CSE251: Electronic Devices and Circuits

Lecture 10 – Zener Diodes

Prepared By:

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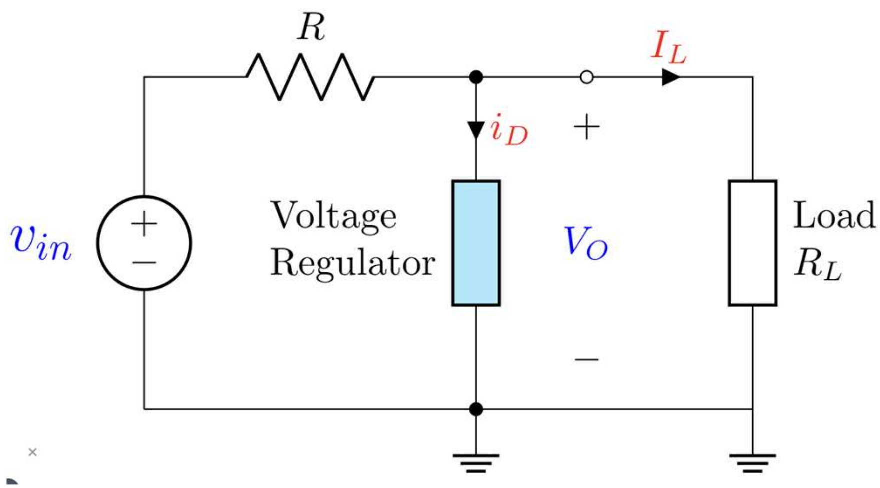
Voltage Regulators

- **Voltage Regulation** is the measure of how well a system can provide near *constant voltage*.

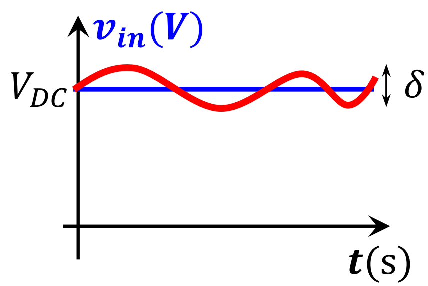
- **Voltage Regulators** provide steady voltage independent of how much power is drawn from the power source

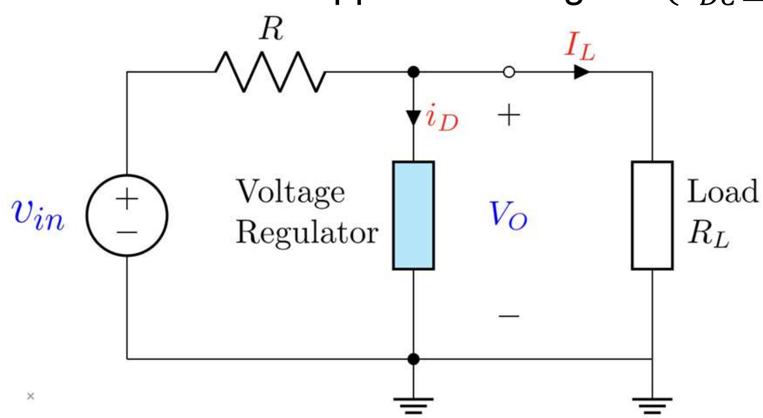


Voltage Regulator:
Tries to maintain a voltage constant at V_O

Voltage Regulators

Let's assume that v_{in} is not a perfect DC source. It supplies a voltage of $(V_{DC} \pm \delta)$ V





Voltage Regulator:

Tries to maintain a voltage constant at V_O **even when v_{in} is varying.**

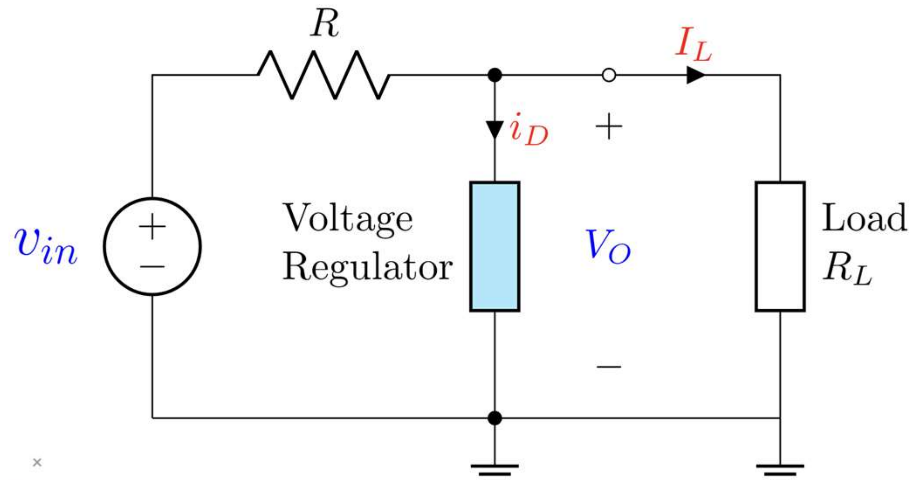
Variables: V_O should remain constant <u>irrespective of the changes</u> in the following quantities:

1. Input Voltage: v_{in} **2. Load Current: I_L** **3. VR current: i_D**

Voltage Regulator – Worst Case Scenario

Worst Case Scenario occurs when the three variables (v_{in}, I_L, and i_D) change in such a way, such that maintaining V_O constant requires the most power (current) from the **Voltage Regulator.**

The **Voltage regulator** is at its maximum capacity at the worst case.

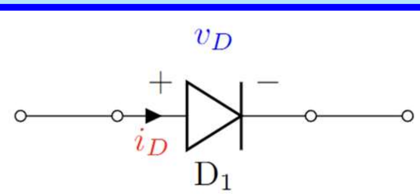


Worst Case Scenario occurs when

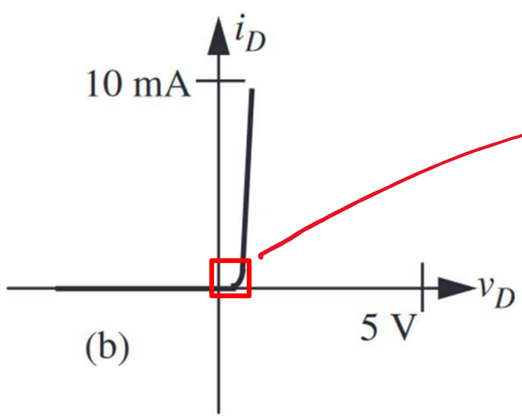
1. **Input Voltage is minimum:** $v_{in}(\text{min})$
2. **Load Current is maximum:** $I_L(\text{max})$
3. **VR current minimum:** $i_D(\text{min})$

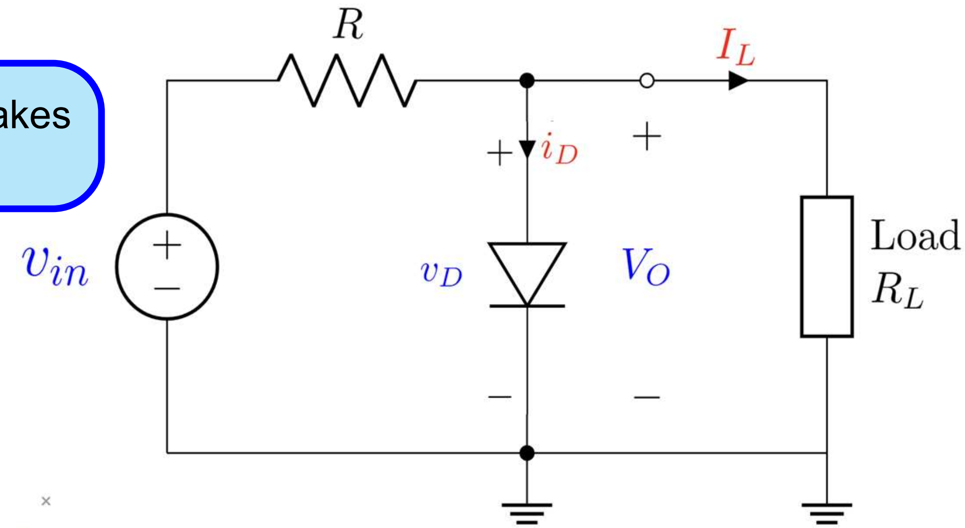
Diodes as Voltage Regulators

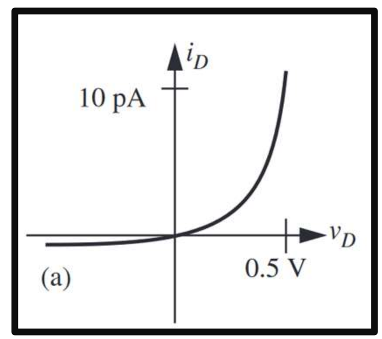
Diodes have (IV) characteristics that makes them ideal for voltage regulation.



Exponential IV characteristics of diodes



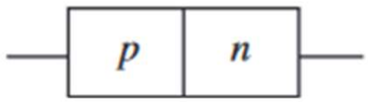


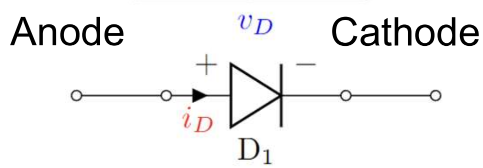


Diodes Revisited

Forward Bias
Net positive Voltage across $p-n$ junction

Reverse Bias
Net negative Voltage across $p-n$ junction

Physical Schematic: 

Circuit Schematic: 

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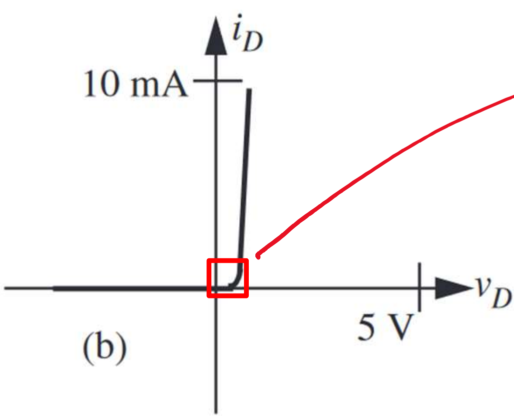
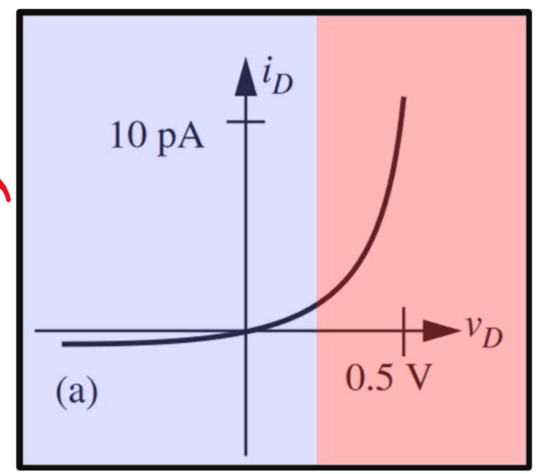




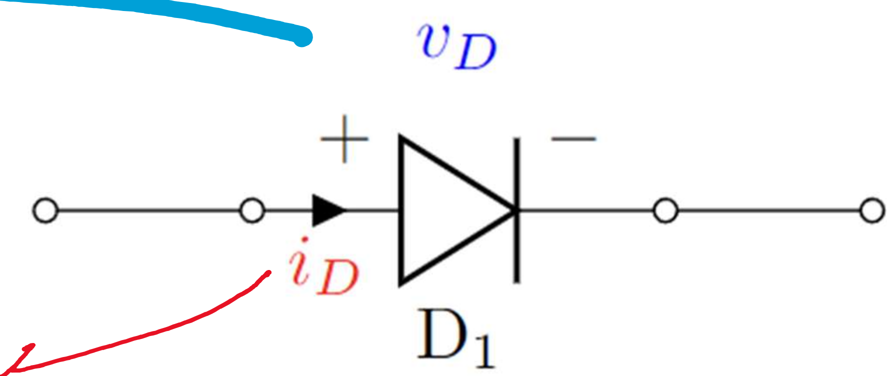
Diodes Revisited

Simple

Increasing Accuracy

Complex

1. Ideal Diode Model:
2. Constant Voltage Drop (CVD) Model:
3. Voltage Source in Series with Resistor Model (CVD+R) Model
4. Exponential Model:



v_D: Total Voltage Across diode
v_d: AC component of the Voltage
V_d: DC component of Voltage

V_{Do}: Diode Cut-off voltage

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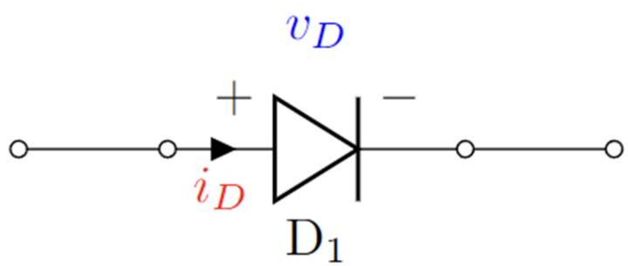
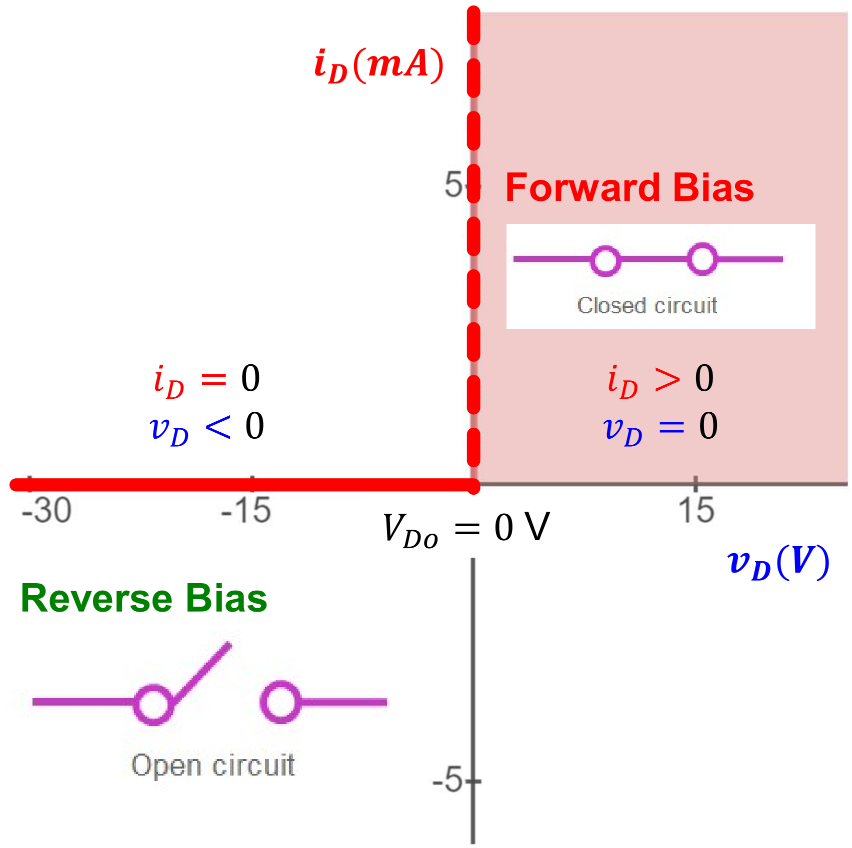
i_D: Total current through diode (Anode to Cathode)

Diode Models

1. Ideal Diode Model:

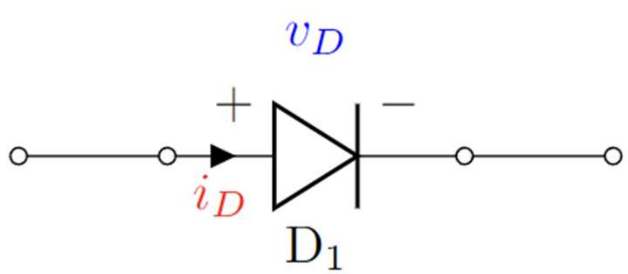


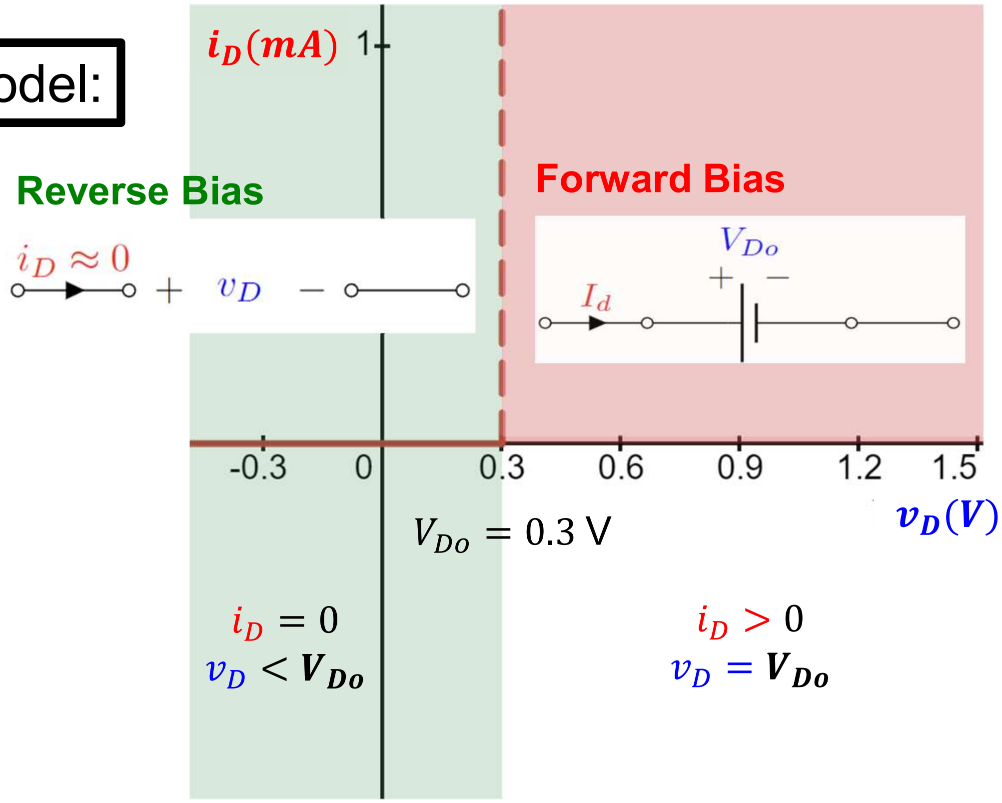
Not suitable as
VOLTAGE REGULATOR



Diode Models

2. Constant Voltage Drop (CVD) Model:





Suitable as
VOLTAGE REGULATOR ?
Maybe!

Diode Models

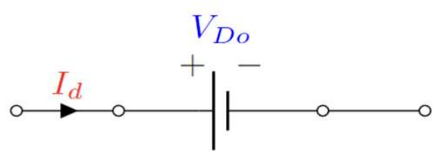
2. Constant Voltage Drop (CVD) Model:

Reverse Bias

$i_D = 0$ $\quad$ $y = 0$

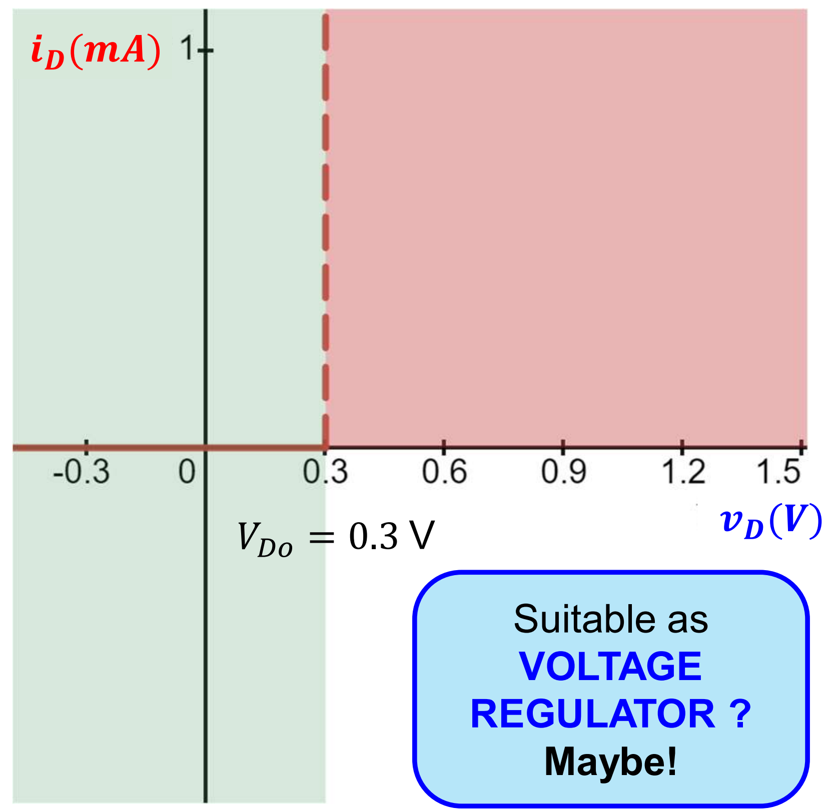
$v_D < V_{Do}$ $\quad$ $x < V_{Do}$

Forward Bias



$i_D > 0$ $\quad$ $y > 0$

$v_D = V_{Do}$ $\quad$ $x = V_{Do}$



Suitable as
VOLTAGE REGULATOR ?
Maybe!

Practice Problem 1

The circuit of the adjacent **Figure** is specified to have the following parameters. The supply voltage $\boldsymbol{V_{in}}$ is nominally $\mathbf{3}$ V but can vary by $\pm\,\mathbf{0.1}\,\boldsymbol{V}$. $\boldsymbol{R_L}$ can draw a maximum of $\mathbf{10}$ mA and $\boldsymbol{i_D}(\text{min}) = \mathbf{1}$ mA.

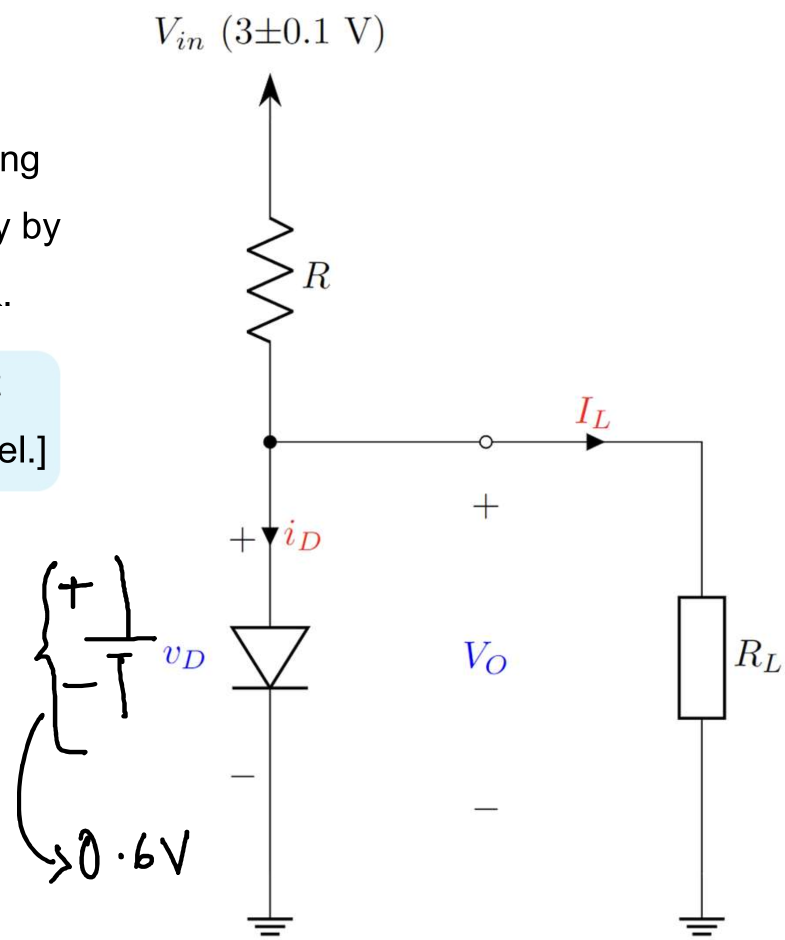
What is $\boldsymbol{R}$ for worst case scenario if $\boldsymbol{v_D}$ ($\boldsymbol{V_O}$) is to be regulated at $\mathbf{0.6}$ V? [Since r_o is not provided, you can consider the CVD model.]

Solution:

Worst Case Scenario occurs when

1. $\boldsymbol{v_{in}}(\text{min}) = \mathbf{3} - \mathbf{0.1}\text{ V} = \mathbf{2.9}\text{ V}$
2. $\boldsymbol{I_L}(\text{max}) = \mathbf{10}\text{ mA}$
3. $\boldsymbol{i_D}(\text{min}) = \mathbf{1}\text{ mA}$

$$\frac{v_{in}(min) - 0\cdot 6}{R} = I_L(max) + i_D(min)$$



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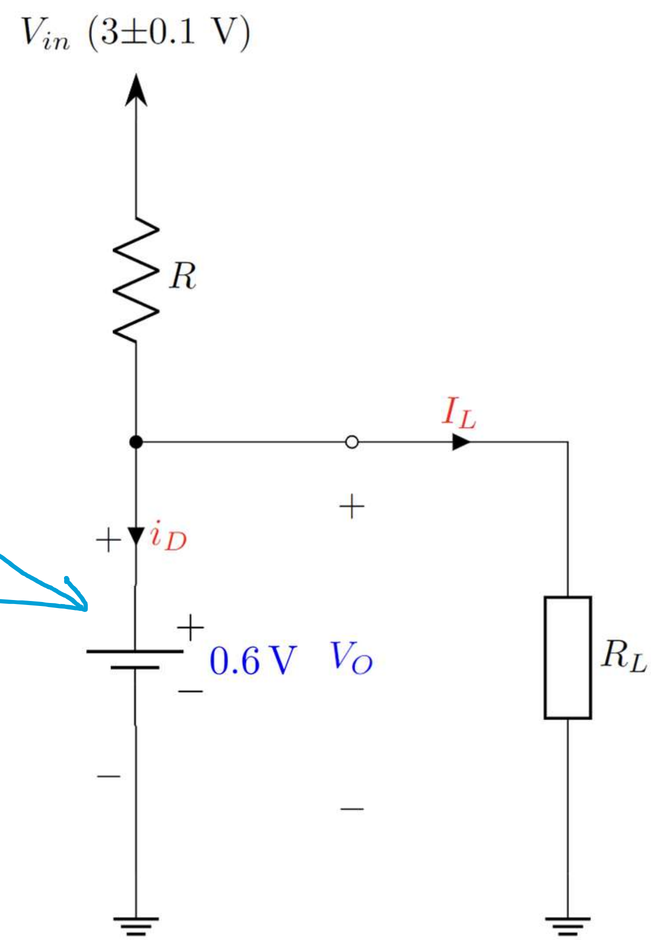


Solution:

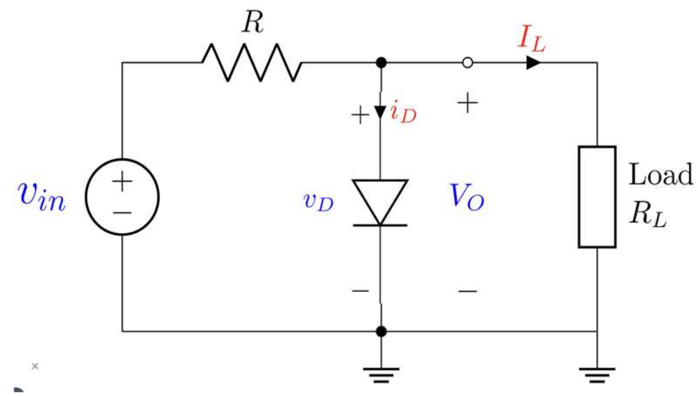
$$\frac{v_{in}(\text{min}) - 0.6}{R} = I_L(\text{max}) + i_D(\text{min})$$

$$R = \frac{2.9 - 0.6}{10 + 1}\ \text{k}\Omega = 0.209\ \text{k}\Omega$$

$$\therefore R = 209\ \Omega$$

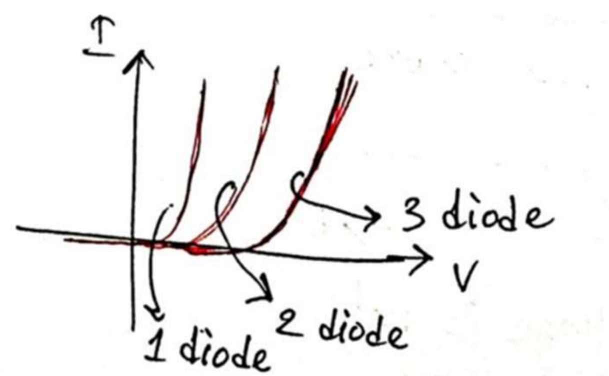
Drawbacks of Diodes as Voltage Regulators

- **Regulation voltage is low:** $\sim \boldsymbol{V_{DO}}$ $(0.3 \sim 1\ \mathrm{V})$
- **High** $\boldsymbol{i_D}(\min)$
- $\boldsymbol{R}$ **can be low → High power loss**



Possible Solution:

Stacked Diodes in Series: -- Regulation Voltage can be increased to $\boldsymbol{n} \cdot \boldsymbol{V_{DO}}$ for $\boldsymbol{n}$ stacked diodes.



However, this can make the diodes deviate more from ideal model. **IV characteristics** become flatter (more lossy).

Drawbacks of Diodes as Voltage Regulators

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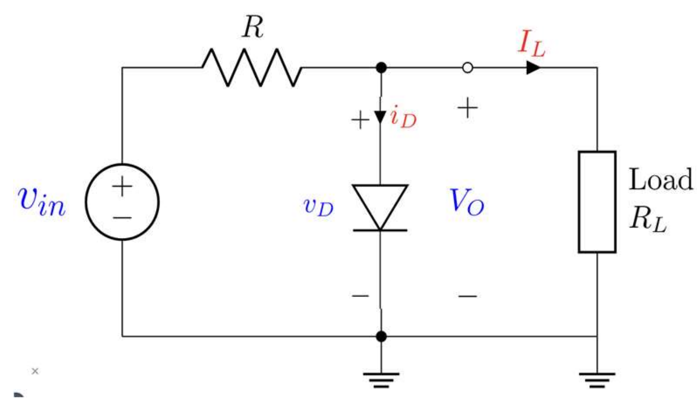


Better Solution:

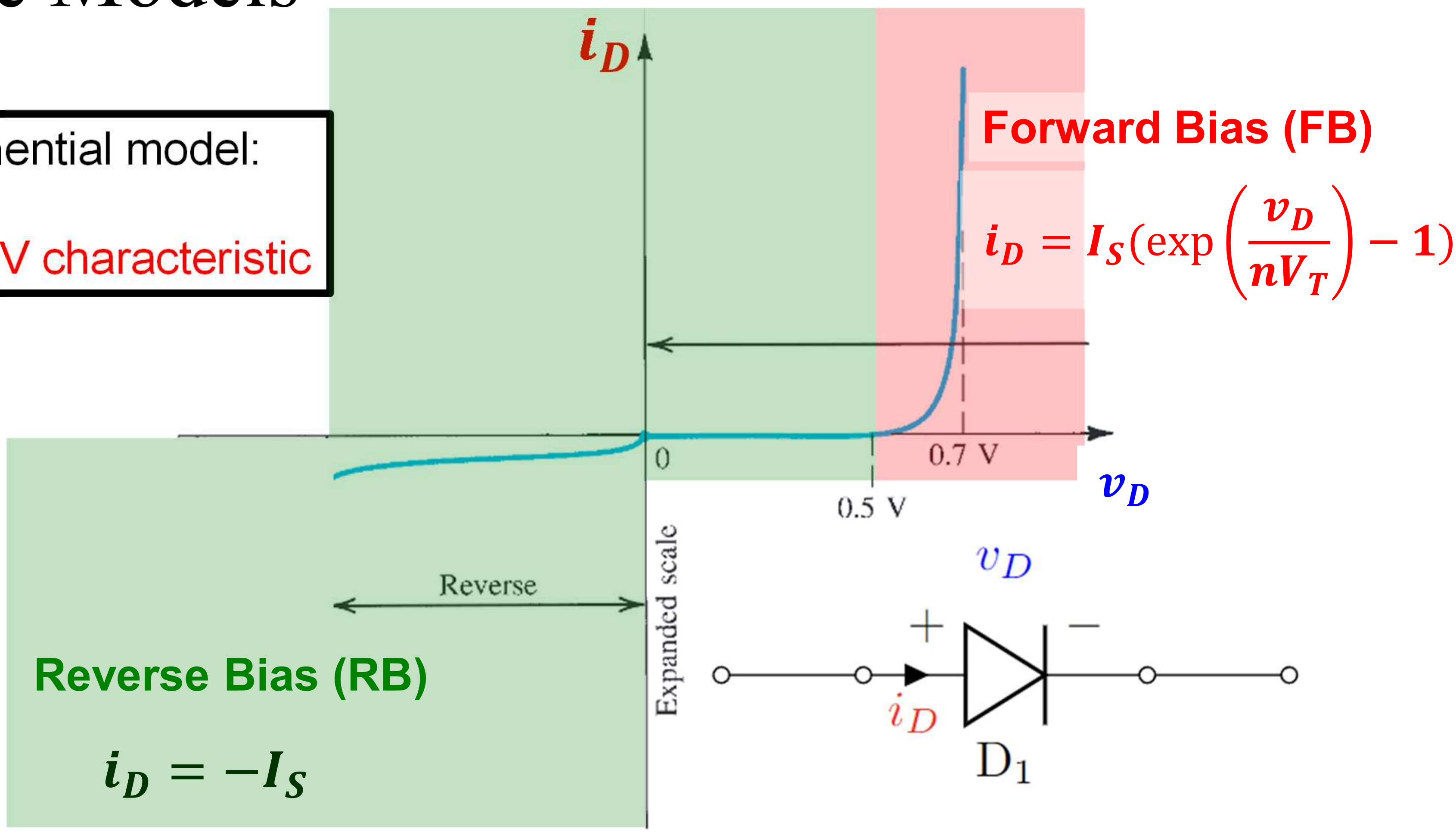
Use **Breakdown Region** of diodes as constant voltage source because:

1. **Breakdown Voltage** can be controlled during fabrication
2. $\boldsymbol{i_D}(\mathrm{min})$ for reverse breakdown is very low!

Diode Models

4. Exponential model:

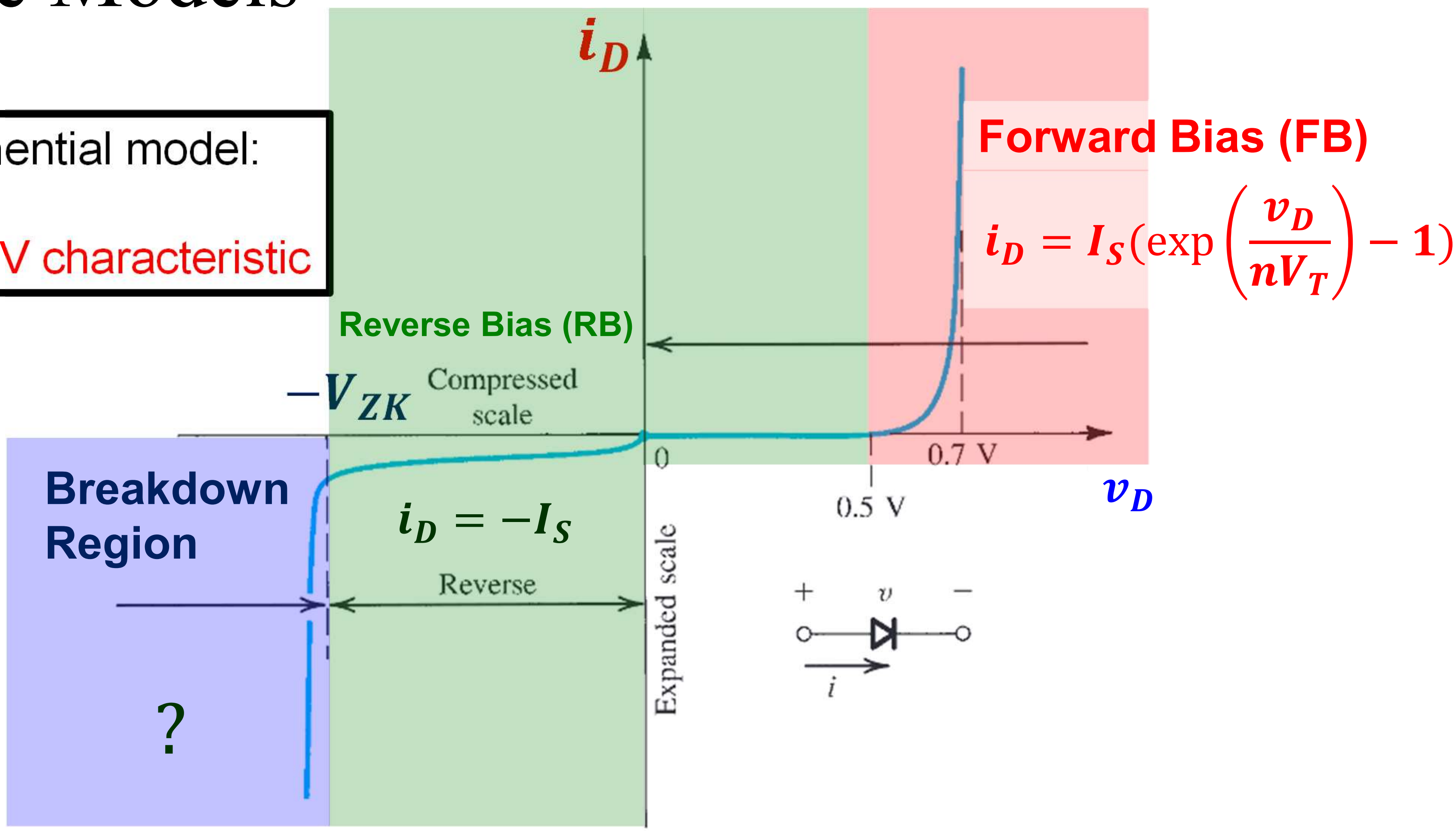
The full IV characteristic



Diode Models

4. Exponential model:

The full IV characteristic



Diode IV Characteristic

Reverse Bias (RB)

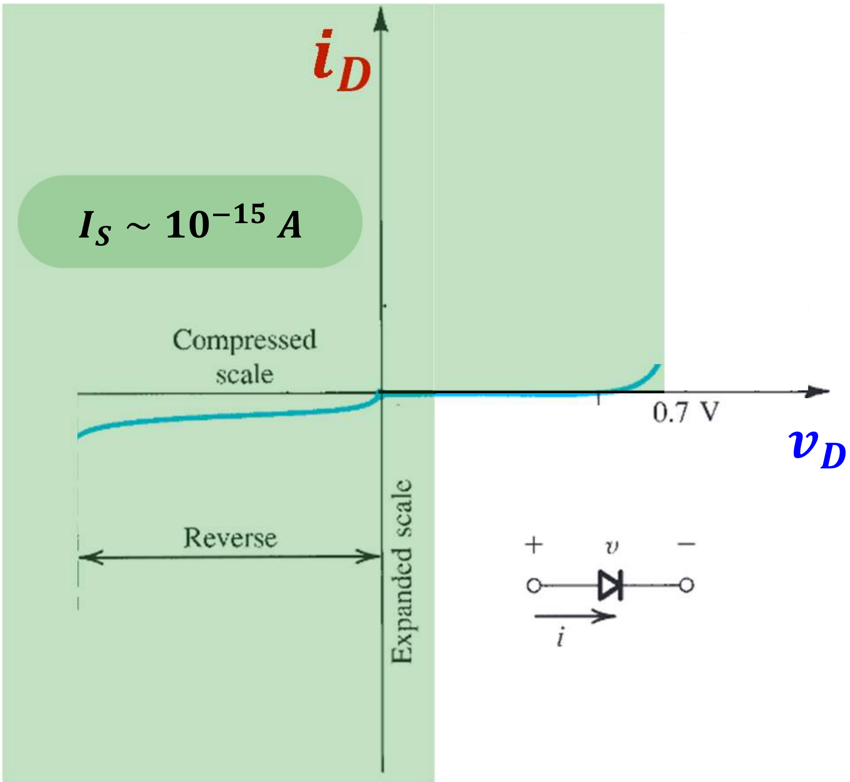
$i_D = -I_S$

I_S in this case is the reverse leakage current.

$y = -I_S$

For $v_D < V_{DO}$ there is negligible current flow through the diode.

Normal diodes cannot tolerate large voltages in reverse bias. **Applying large voltages in reverse bias may damage the diode**.



Diode IV Characteristic

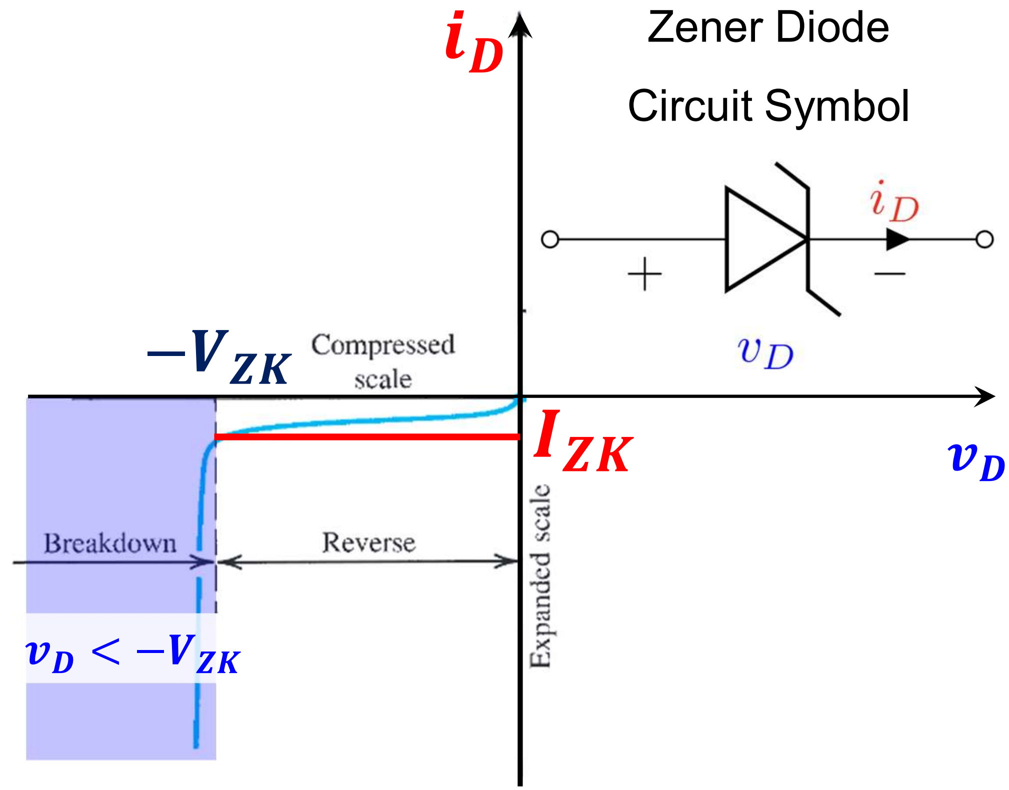
Breakdown Region

Normal diodes cannot tolerate large voltages in reverse bias. **Applying large voltages in reverse bias may damage the diode**.

Special classes of diodes exist, that are primed to operate in large reverse bias voltages. These diodes are called

Zener diodes

In this **Breakdown region**, the diode acts almost like a **“constant voltage source”.**



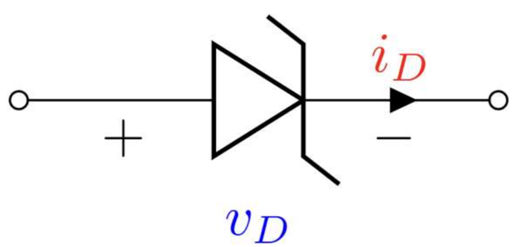
Zener Diode IV

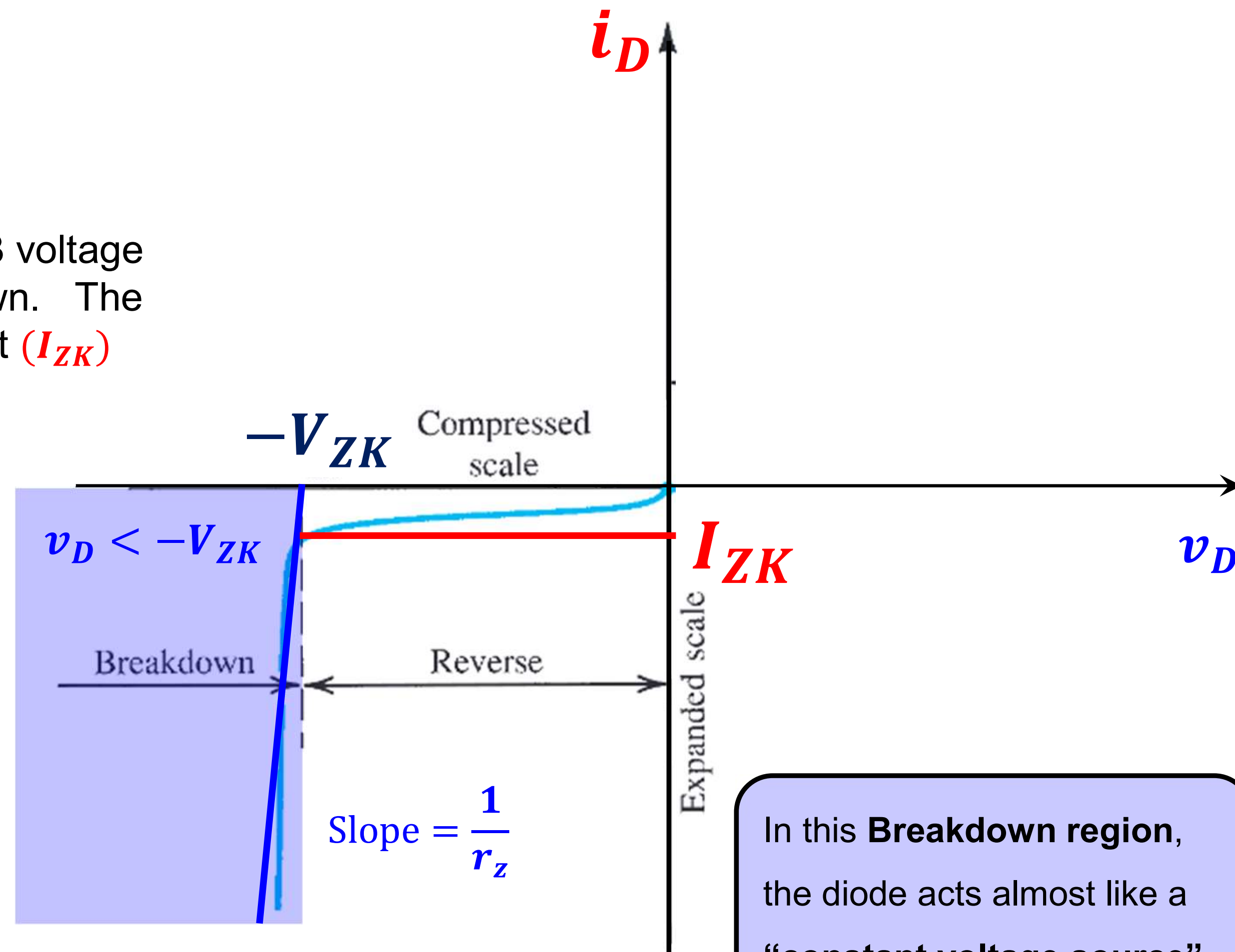
Breakdown Region

Zener knee voltage ($-V_{ZK}$): The RB voltage beyond which diode breaks down. The corresponding current is knee current (I_{ZK})

For $v_D < -V_{ZK}$,

$$\text{Slope} = \frac{1}{r_z}$$





In this **Breakdown region**, the diode acts almost like a **"constant voltage source".**

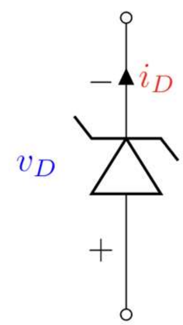
Zener Diode IV

Breakdown Region

Since this region is like the forward bias region of a normal diode, we **invert the signs of voltage and currents** across a Zener diode operating at breakdown voltage, to solve Zener diode circuits in a similar way.

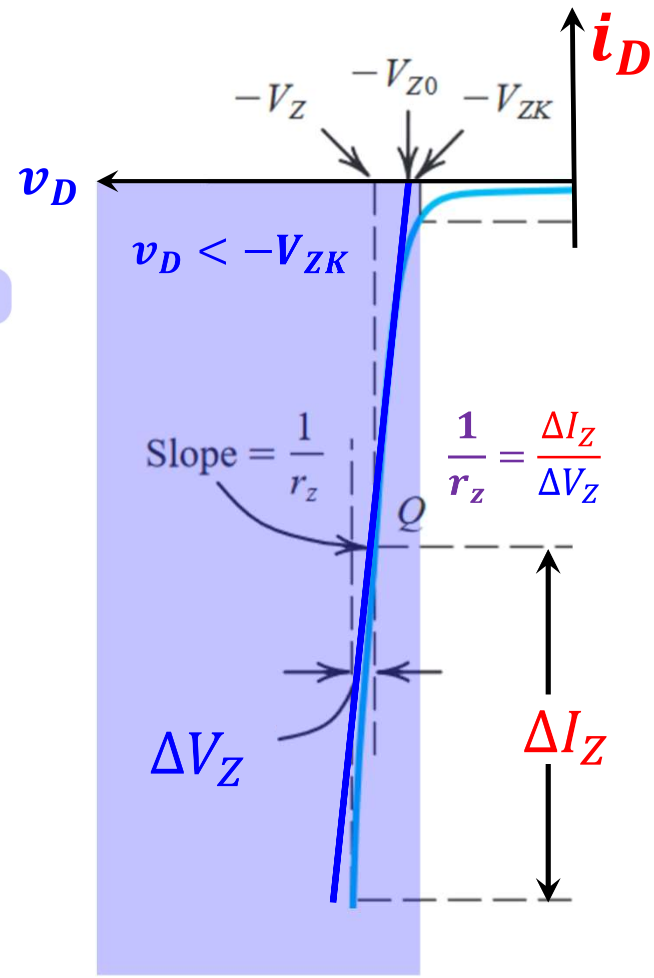
For a voltage of $-V_Z$, the diode allows a breakdown current of $-I_Z$.

The slope at this point of the graph is $\frac{1}{r_z}$



$V_Z = -v_D$
$I_Z = -i_D$

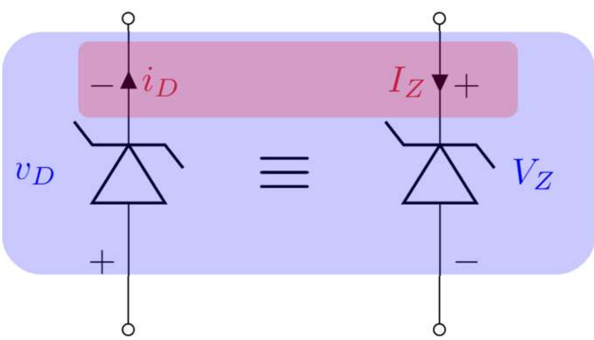
If we extrapolate a straight line from $(-V_Z, -I_Z)$ point, and extend it towards the x –**axis**, ($i_D = 0$ **A**), the intersecting point is V_{Z0}. $(V_{ZK} \approx V_{Z0})$

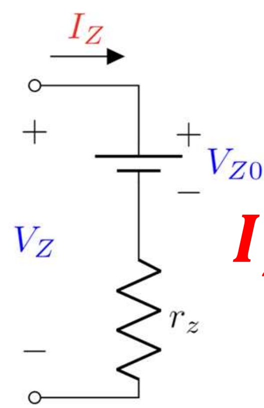


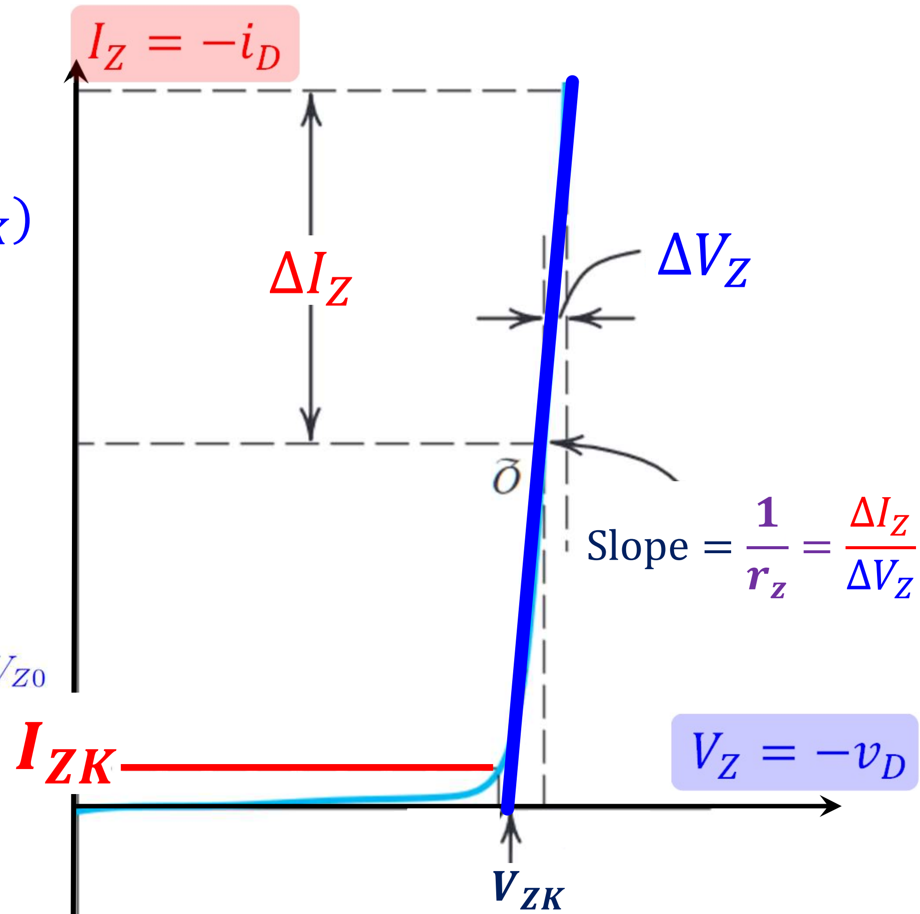
Zener Diode IV

Breakdown Region $(V_Z > V_{Z0} \approx V_{ZK})$

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



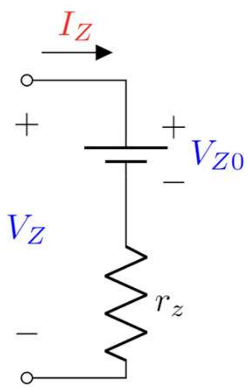




In this **Breakdown region**, the diode acts almost like a **"constant voltage source"**.

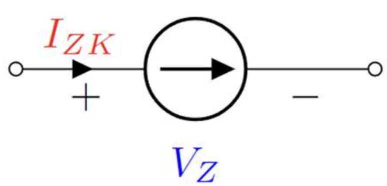
Zener Diode Breakdown IV Characteristic

Breakdown Region $(V_Z > V_{Z0} \approx V_{ZK})$



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

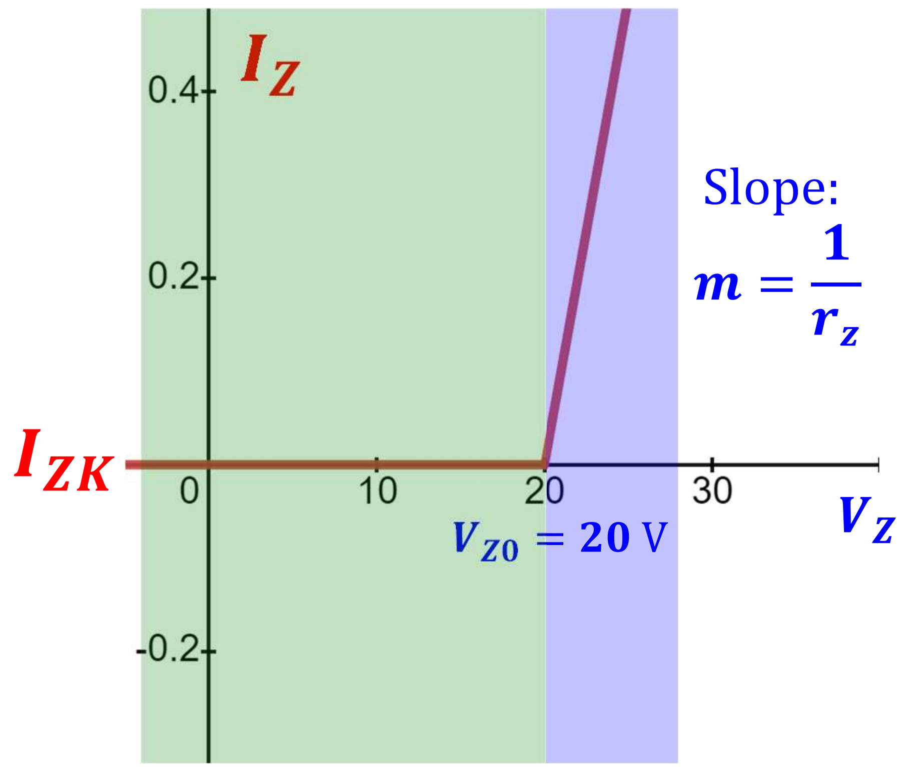
Reverse Bias Region $(V_Z < V_{Z0} \approx V_{ZK})$



$$I_Z = I_{ZK}$$

V_Z: Total RB Voltage Across **Zener** diode

V_{Z0}: Zener knee voltage



Practice Problem 2

The $6.8 - V$ Zener diode in the circuit of **Figure** is specified to have the following parameters. The supply voltage V^+ is nominally $\mathbf{10\ V}$ but can vary by $\pm\mathbf{1\ V}$.

$V^+ = 10 \pm 1\,V$

$V_Z = 6.8\,V$ at $I_Z = 5\,mA$
$r_z = 20\,\Omega.$
$I_{ZK} = 0.2\,mA.$

(a) Find V_0 with no load and with V^+ at its nominal value

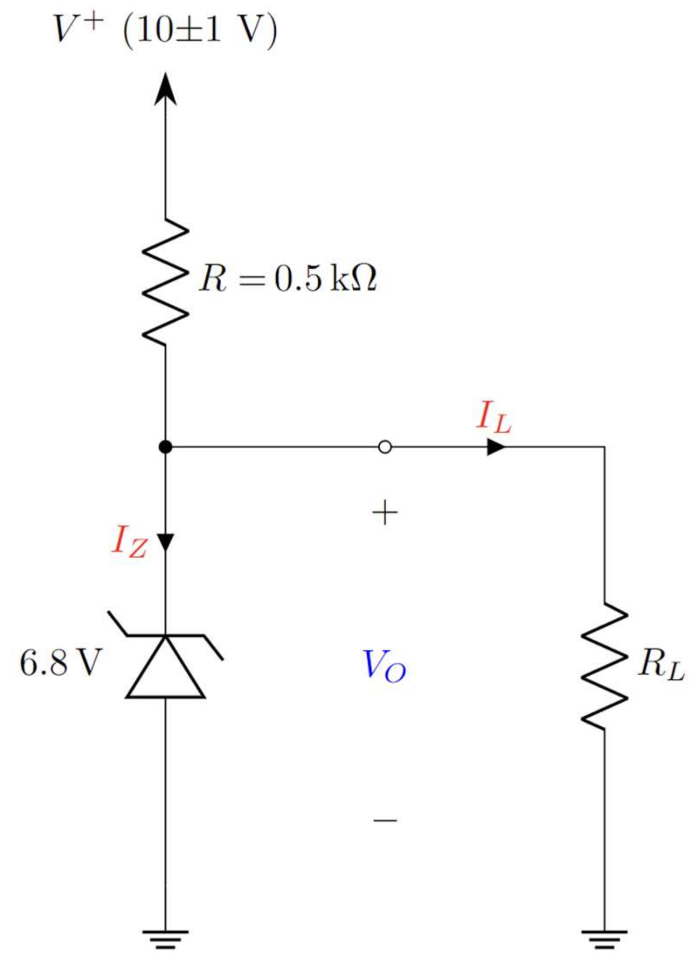
(b) (For $\boldsymbol{R_L = 0.5\ \mathrm{k\Omega}}$). Find the $\boldsymbol{I_Z}$. In this scenario, calculate the Zener voltage $\boldsymbol{V_O}$, load current $\boldsymbol{I_L}$ and input current $\boldsymbol{I}$

(c) Find the $\boldsymbol{R_L}$ that would give rise to worst-case scenario at worst case V^+. In this worst-case scenario, calculate the Zener voltage $\boldsymbol{V_Z}$, load current $\boldsymbol{I_L}$ and input current $\boldsymbol{I}$

(d) (For $\boldsymbol{R_L = 2\ \mathrm{k\Omega}}$). Find the $\boldsymbol{I_Z}$. In this scenario, calculate the Zener voltage $\boldsymbol{V_O}$, load current $\boldsymbol{I_L}$ and input current $\boldsymbol{I}$

(e) Design the circuit, i.e., find the minimum value of the input voltage $\boldsymbol{V^+}$ such that, voltage regulation is maintained even in the worst-case scenario for $\boldsymbol{R_L} = 2\ \mathrm{k\Omega}$. (Forget that $\boldsymbol{V^+}$ is 10 V)

(f) Determine whether the circuit will maintain regulation if $\boldsymbol{V^+}$ is increased. If yes, argue if it should be increased or not.



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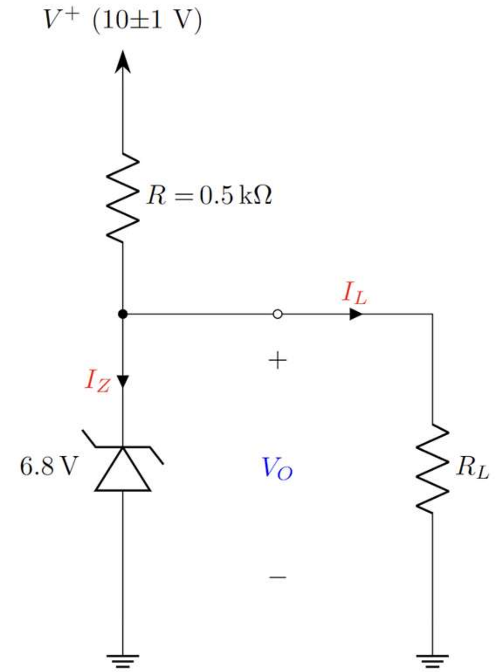
$V^+ = 10 \pm 1\,V$

$V_{Z1} = 6.8\,V$ at $I_{Z1} = 5\,mA$

$r_z = 20\ \Omega = 0.02\ \text{k}\Omega.$

$I_{ZK} = 0.2\,mA.$



(a) Find V_0 with no load and with V^+ at its nominal value

Practice Problem 2

The $6.8 - V$ Zener diode in the circuit of **Figure** is specified to have the following parameters. The supply voltage V^+ is nominally $\mathbf{10\ V}$ but can vary by $\pm\mathbf{1\ V}$.

$V^+ = 10 \pm 1\,V$

$V_{Z1} = 6.8\,V$ at $I_{Z1} = 5\,mA$

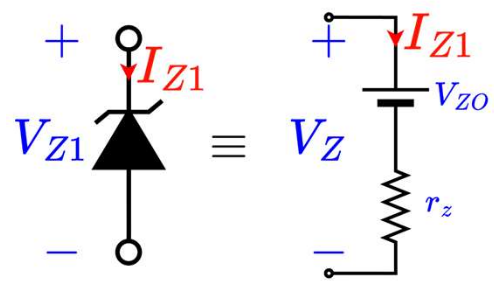
$r_z = 20\,\Omega = 0.02\,\text{k}\Omega.$

$I_{ZK} = 0.2\,mA.$

(a) Find V_0 with no load and with V^+ at its nominal value

Solution:

Extracting Zener diode 's reverse cut-in voltage



$$V_{ZO} = 6.8 - 5 \times 0.02\ \text{V}$$
$$\therefore V_{ZO} = 6.7\ \text{V}$$

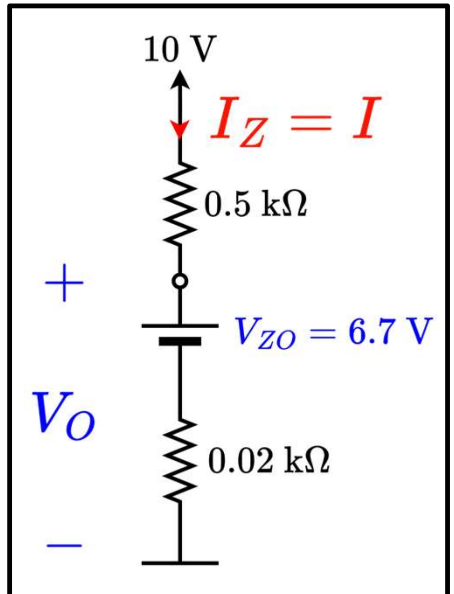
Determining current from the 10 V source

$$I = \underline{\qquad\qquad}$$

$$I = \frac{10 - 6.7}{0.5 + 0.02}\,\text{mA} = 6.346\ \text{mA}$$

Determining output voltage

$$V_O = 6.7 + 6.346 \times 0.02\ \text{V}$$
$$V_O = 6.82692\ \text{V}$$



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(b) (For $\boldsymbol{R_L} = \mathbf{0.5}\ \mathbf{k\Omega}$). Find the $\boldsymbol{I_Z}$. In this scenario, calculate the Zener voltage $\boldsymbol{V_O}$, load current $\boldsymbol{I_L}$ and input current $\boldsymbol{I}$

Solution:

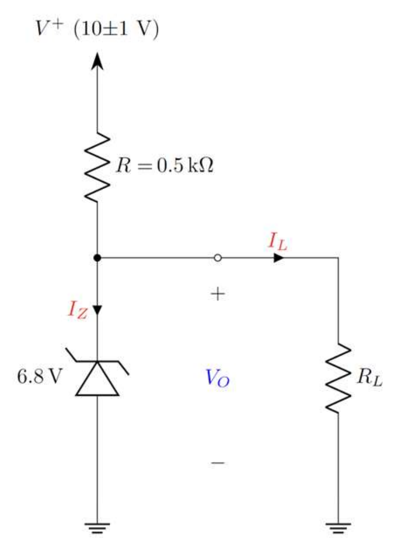
$V^+ = 10 \pm 1\,V$

$\cancel{V_Z = 6.8\,V \text{ at } I_Z = 5\,mA}$

$\boldsymbol{V_{ZO}} = \mathbf{6.7\ V}$

$r_z = 20\ \Omega.$

$I_{ZK} = 0.2\ mA.$



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The $6.8-V$ Zener diode in the circuit of **Figure** is specified to have the following parameters. The supply voltage V^+ is nominally $\mathbf{10\ V}$ but can vary by $\pm\mathbf{1\ V}$.

$V^+ = 10 \pm 1\,V$

~~$V_Z = 6.8\,V$ at $I_Z = 5\,mA$~~

$\mathbf{V_{ZO} = 6.7\ V}$

$r_z = 20\,\Omega.$

$I_{ZK} = 0.2\,mA.$

(b) (For $\mathbf{R_L = 0.5\ k\Omega}$). Find the $\mathbf{I_Z}$. In this scenario, calculate the Zener voltage $\mathbf{V_O}$, load current $\mathbf{I_L}$ and input current $\mathbf{I}$

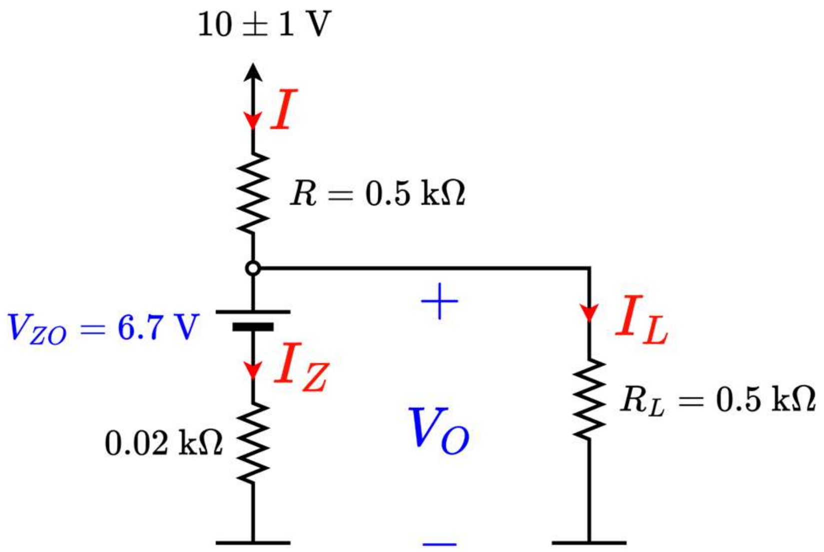
Solution:

Solving the node equation at $\mathbf{V_O}$.

$$\frac{(10 \pm 1) - V_O}{R} = \frac{V_O - V_{ZO}}{r_z} + \frac{V_O}{R_L}$$

$$\frac{(10 \pm 1) - V_O}{0.5} = \frac{V_O - 6.7}{0.02} + \frac{V_O}{0.5}$$

$$\therefore V_O = 6.537 \sim 6.611\text{ V}$$



As, $V_O < V_{ZO}$, the Zener diode will not be in reverse breakdown mode, but in cut off

$$I_Z = I_{ZK}$$

Practice Problem 2

The $6.8 - V$ Zener diode in the circuit of **Figure** is specified to have the following parameters. The supply voltage V^+ is nominally $\mathbf{10\ V}$ but can vary by $\pm\mathbf{1\ V}$.

$V^+ = 10 \pm 1\,V$

~~$V_Z = 6.8\,V$ at $I_Z = 5\,mA$~~

$\boldsymbol{V_{ZO} = 6.7\ \mathrm{V}}$

$r_z = 20\ \Omega.$

$I_{ZK} = 0.2\,mA.$

(b) (For $\boldsymbol{R_L = 0.5\ \mathrm{k\Omega}}$). Find the $\boldsymbol{I_Z}$. In this scenario, calculate the Zener voltage $\boldsymbol{V_O}$, load current $\boldsymbol{I_L}$ and input current $\boldsymbol{I}$

Solution:

$$\therefore V_O = 6.537 \sim 6.611\ \mathrm{V}$$

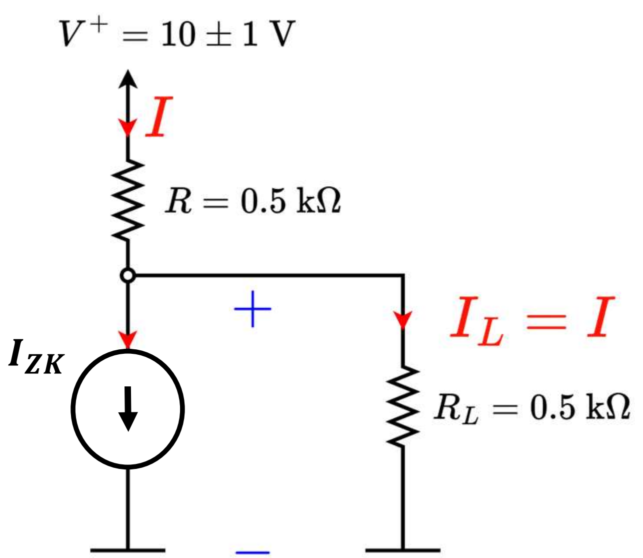
As, $V_O < V_{ZO}$, the Zener diode will not be in reverse breakdown mode, but in cut off

$$\boldsymbol{I_Z = I_{ZK}}$$

So,

$$V_O\left(\frac{1}{0.5} + \frac{1}{0.5}\right) = \frac{10 \pm 1}{0.5} - 0.2$$
$$V_O = 4.95 \pm 0.5\ \mathrm{V}$$

$$I_L = \frac{V_O}{R_L} = \frac{4.95 \pm 0.5}{0.5}\ \mathrm{mA} = 9.9 \pm 1\ \mathrm{mA}$$



(c) Find the $\boldsymbol{R_L}$ that would give rise to worst-case scenario at worst case V^+. In this worst-case scenario, calculate the Zener voltage $\boldsymbol{V_Z}$, load current $\boldsymbol{I_L}$ and input current $\boldsymbol{I}$

(d) (For $\boldsymbol{R_L} = \mathbf{2\ k\Omega}$). Find the $\boldsymbol{I_Z}$. In this scenario, calculate the Zener voltage $\boldsymbol{V_O}$, load current $\boldsymbol{I_L}$ and input current $\boldsymbol{I}$

(c) The determining factor for worst-case scenario:

$I_z \geq I_{zk}$

$\therefore$ At $I_z = I_{zk}$ mA.

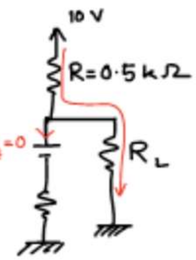
$V_o = V_{z0} + I_{zk} r_z = 6.704\ \text{V}$

$\therefore\ I = I_L + I_z$.

(Since $I_z = I_{zk}$)

$\therefore\ I_L = I - I_{zk}$

$\therefore\ I_L \leq I - I_{zk}$



$\dfrac{V_o}{R_L} \leq \dfrac{V^+ - V_o}{R} - I_{zk}$

$R_L \geq \dfrac{6.704}{\frac{9-6.704}{0.5} - 0.2}\ \text{k}\Omega$

$R_L \geq 1.526\ \text{k}\Omega$

$\boxed{R_L \geq 1.526\ \text{k}\Omega}$

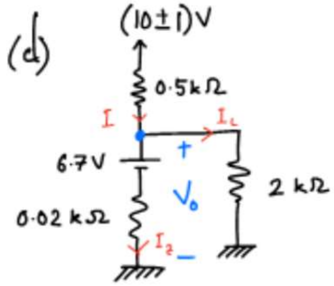
$V_o = 6.704\ \text{V}$

$I_L \leq \dfrac{V_o}{R_L} = \boxed{4.392\ \text{mA}}$

$I \geq I_L + I_{zk}$

$\boxed{I \geq 4.592\ \text{mA}}$

(d)



$I = I_z + I_L$

$\dfrac{V^+ - V_o}{R} = \dfrac{V_o - V_{z0}}{r_z} + \dfrac{V_o}{R_L}$

$\Rightarrow V_o\left(\dfrac{1}{R} + \dfrac{1}{r_z} + \dfrac{1}{R_L}\right) - V_{z0}\left(\dfrac{1}{r_z}\right) = \dfrac{10}{R}$

$\Rightarrow V_o\left(\dfrac{1}{0.5} + \dfrac{1}{2} + \dfrac{1}{0.02}\right) = \dfrac{10}{0.5} + \dfrac{6.7}{0.02}$

$\Rightarrow V_o = \dfrac{355}{54}\ \text{V} = 6.76\ \text{V}$

$I_z = \dfrac{V_o - V_{z0}}{r_z} = \dfrac{6.76 - 6.7}{0.02} = 3.1\ \text{mA} > I_{zk}$

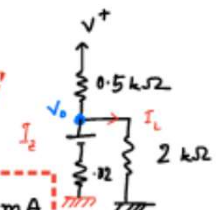
So, the zener diode can sustain this load.

$\therefore$

$V_o = 6.76\ \text{V}$

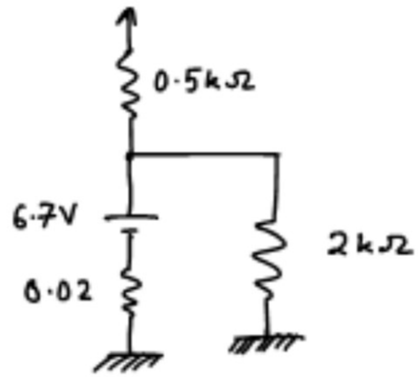
$I_z = 3.1\ \text{mA}$

$I_L = \dfrac{6.76}{2}\ \text{mA} = 3.38\ \text{mA}$



(e) Design the circuit, i.e., find the minimum value of the input voltage V^+ such that, voltage regulation is maintained even in the worst-case scenario for $R_L = 2\ \mathrm{k\Omega}$. (Forget that V^+ is 10 V)

(e)



At worst case : $I_z = I_{zk}$

$\therefore V_o = V_{z0} + I_{zk} r_z$

$= 6.7 + 0.2 \times 0.02 = 6.704\ \mathrm{V}$

For $R_L = 2k\Omega$

$I_L = \frac{6.704}{2} = 3.352\ \mathrm{mA}$

$I = I_L + I_{zk}$

$\boxed{I = 3.552\ \mathrm{mA}}$

$\therefore V^+ \geq V_o + IR$

$\boxed{V^+ \geq 8.48\ \mathrm{V}}$

Solving Problems

Modifiable Parameters

Circuit parameters .

$\boldsymbol{R, R_L}$

Zener diode parameters

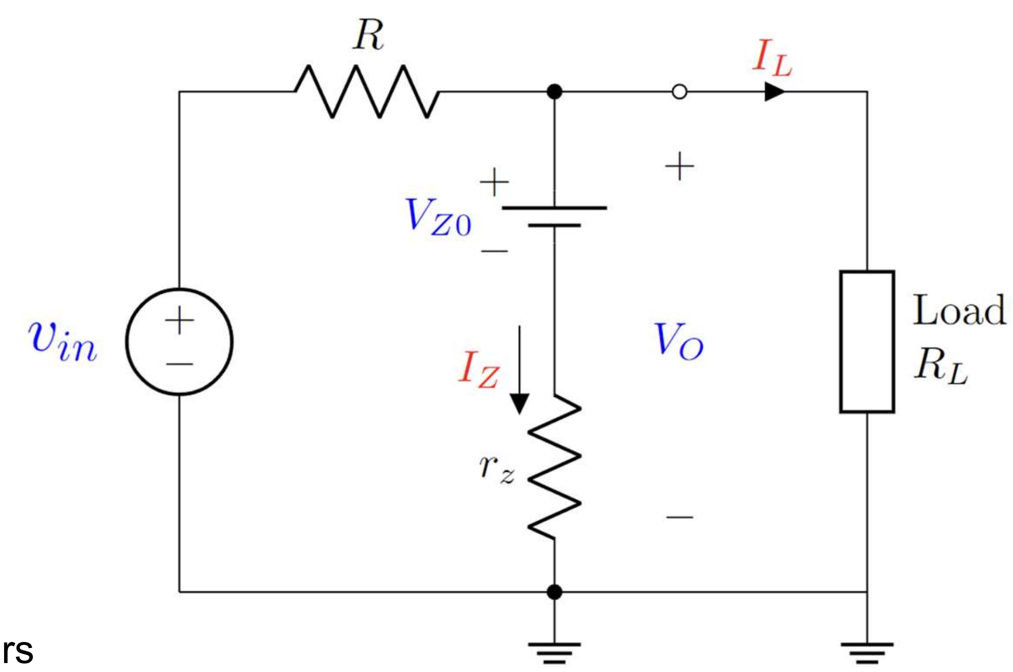
$\boldsymbol{V_{Z0}}$.

$\boldsymbol{r_z}$

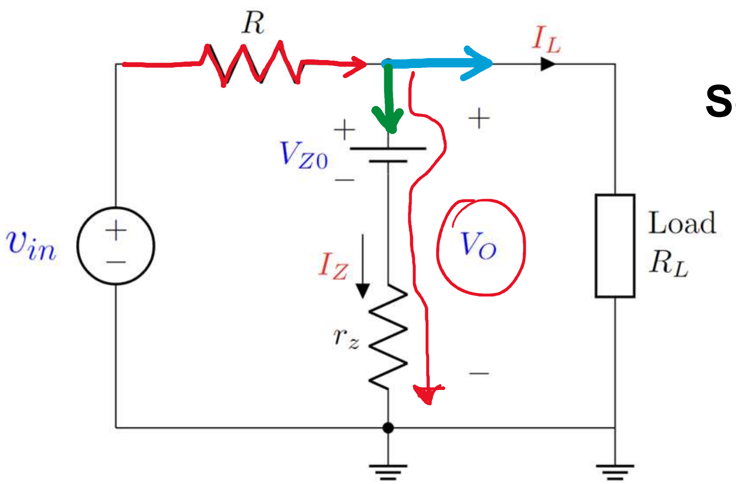
Worst-Case Parameters

$\boldsymbol{I_{ZK}}$

Fixed Parameters



Measures of Worst-Case Scenario (General)



Solving:

$$V_O = V_{ZO} + I_Z r_z$$

$$I_Z = \frac{V_O - V_{ZO}}{r_Z}$$

Minimum Current through VR:

$$I_Z(\text{min}) \geq I_{ZK}$$

$$\frac{V_O - V_{ZO}}{r_Z} \geq I_{ZK}$$

$$\boxed{V_O \geq V_{ZO} + I_{ZK} r_z}$$

Minimum Input Voltage:

$$v_{in}(\text{min}) > V_{ZO} + I_{ZK}(r_z + R) + I_L R$$

Maximum Load Current

$$I_L(\text{max}) \leq \frac{v_{in} - V_O}{R} - I_{ZK}$$

Worst Case Scenario occurs when

1. **Input Voltage is minimum:** $v_{in}(\text{min})$
2. **Load Current is maximum:** $I_L(\text{max})$
3. **VR current minimum:** $I_Z(\text{min})$

Some important tips

- If V_{ZK}, V_{ZO} and r_Z are given, we can calculate $I_{ZK} = \frac{V_{ZK} - V_{ZO}}{r_z}$
- If V_{ZO} and r_Z are **not** provided, consider $V_{ZK} = V_Z = V_{ZO}$
- Consider $I_{ZK} = 0$ if not provided