saturation current or scale current

- Proportional to the junction area

- $10^{-12} \sim 10^{-15}$ A

-*Temperature dependence*: doubled / 5°C

- V_T (thermal voltage) = kT/q = 25 mV @ T = 20°C

- k (Boltzman's constant) = 1.38×10^{-23} [joules/kelvin]

- T = the absolute temperature in kelvins = 273 + temperature in °C

- q = the magnitude of electronic charge = 1.60×10^{-19} coulomb

- n : 1 ~ 2 (normally 1) , depends on material & physical structure

The Forward-Bias Region

$$\begin{cases} I_1 = I_S e^{V_1/nV_T} \\ I_2 = I_S e^{V_2/nV_T} \end{cases}$$

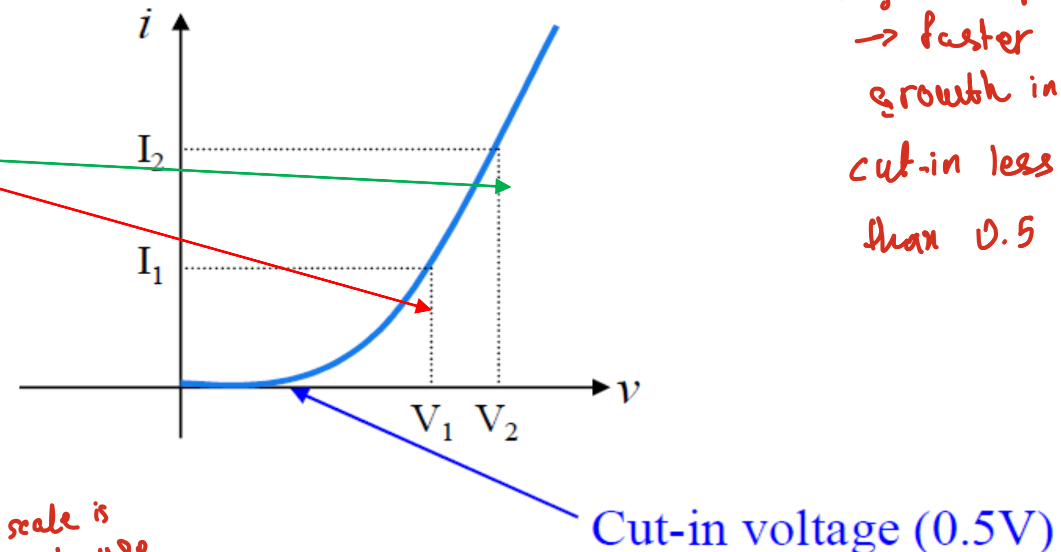
$$\rightarrow I_2 / I_1 = e^{(V_2 - V_1)/nV_T}$$

$$\therefore V_2 - V_1 = nV_T \ln I_2 / I_1$$

$$\text{or } V_2 - V_1 = 2.3nV_T \log I_2 / I_1$$

where, ln 10 = 2.3

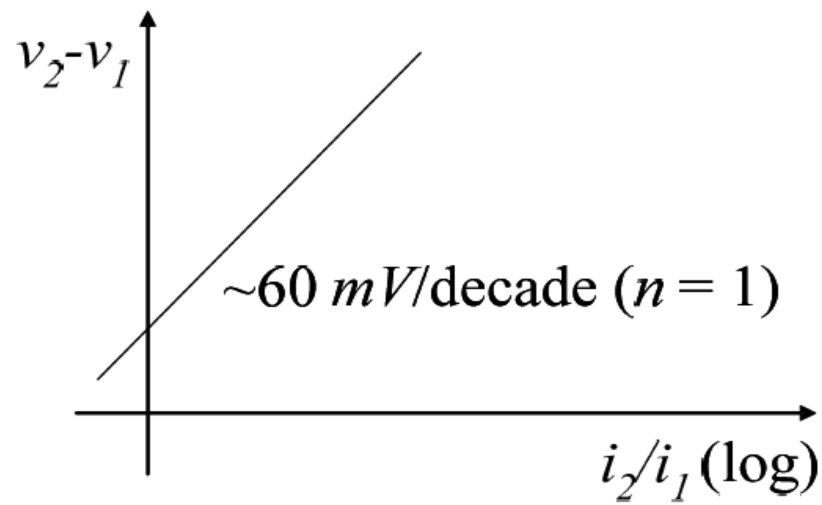
$$\log_{10} A = \frac{\ln A}{\ln 10}$$



higher temp → faster growth in i

cut-in less than 0.5

log scale is easier to use

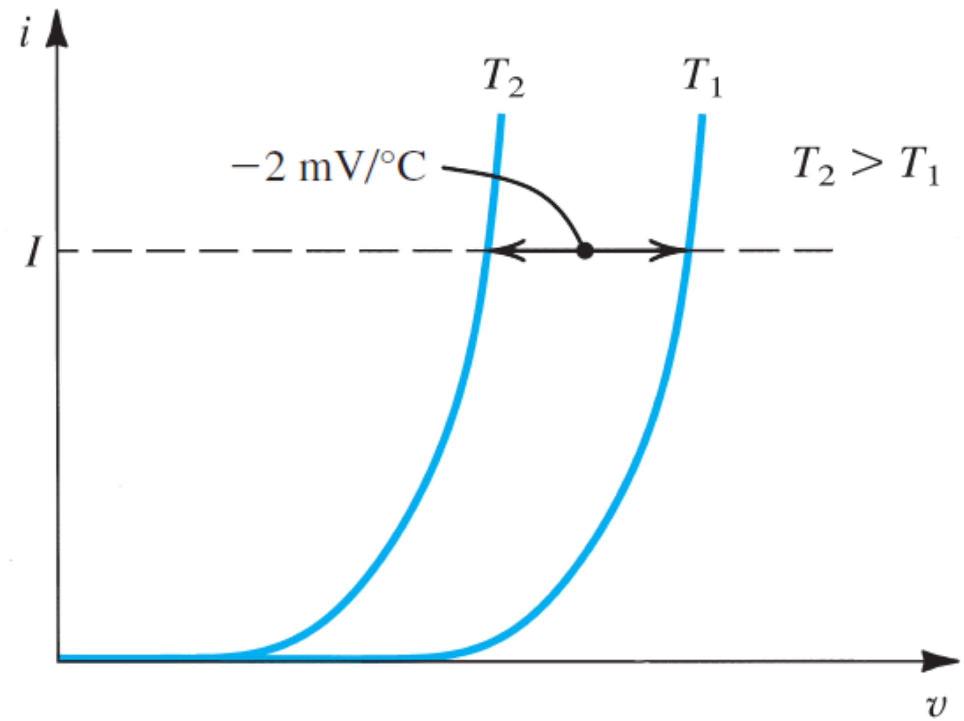


For a decade change in current, the voltage drop changes by $2.3nV_T$ (60mV for n=1, 120mV for n=2 or 0.1V/decade, approximately)

The Forward-Bias Region

$$I = I_S\left(e^{V/nV_T} - 1\right)$$

Since both I_S and V_T are functions of temperature, the forward i–v characteristic varies with temperature, as illustrated in Fig.



At a constant current, the voltage drop decreases by approximately 2 mV for every 1°C increase in temperature.

Example 3

x changes with room temp.

Find the diode voltage for a silicon diode with $I_S = 0.1$ fA operating at room temperature at a current of 300 μA. What is the diode voltage if $I_S = 10$ fA? What is the diode voltage if the current increases to 1 mA?

$$I/I_s + 1 = e^{V/nV_T}$$

$$V_D = nV_T \ln\left(1 + \frac{I_D}{I_S}\right)$$

(a) $I_s = 0.1 \times 10^{-15}$, $I_D = 300$

assume $n=1$ if not given

$$V_D = [25 \times 10^{-3}] \ln\left[1 + \frac{300 \times 10^{-6}}{0.1 \times 10^{-15}}\right] = 0.718\,V$$

(b) $I_s = 10 \times 10^{-15}$

$$V_D = (25 \times 10^{-3}) \ln[1 + \quad] = 0.603\,V$$

(c) $I = 0.18\,A$, $I_D = 1\,mA$ → $V_D = 0.745\,V$

Example 4

Find the diode voltage for a silicon power diode with $I_S = 10$ nA and $n = 2$ operating at room temperature at a current of 10 A.

Assumptions: At room temperature, we will use $V_T = 0.025\text{ V} = 1/40\text{ V}$.

Analysis: The diode voltage will be

$$V_D = nV_T \ln\left(1 + \frac{I_D}{I_S}\right) = 2(0.025\text{ V}) \ln\left(1 + \frac{10\text{ A}}{10^{-8}\text{ A}}\right) = 1.04\text{ V}$$

Example 5

A silicon diode is operating with a temperature of 50°C and the diode voltage is measured to be 0.736 V at a current of 2.50 mA. What is the saturation current of the diode?

Reverse-Bias and Breakdown Regions

- Reverse-bias region

  ($v < 0$ & $v > 2\text{~}3\ V_T$)

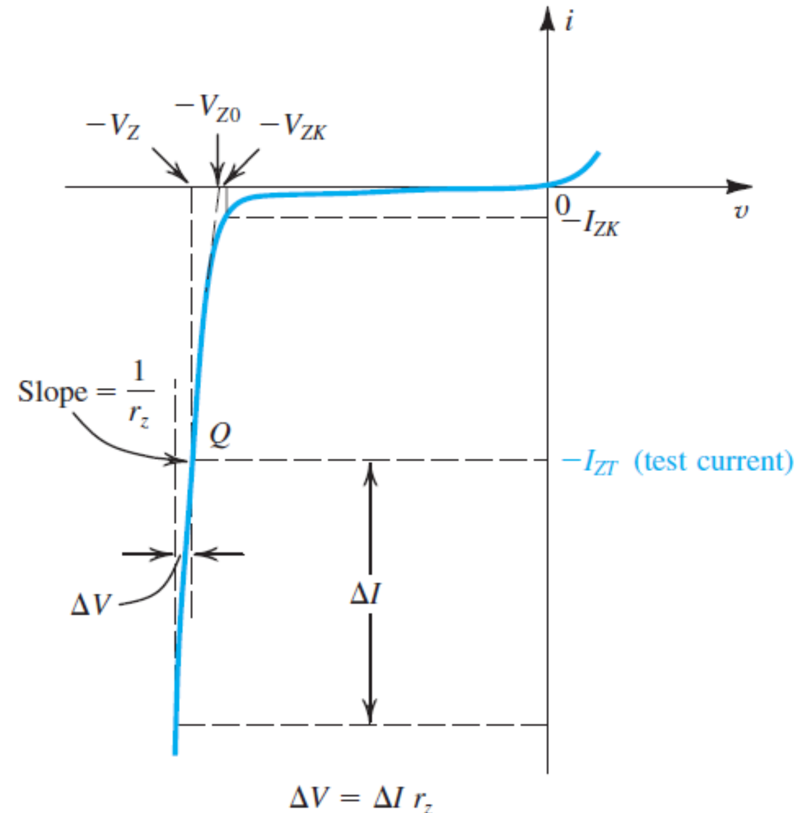
$$i = I_S\left(e^{v/nV_T} - 1\right)$$
$$= -I_S$$

i is reverse directed & constant

→ *Saturation current*

I_S doubles for every 5°C rise in temperature

- Breakdown region ($v < -V_{ZK}$)
  - Z : Zener, K : Knee



- *Reverse current increases rapidly, with the small increase in voltage drop*

Today we'll talk abt Zener

why is it called zener?

Because it'll work in reverse breakdown

$|V| > V_{ZK}$

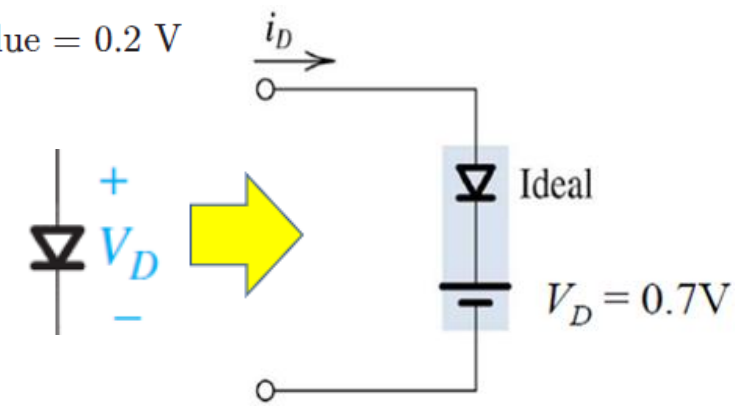
needs to be larger in mag. to work

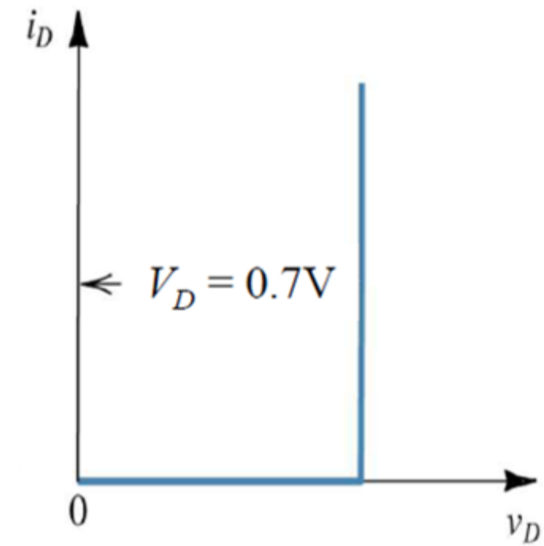
Modeling the Diode Forward Characteristic

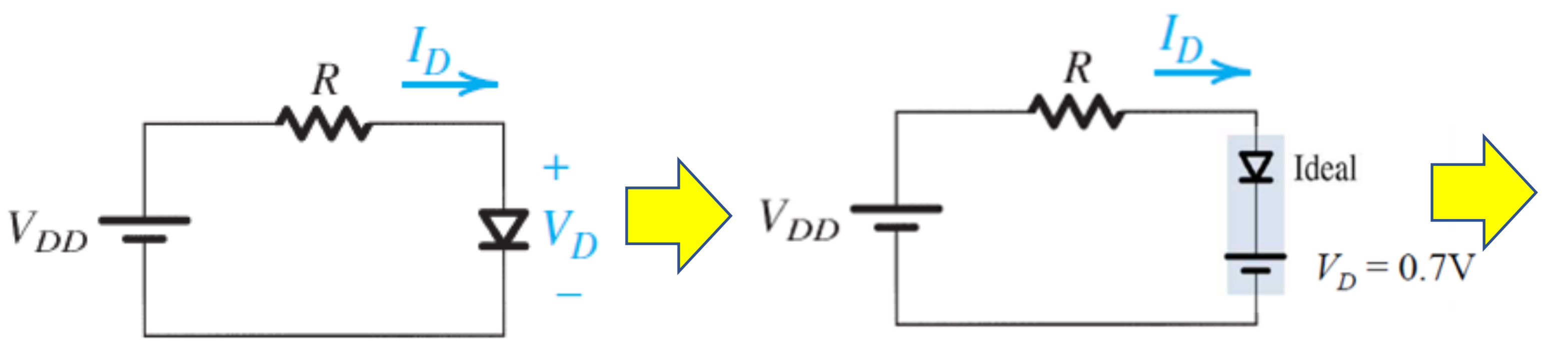
1- Simpler model for diode forward characteristics is a forward-conducting diode exhibits a constant voltage drop V_D (=0.7V).

For Si diode $V_D = 0.6$ V to 0.9 V, typical value = 0.7 V

For Ge diode $V_D = 0.1$ V to 0.5 V, typical value = 0.2 V





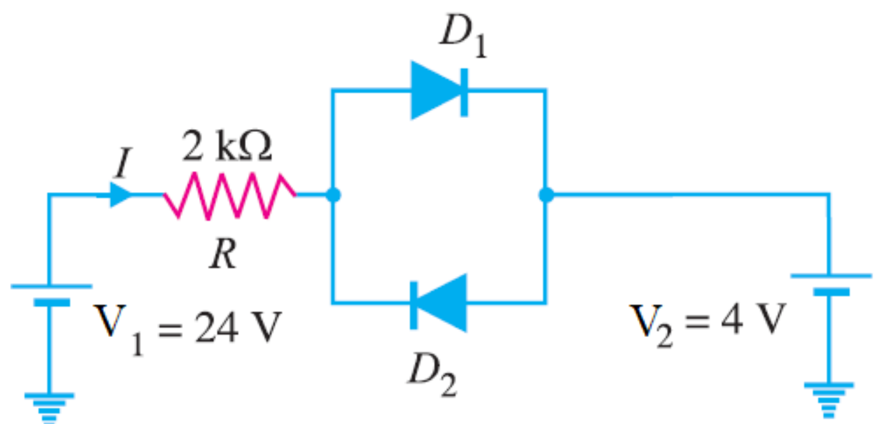


$$I_D = \frac{V_{DD} - 0.7}{R}$$

$$= \frac{5 - 0.7}{1} = 4.3 \text{ mA}$$

Example 6

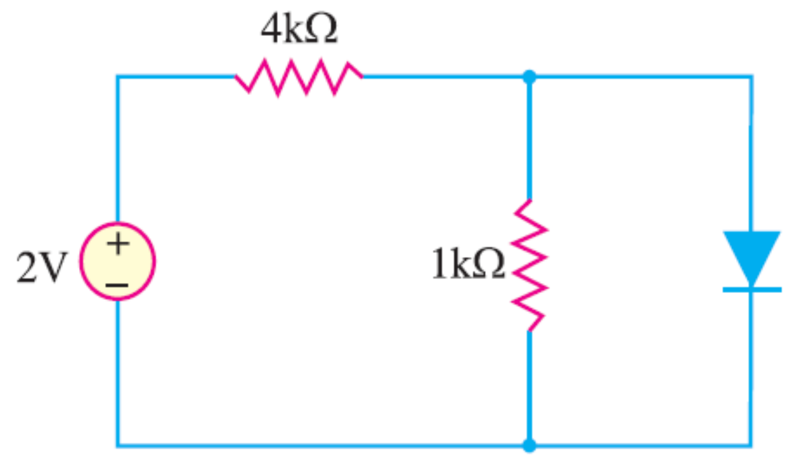
Determine the current I in the circuit shown



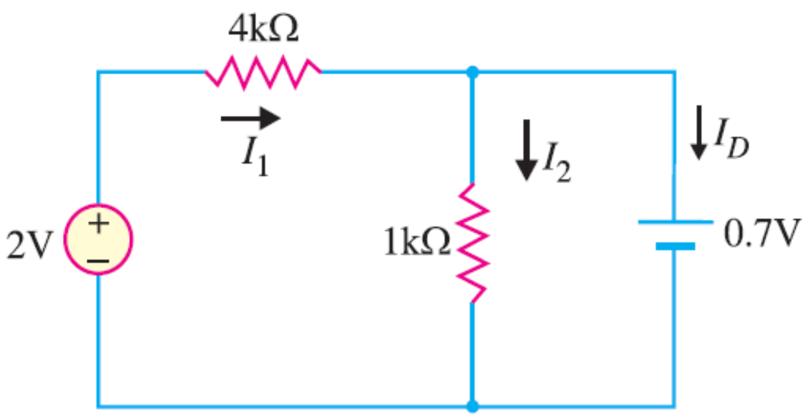
Suggest that diode D_1 is forward biased and diode D_2 is reverse biased

Example 7

Determine the state of diode f
or the circuit shown, find I_D and V_D.

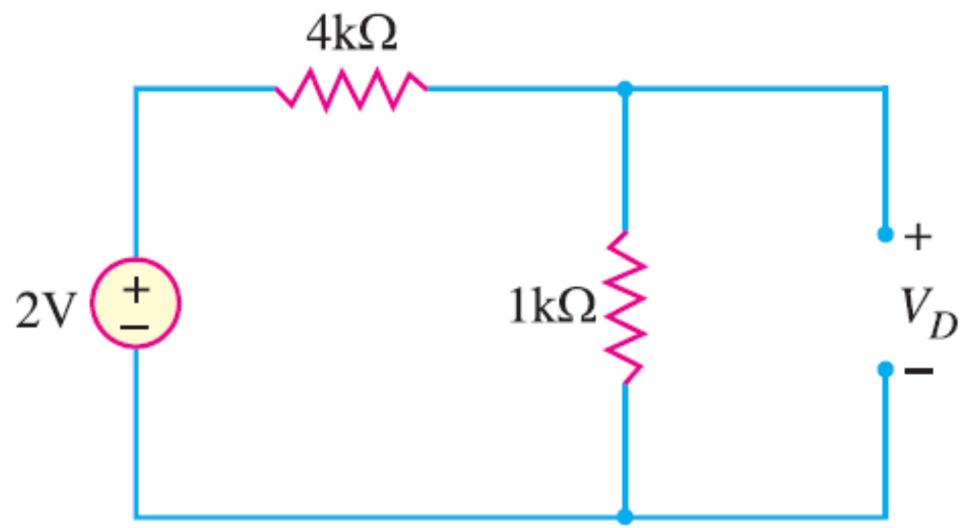


Solution. Let us assume that the diode is *ON*



Example 7 Continue

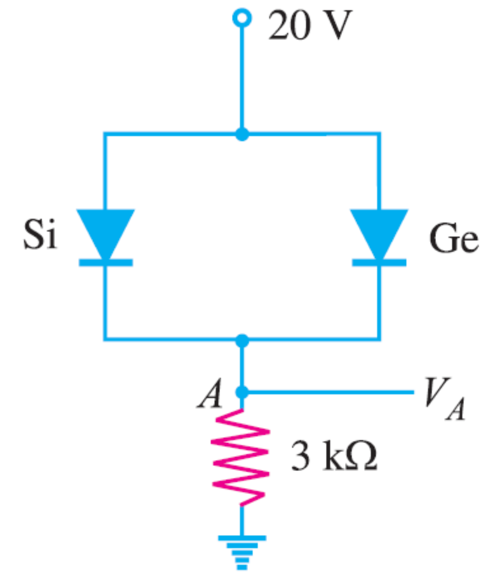
Since the diode current is negative, the diode must be **OFF** and the true value of diode current is $I_D = \mathbf{0\ mA}$.

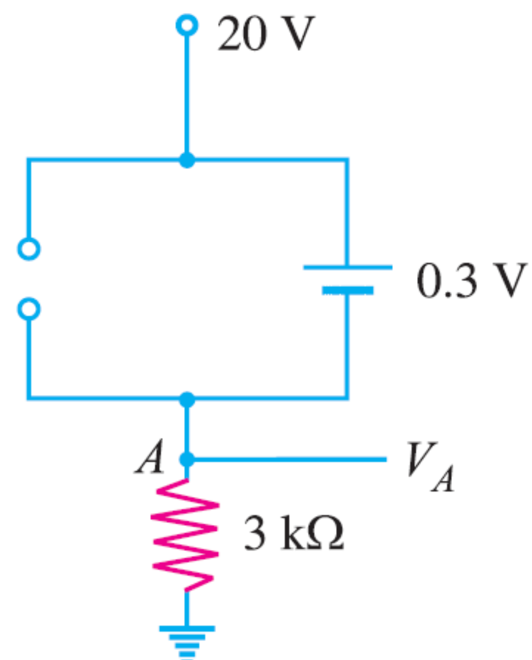


We know that 0.7V is required to turn *ON* the diode. Since V_D is only 0.4V, the answer confirms that the diode is *OFF*.

Example 8

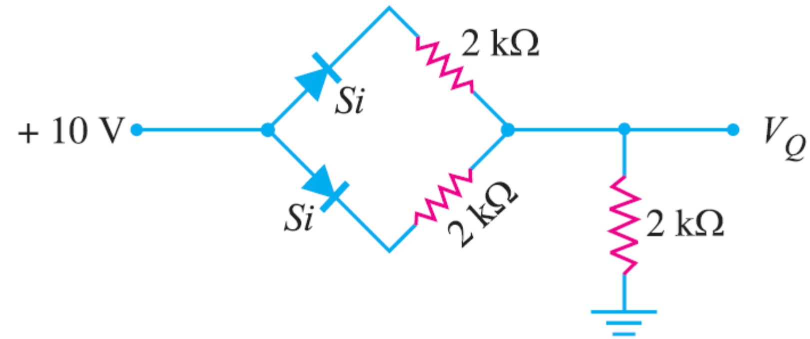
Find the voltage V_A in the circuit shown.



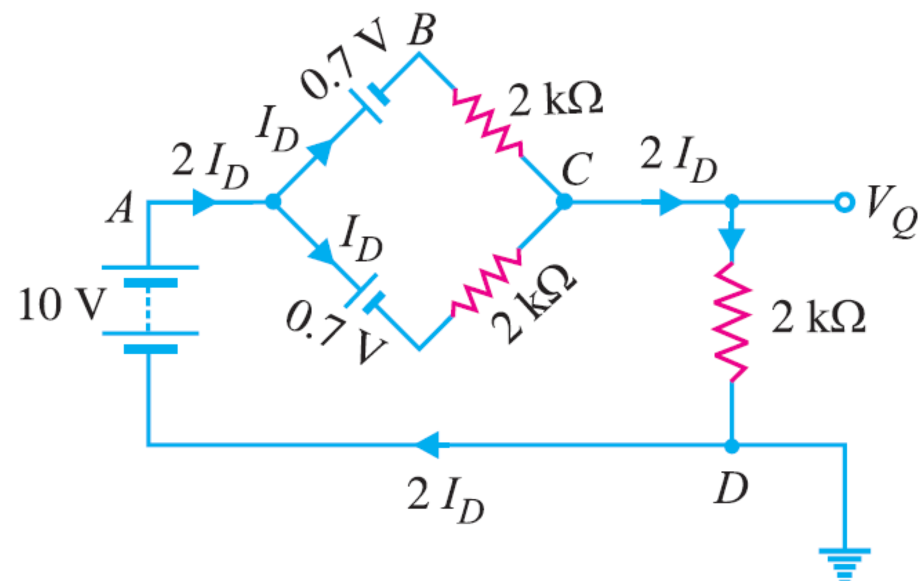


Example 9

Find V_Q and I_D in the network shown

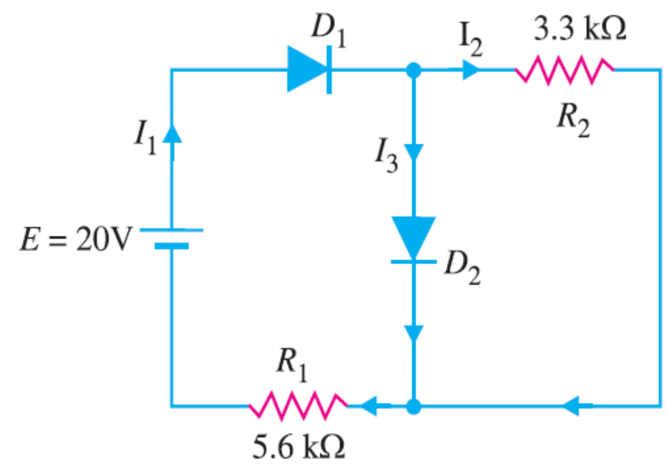


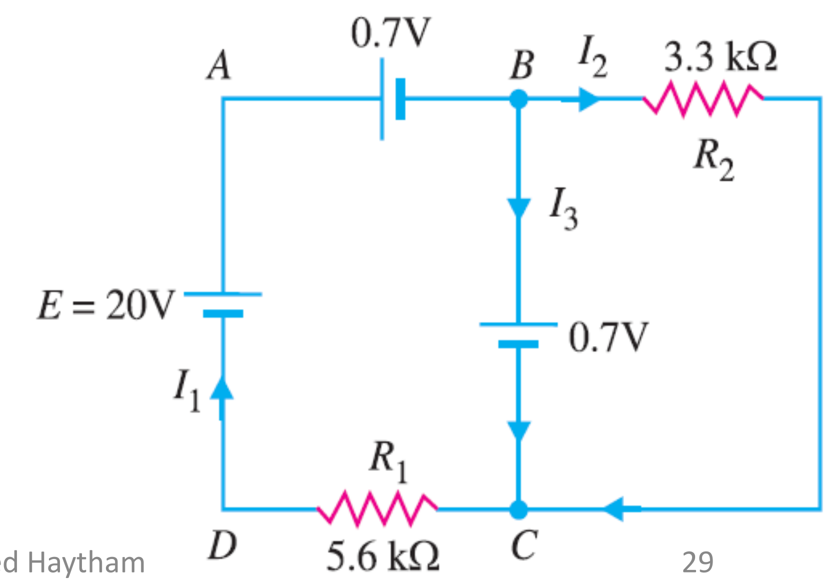
Applying Kirchhoff's voltage law to the closed circuit *ABCDA*, we have,



Example 10

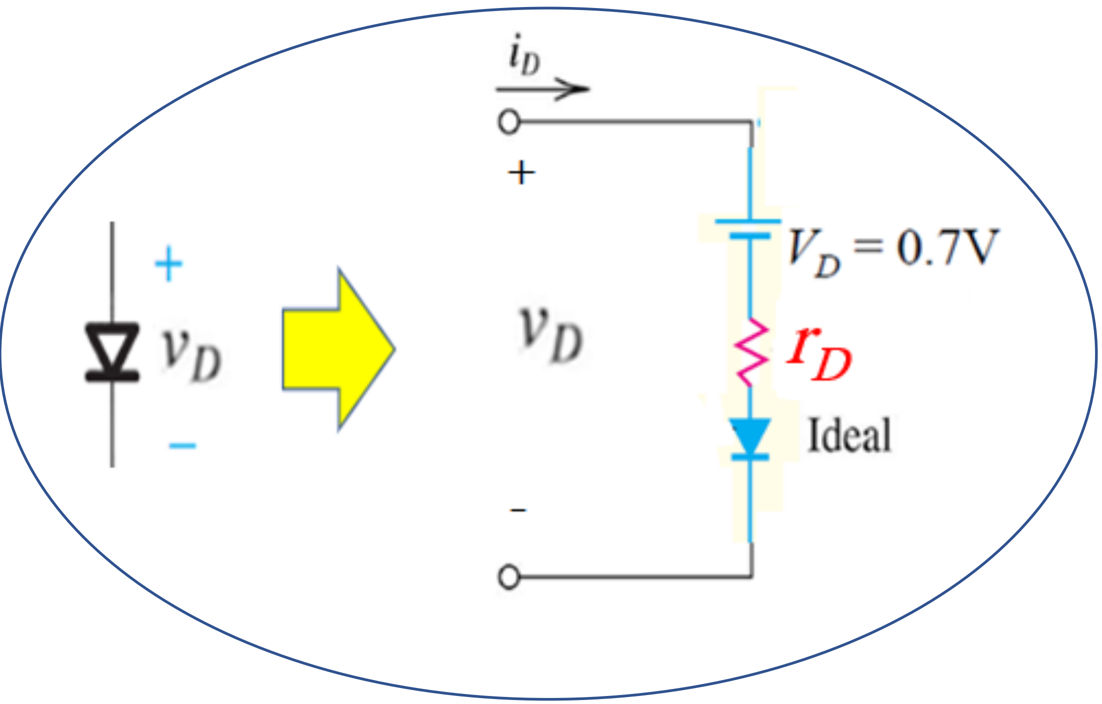
Determine the currents I_1, I_2 and I_3 for the network shown

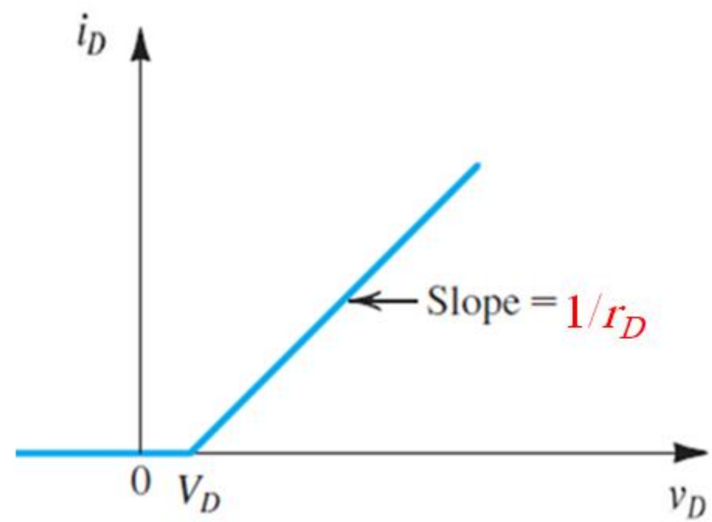




Modeling the Diode Forward Characteristic

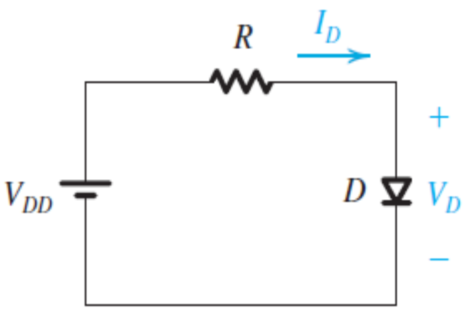
2- More exact and approximate model for diode forward characteristics is a forward-conducting diode exhibits a constant voltage drop V_D (=0.7V) with a series Forward resistance, r_D = (10-60)Ω.

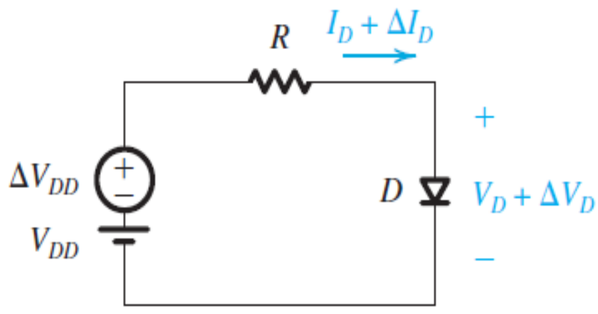


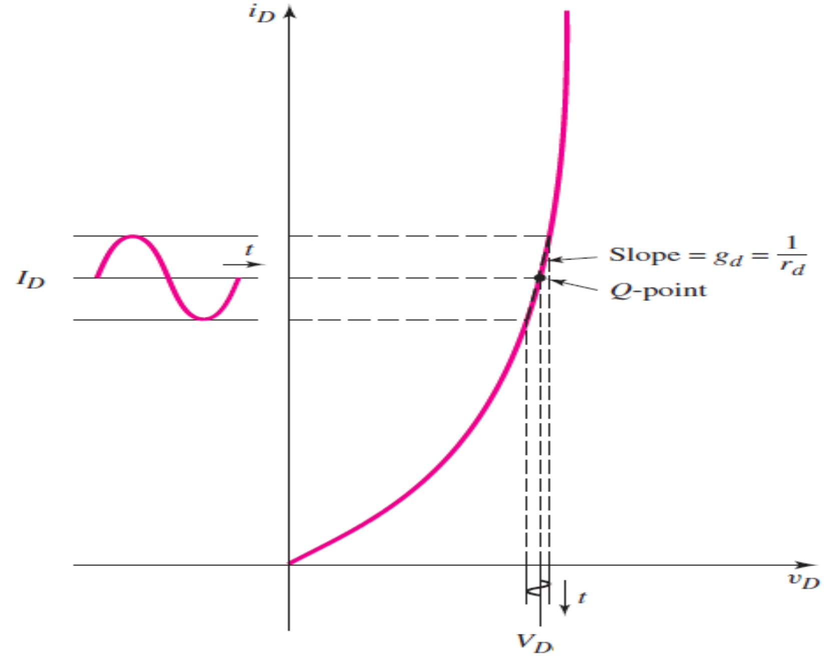


Diode Small-Signal Model

Application, where a small ac signal is superimposed on the dc quantities







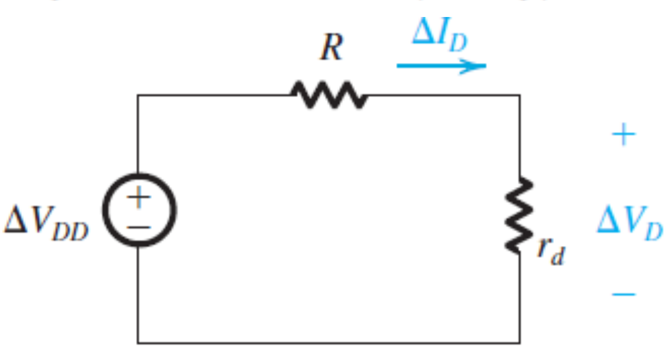
Ac

$$v_D(t) = V_D + v_d(t) \qquad i_D(t) = I_S e^{v_D/V_T}$$

Ac

$$i_D(t) = I_S e^{(V_D+v_d)/V_T} = I_S e^{V_D/V_T} e^{v_d/V_T} \qquad I_D = I_S e^{V_D/V_T} \qquad i_D(t) = I_D e^{v_d/V_T}$$

$$\frac{v_d}{V_T} \ll 1 \qquad i_D(t) \simeq I_D\left(1 + \frac{v_d}{V_T}\right) \qquad i_D(t) = I_D + \frac{I_D}{V_T} v_d = I_D + i_d \qquad i_d = \frac{I_D}{V_T} v_d$$

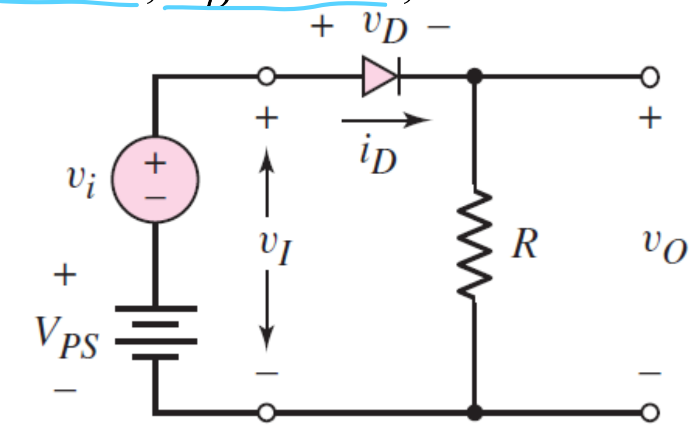


$$r_d = 1\Big/\left[\frac{\partial i_D}{\partial v_D}\right]_{i_D = I_D} \qquad r_d = \frac{V_T}{I_D}$$ **diode small-signal resistance**

→ from Dc analysis

Example 11

Assume circuit and diode parameters of $V_{PS} = 5$ V, $R = 5$ k, $V_D = 0.6$ V, and $v_i = 0.1\sin\omega t$ (V). Determine v_O and i_D



DC

$$I_D = \frac{5 - 0.6}{R} = 0.88\,mA$$

$$V_o = I_{DQ} R = 4.4V$$

$$r_d = \frac{V_T}{I_D} = \frac{0.026}{0.88} = 0.0295k\,\Omega$$

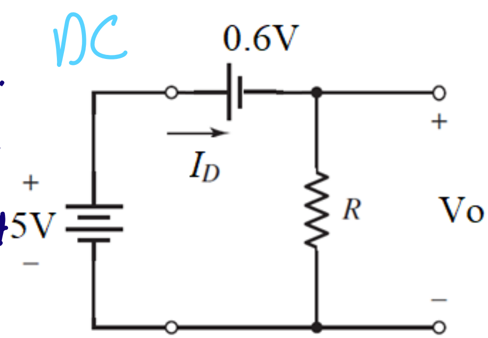
AC:

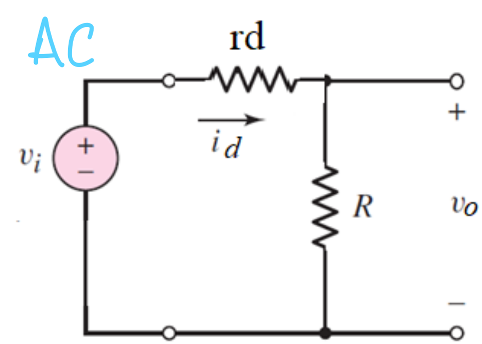
$$i_d = \frac{V_i}{r_d + R} = \frac{0.1\sin\omega t}{0.0295k + 5k} = 19.9\sin\omega t\ \mu A$$

$$V_o = i_d R = 0.0995\sin\omega t$$

$V_o = 4.4 + 0.995\sin\omega t$

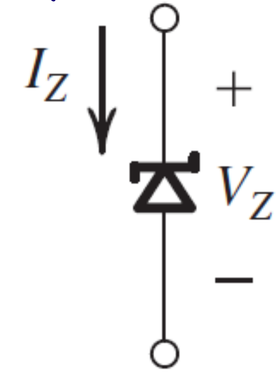
$i_D = 888 + 19.9\sin\omega t$ μA





Operation in the Reverse Breakdown Region
Zener Diodes

ON when $|V| > |V_{ZK}|$



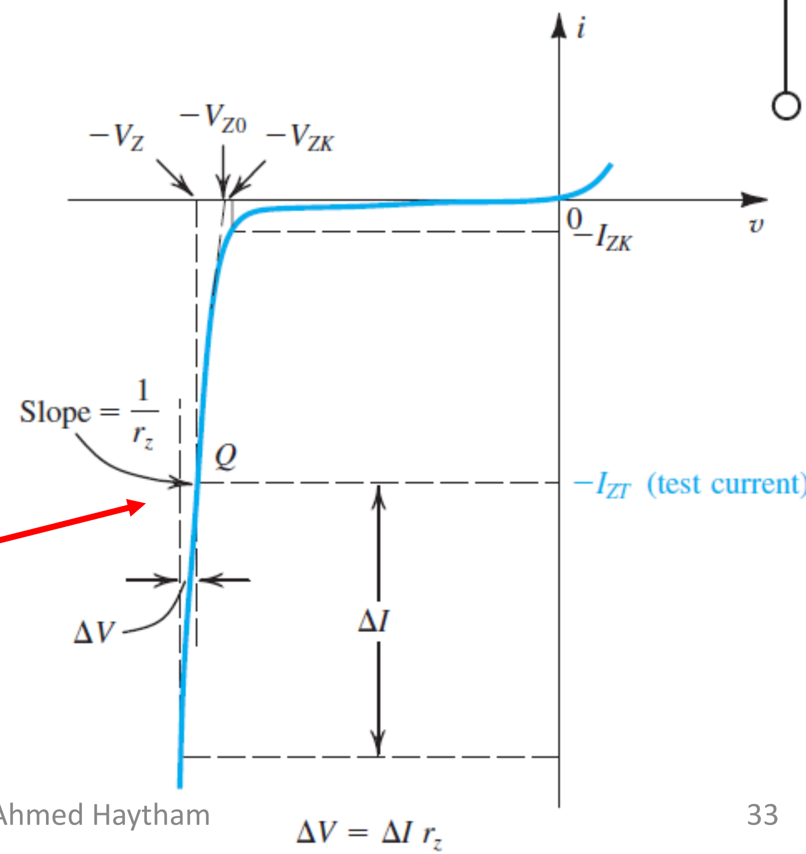
Very steep *i*-*v* curve in the **breakdown region**

- Almost constant voltage drop regardless of load current & power supply ripple
- Breakdown diode, Zener diode : operation in the breakdown region

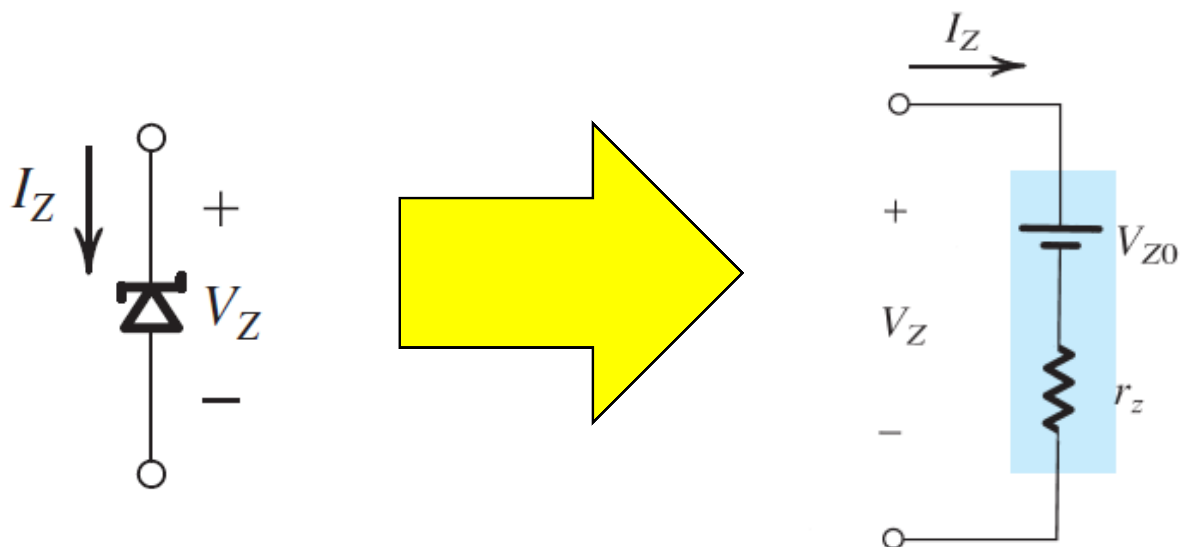
Zener diodes are fabricated with voltages V_Z in the range of a few volts to a few hundred volts. In addition to specifying V_Z (at a particular current I_{ZT}), r_z , and I_{ZK} , the manufacturer also specifies the maximum power that the device can safely dissipate

works after BD

$$\Delta V = r_z \Delta I$$



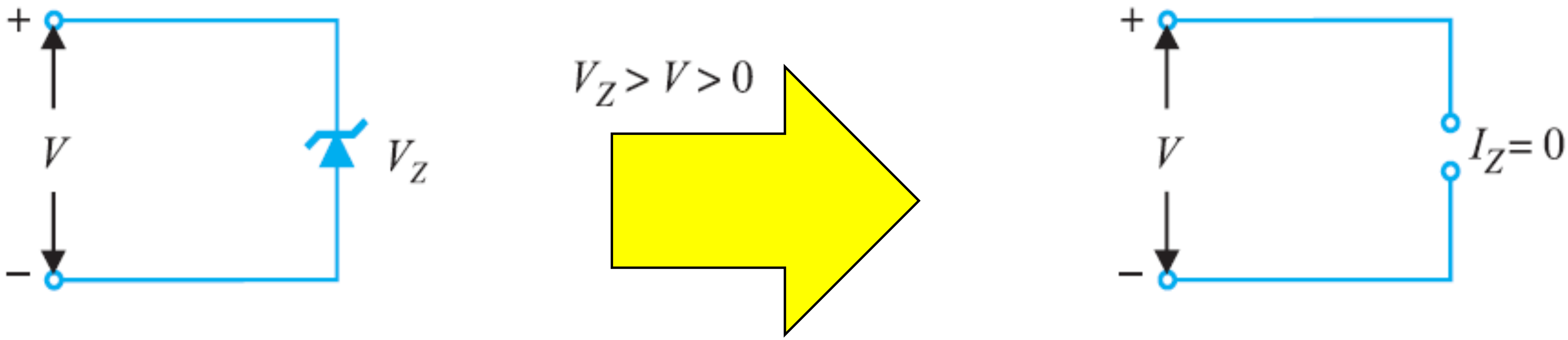
Operation in the Reverse Breakdown Region
Zener Diodes



shunt regulator

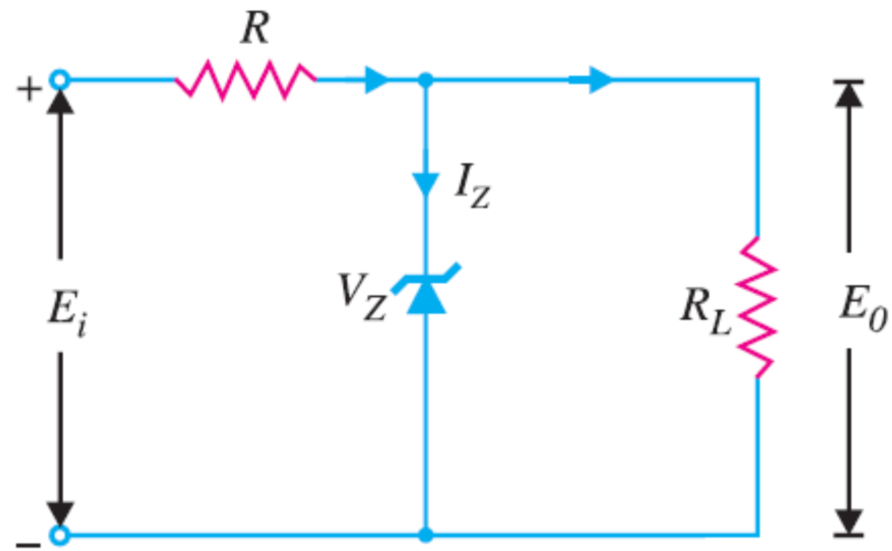
$$V_Z = V_{Z0} + r_z I_Z$$

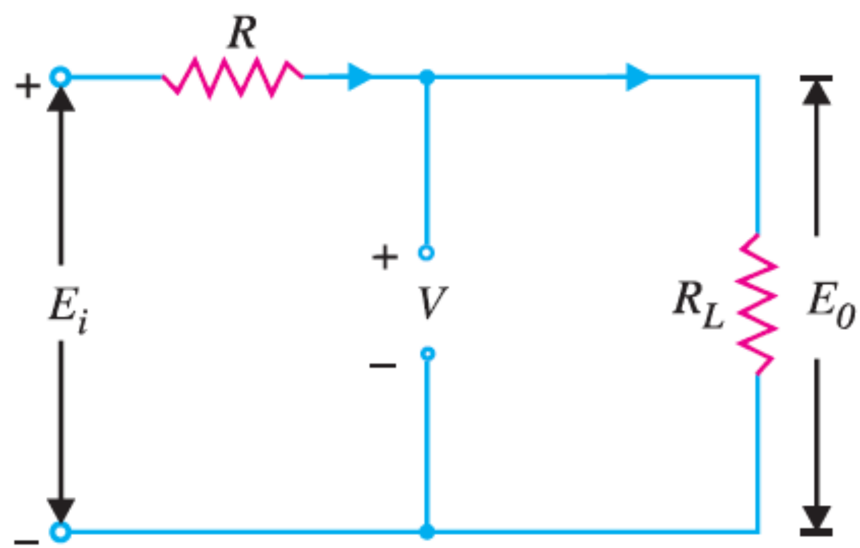
and it applies for $I_Z > I_{ZK}$ and, obviously, $V_Z > V_{Z0}$.



Solving Zener Diode Circuits

1- E_i and R_L are fixed.





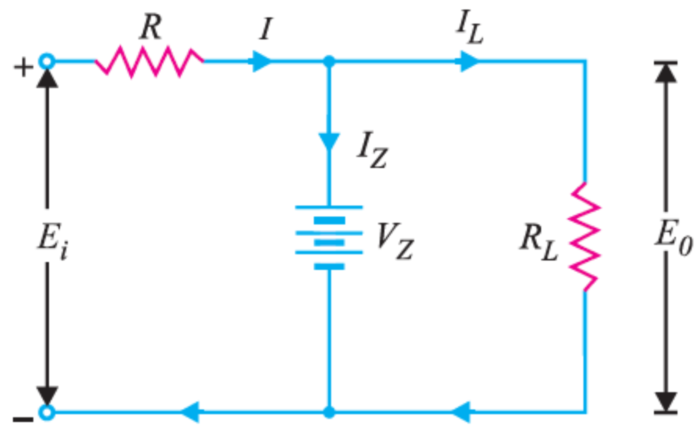
First Calculate:

$$V = E_0 = \frac{R_L E_i}{R + R_L}$$

Use of Zener Diode as Shunt Regulator

Then:

- If $V \geq V_Z$, the Zener diode is in the "on" state and its equivalent model can be substituted as



$$E_0 = V_Z$$

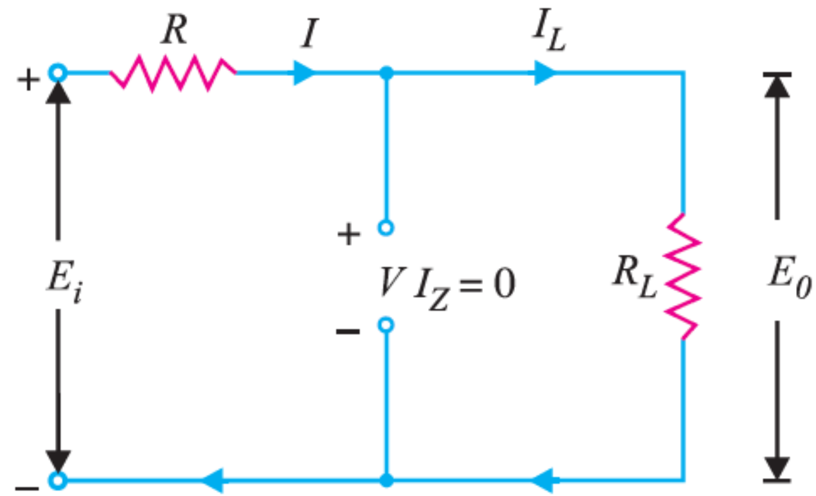
$$I_Z = I - I_L \quad \text{where } I_L = \frac{E_0}{R_L} \quad \text{and } I = \frac{E_i - E_0}{R}$$

Power dissipated in zener, $P_Z = V_Z I_Z$

Use of Zener Diode as Shunt Regulator

- If $V < V_Z$, the diode is in the "off" state as

$$V = E_0 = \frac{R_L E_i}{R + R_L}$$



$$I = I_L \quad \text{and} \quad I_Z = 0$$

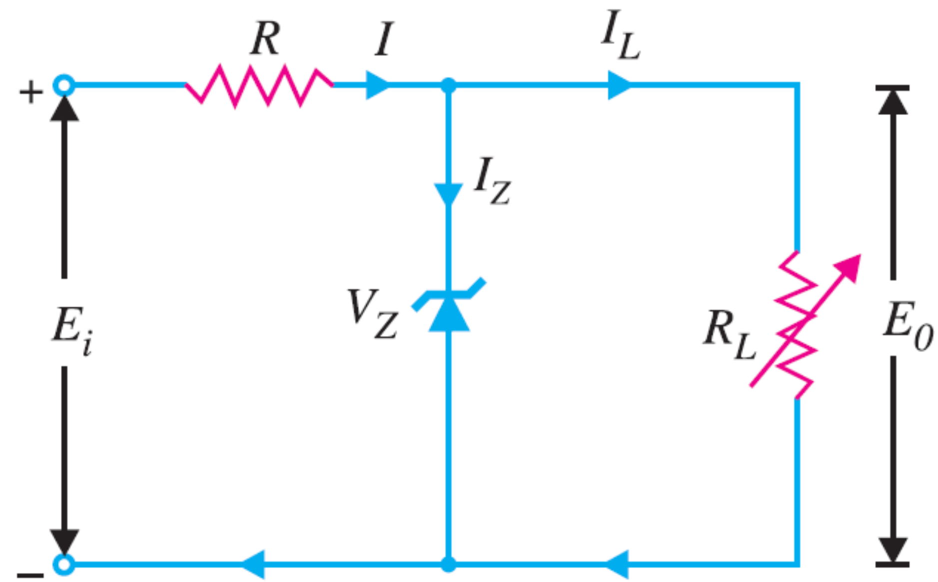
$$V_R = E_i - E_0 \quad \text{and} \quad V = E_0 \quad (V < V_Z)$$

$$P_Z = V I_Z = V(0) = 0$$

Use of Zener Diode as Shunt Regulator

2- E_i is fixed and R_L is varying.

(i) R_{Lmin} and I_{Lmax}.



$$E_0 = V_Z = \frac{R_L E_i}{R + R_L}$$

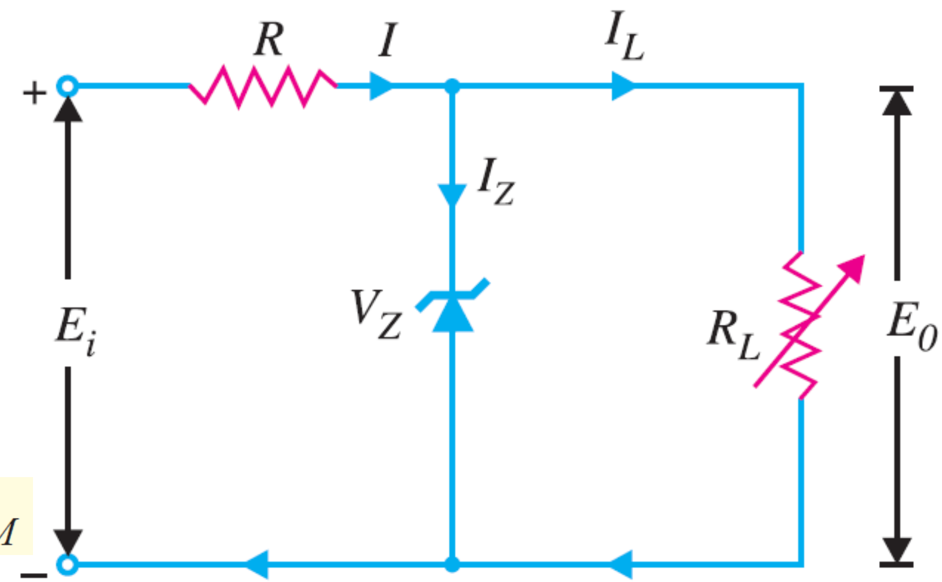
$$R_{Lmin} = \frac{R V_Z}{E_i - V_Z}$$

$$I_{Lmax} = \frac{E_0}{R_{Lmin}} = \frac{V_Z}{R_{Lmin}}$$

Use of Zener Diode as Shunt Regulator

2- E_i is fixed and R_L is varying.

(i) I_{Lmin} and R_{Lmax}.



If the maximum current that a Zener can carry safely is I_{ZM},

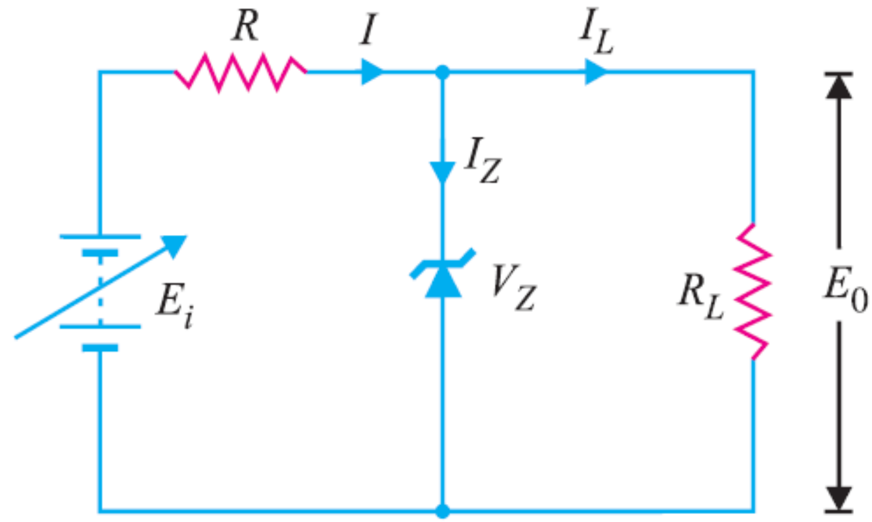
Max. power dissipation in zener, $P_{ZM} = V_Z I_{ZM}$

$$I_{Lmin} = I - I_{ZM}$$

$$R_{Lmax} = \frac{E_0}{I_{Lmin}} = \frac{V_Z}{I_{Lmin}}$$

Use of Zener Diode as Shunt Regulator

3- Variable E_i and fixed R_l



(i) E_i (min). To determine the minimum applied voltage that will turn the zener on, simply calculate the value of E_i that will result in load voltage $E_0 = V_Z$ *i.e.*,

V on zener ?

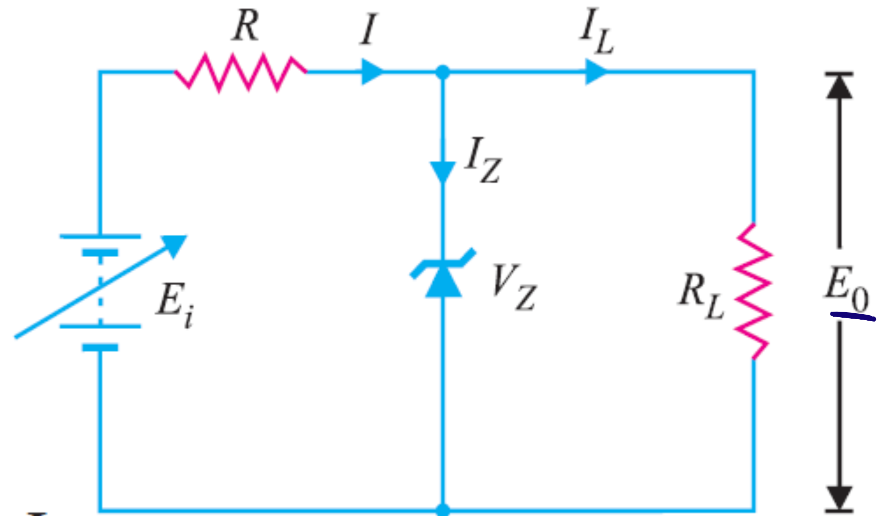
VDR

$$E_0 = V_Z = \frac{R_L E_i}{R + R_L}$$

$$E_{i\,(min)} = \frac{(R + R_L)\, V_Z}{R_L}$$

Use of Zener Diode as Shunt Regulator

3- Variable E_i and fixed R_l



(*ii*) E_i (*max*)

Now, current through R, $I = I_Z + I_L$

when zener is on the current thro is max. current

Since I_L $(= E_0/R_L = V_Z/R_L)$ is fixed,

$$I_{max} = I_{ZM} + I_L$$

$$E_i = I\,R + E_0$$

Since E_0 $(= V_Z)$

$$E_{i\,(max)} = I_{max}\,R + V_Z$$

① ?

Example 12

① check V across zener > 50
③ Draw circuit

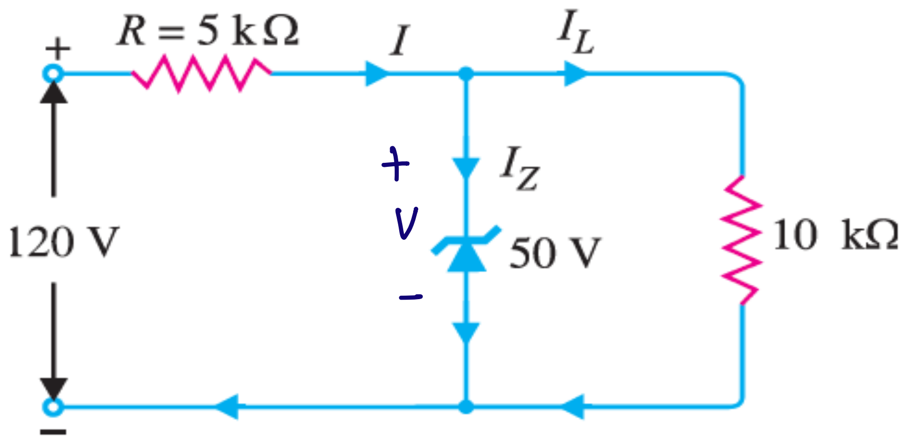
find :

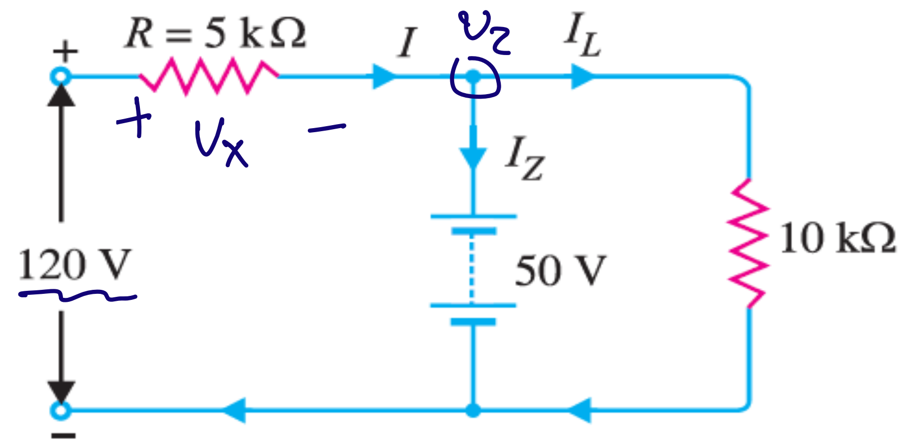
(i) the output voltage

(ii) the voltage drop across series resistance

(iii) the current through zener diode.

$V_Z (= 50\text{ V})$





$V = 120 \dfrac{10K}{10K + 5K} = 80V$ zener is ON

? They call it Regulator cause it regulates voltage

(i) $V_o = 50\ V$

(ii) $V_x = 120 - 50 = 70V$

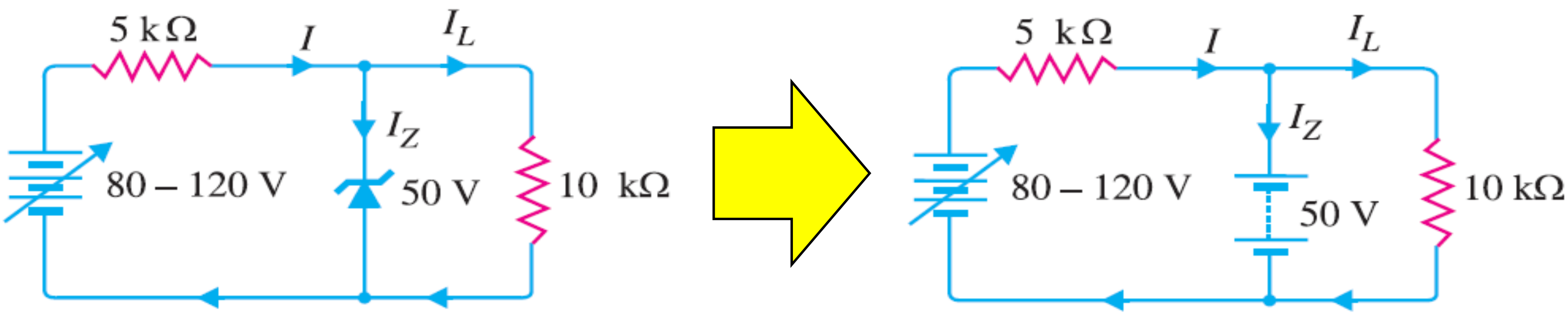
(iii) $I_Z = I - I_L = 14m - 5m = 9mA$

$I = I_{5K} = \dfrac{70}{5K} = 14mA$

$I_L = \dfrac{50}{10K} = 5mA$

Example 13

find the maximum and minimum values of zener diode current. $V_Z (= 50\text{ V})$



imp. notes ??

V on zener is 50 but current?

$I_{z\,max} \longrightarrow E_{i\,max} = 120V$, $I_L = \frac{50}{10K} = 5\text{ mA}$

$I_{z\,max} = I_{max} - I_L$, $I_{max} = \frac{\overset{120}{E_{i\,max}} - 50}{5K} = 14\text{ mA}$

current is constant

$I_{z\,max} = 9\text{ mA}$, $I_{z\,min} = I_{min} - I_L = \frac{80-50}{5K} - 5\text{ mA}$

$= 6 - 5 = 1\text{ mA}$

V, I on load changed?

No

what do we know abt zener?

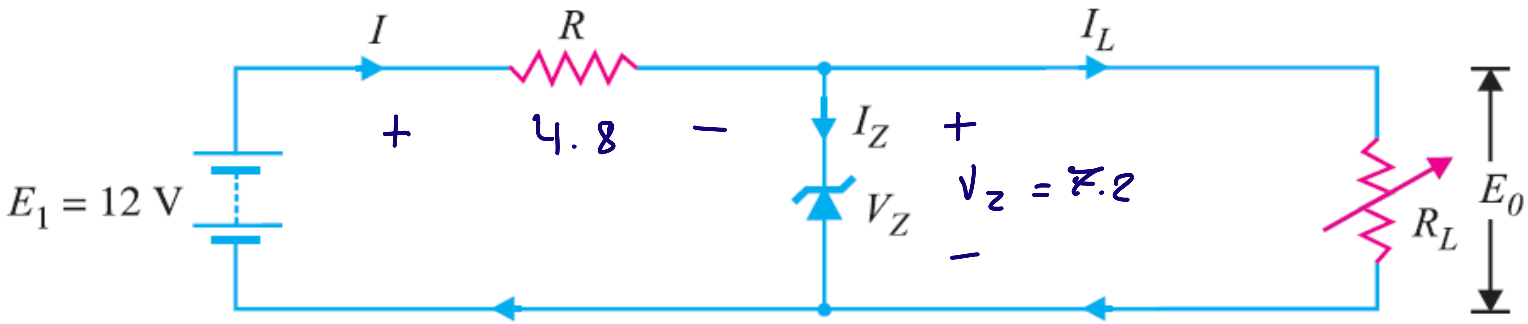
even when we changed the inpt,

the output on load

Example 14

the output on load didn't change. Load gets the same out.

V zener is used in the circuit shown and the load current is to vary from 12 to 100 mA. Find the value of series resistance R to maintain a voltage of 7.2 V across the load. The input voltage is constant at 12V and the minimum zener current is 10 mA.



$V_z = 7.2$

if I_L is max. $\rightarrow I_z$ will be at min.

$I = I_z + I_L$

$R = \dfrac{4.8}{I}$, $I = I_z + I_L = 10m + 100m = 110mA$

$= \dfrac{4.8}{110m} = 43.5\Omega$

what we do is we check on of the edges then the other and if it's on it means that the middle

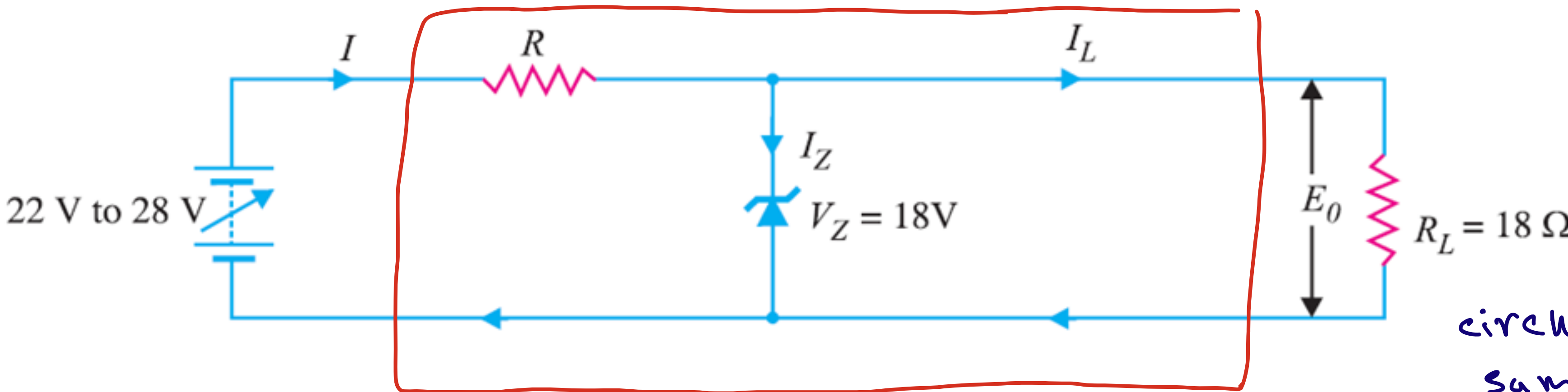
zener has a limit for?

is ON

Example 15

The zener diode shown has $V_Z = 18$ V. The voltage across the load stays at 18 V as long as I_Z is maintained between 200 mA and 2 A. Find the value of series resistance R so that E_0 remains 18 V while input voltage E_i is free to vary between 22 V to 28V.

off ← ⇒ burn



→ regulator

circuit is the same (the regulator) what we can change is the input or output.

$$I_L = \frac{18}{18} = 1\ mA$$

$$R = \frac{E_i - 18}{I} = \frac{22 - 18}{1200\ m} = 3.33\ \Omega$$

$\hookrightarrow I = I_{Z\,min} + 1 = 200\ m + 1 = 1200\ mA$

↳ changing

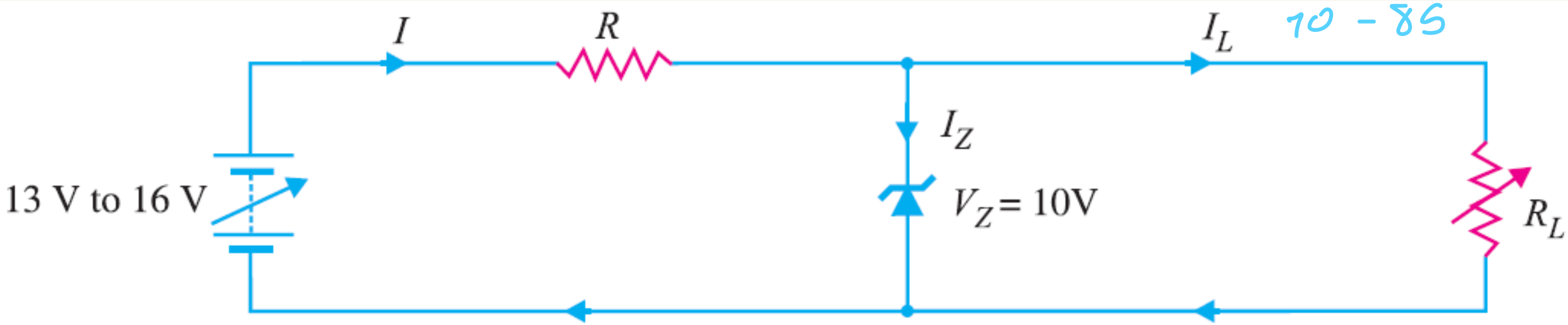
$E_{i\,min}$

$$\frac{10}{I} = 3.33 \rightarrow I = 3A \rightarrow I_z = 3 - 1 = 2A$$

Example 16

H.w

A 10-V zener diode is used to regulate the voltage across a variable load resistor The input voltage varies between 13 V and 16 V and the load current varies between 10 mA and 85 mA. The minimum zener current is 15 mA. Calculate the value of series resistance R.



$E_i = 13 - 16$

$I_L = 10 - 85$

$I_{z\,min} = 15$

min input 13 10

$R_s = \dfrac{E_i - \cancel{V_{out}}\ 10}{I}$

$I = I_z + I_L = 100\,mA$

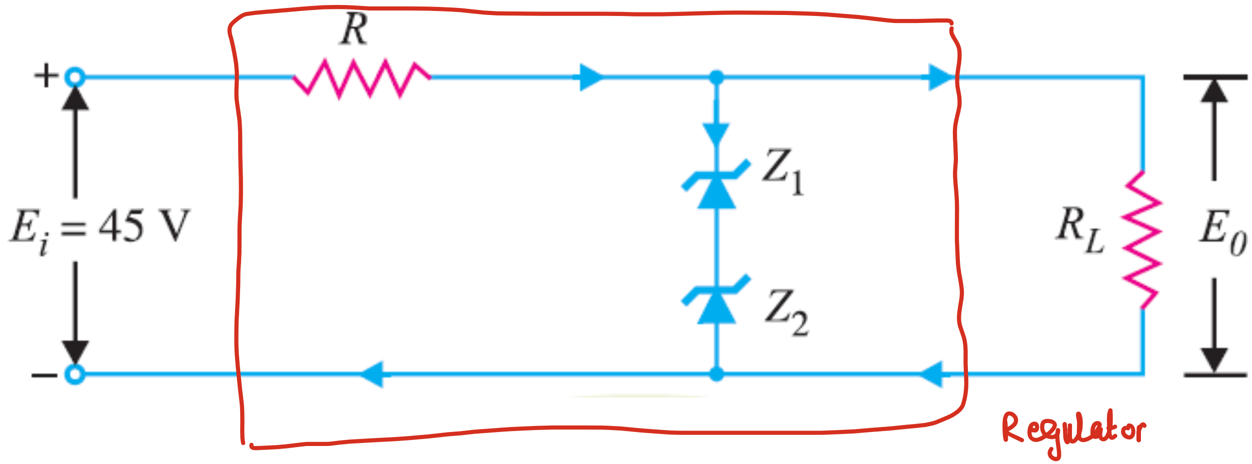
$I_z = 15$, $I_L = 85$

Example 17

example
Q will be submitted on Tue.

The circuit of Fig. 6.66 uses two zener diodes, each rated at 15 V, 200 mA. If the circuit is connected to a 45-volt unregulated supply, determine :

(i) The regulated output voltage *(ii) The value of series resistance R*



In exam may not be given the circuit may be asked about a regulator

$I_z = 2$ mA

$V_z = 15$V

$E_0 = 15 + 15 = 30$ zener ON

$I_{max} = I_z = 200$

$R = \frac{45 - 30}{200m} = 75\ \Omega$ → worst case

R will always have 200m but zener won't

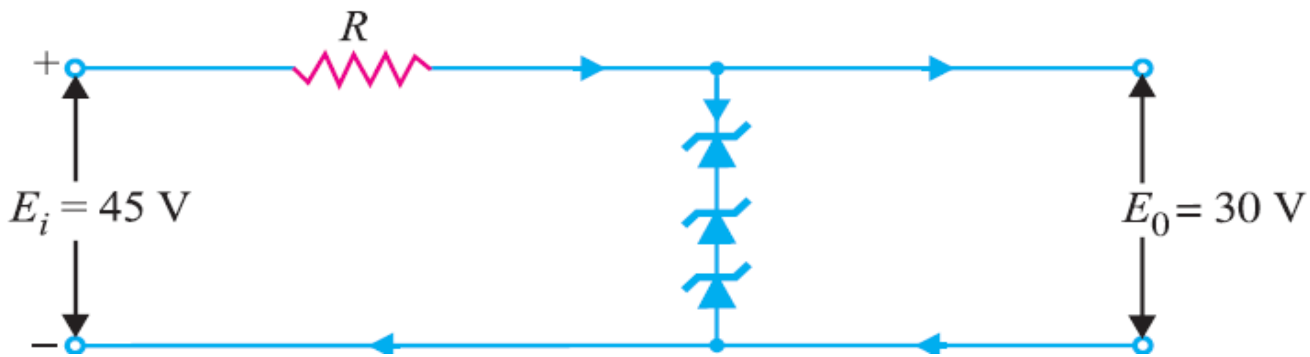
Exam discussion

In exam will be asked to draw the circuit

Example 17

What value of series resistance is required when three 10-watt, 10-volt, 1000 mA zener diodes are connected in series to obtain a 30-volt regulated output from a 45 volt d.c. power source ?

Solution. Fig. 6.67 shows the desired circuit. The worst case is at no load because then zeners carry the maximum current.

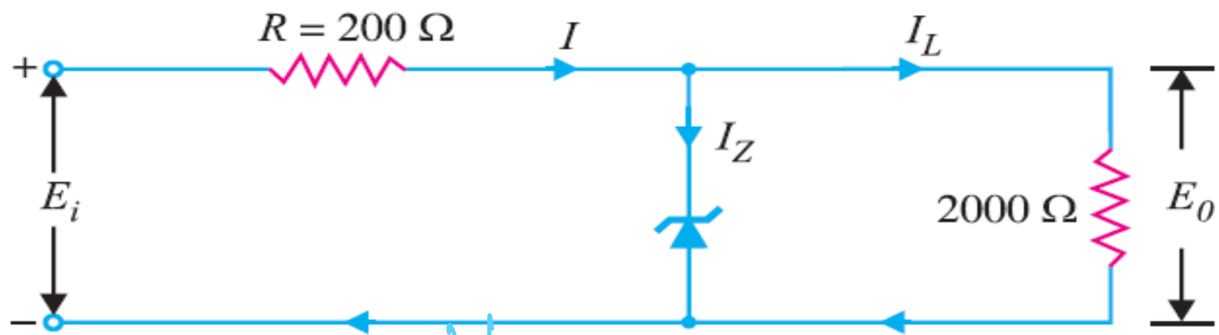


we put 3 zeners here so V=30 how much is R?

here design is on max. current → min. R

Example 18

Over what range of input voltage will the zener circuit shown in Fig. 6.68 maintain 30 V across 2000 Ω load, assuming that series resistance R = 200 Ω and zener current rating is 25 mA ?



$V_0 = 30V$

$R_L = 2000$

$R_s = 200$

$I_Z = \underline{25}$ max

min V

$I_Z = 0$

$I_L = I$

$\frac{30}{2000}$

$30 + \frac{30}{2000}$ 200

$30 + IR$

max V

$I = I_L + I_Z$

$= 15 + 25$

$30 + IR$

$\boxed{IR_s}$

Example 19

In the circuit shown in Fig. 6.69, the voltage across the load is to be maintained at 12 V as load current varies from 0 to 200 mA. Design the regulator. Also find the maximum wattage rating of zener diode.

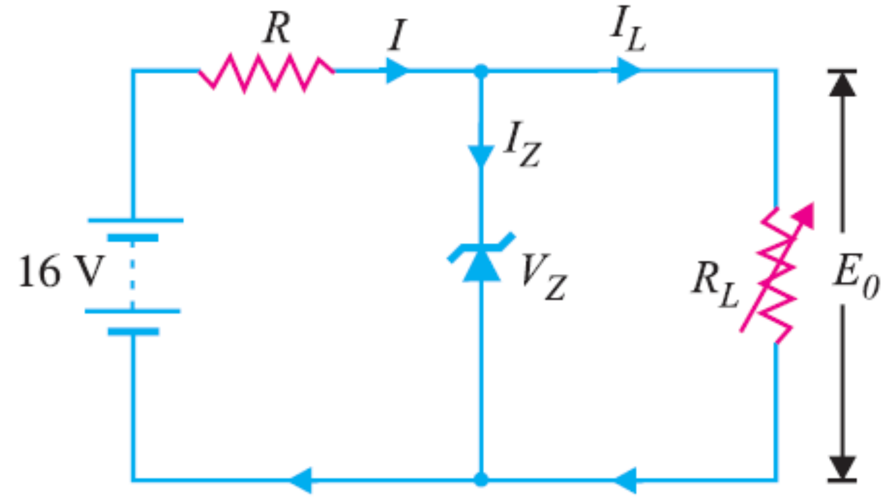


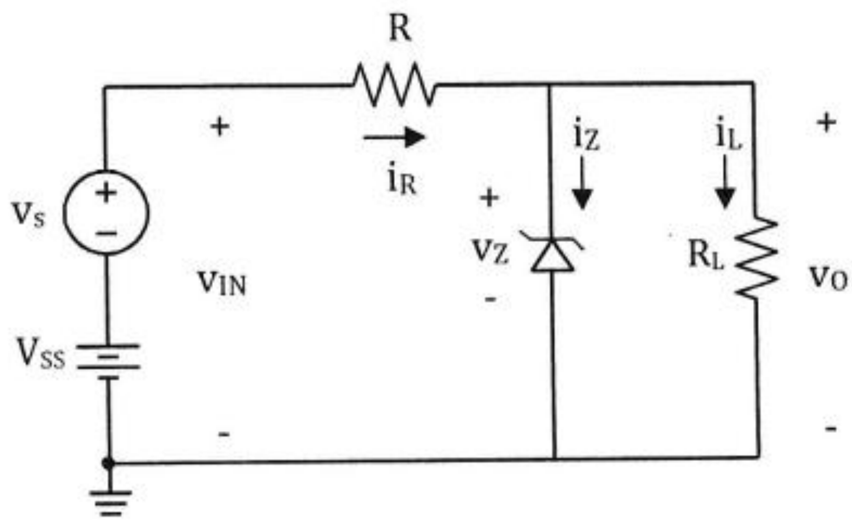
Fig. 6.69

Solution. By designing the regulator here means to find the values of V_Z and R. Since the load voltage is to be maintained at 12 V, we will use a zener diode of zener voltage 12 V *i.e.*,

$$V_Z = \mathbf{12\ V}$$

Example 20

Long very imp. for exam.



<u>Circuit Parameters</u>

V_{SS} = 8 volts

v_S = 0.8 sin $\omega_o t$ volts

R = 100 Ω

R_L = 200 Ω

<u>Zener Diode</u>

V_Z = 3 volts

r_Z = 20 Ω

a) Draw the DC equivalent circuit.

b) Determine the DC component of the output voltage v_O.

c) Determine the DC component of the load current I_L.

d) Draw the AC small signal equivalent circuit.

e) Determine the AC small signal component of the output voltage v_O.

f) Also calculate $V_{ripple\text{-}peak}/V_{DC}$ ratio at the input and output.