ECE 65: Components & Circuits Lab

Lecture 5

Zener Diode

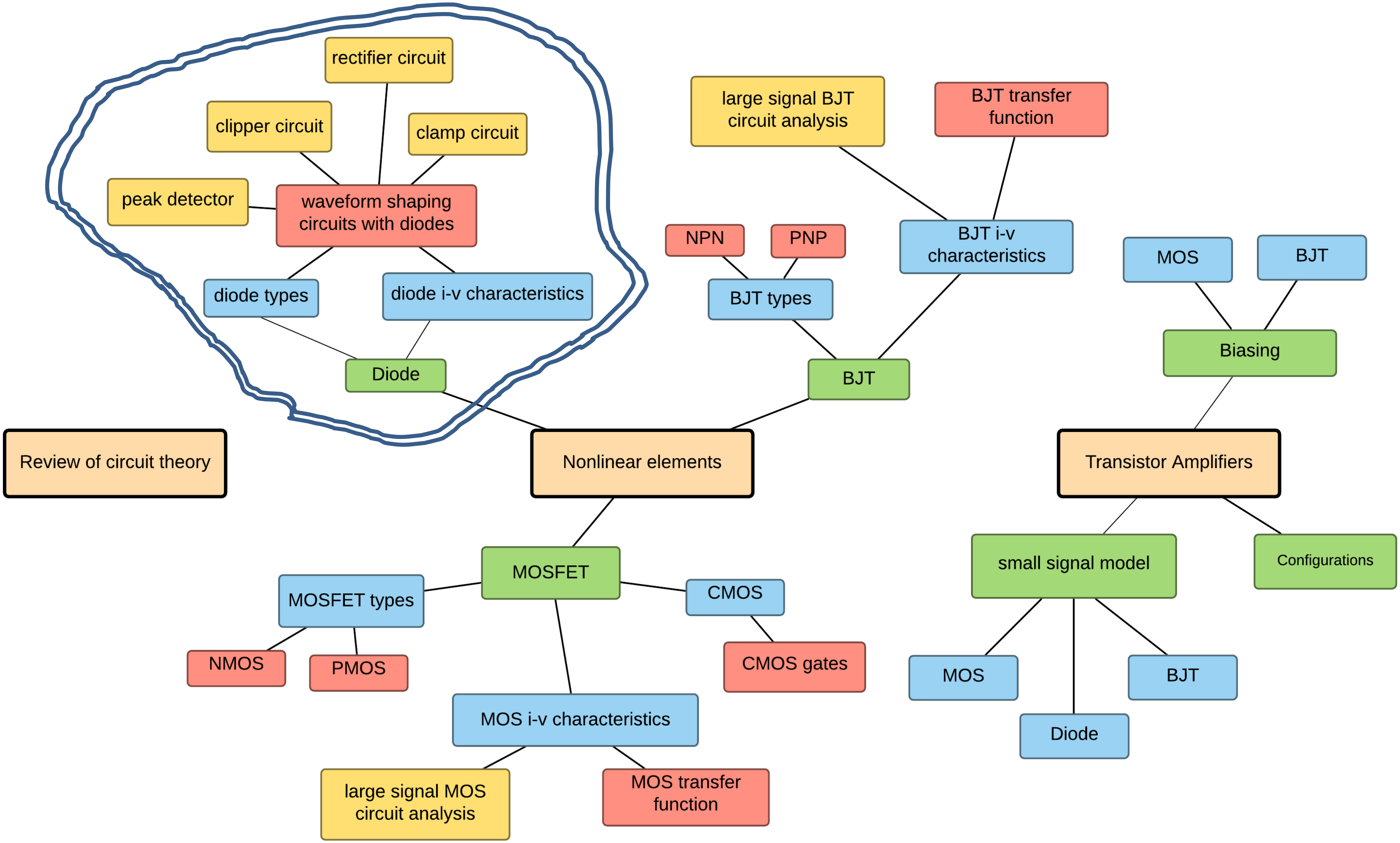
Reference notes: sections 2.1-2.8

Sedra & Smith (7^{th} Ed): sections 4.3-4.4

Saharnaz Baghdadchi

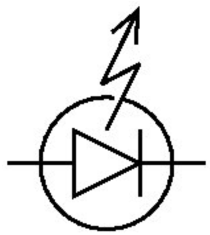
Course map

2. Diodes



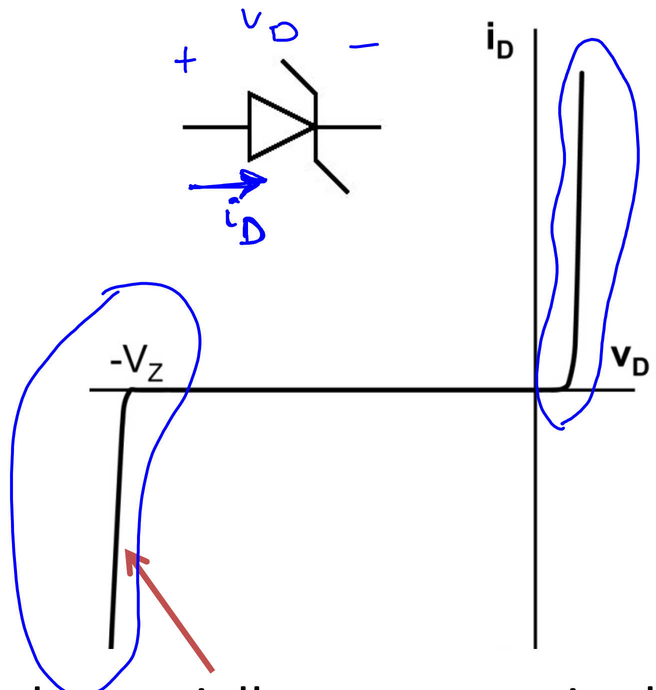
Other types of diodes

Light-emitting diode (LED)



$V_{D0} = 1.7 - 1.9$ V

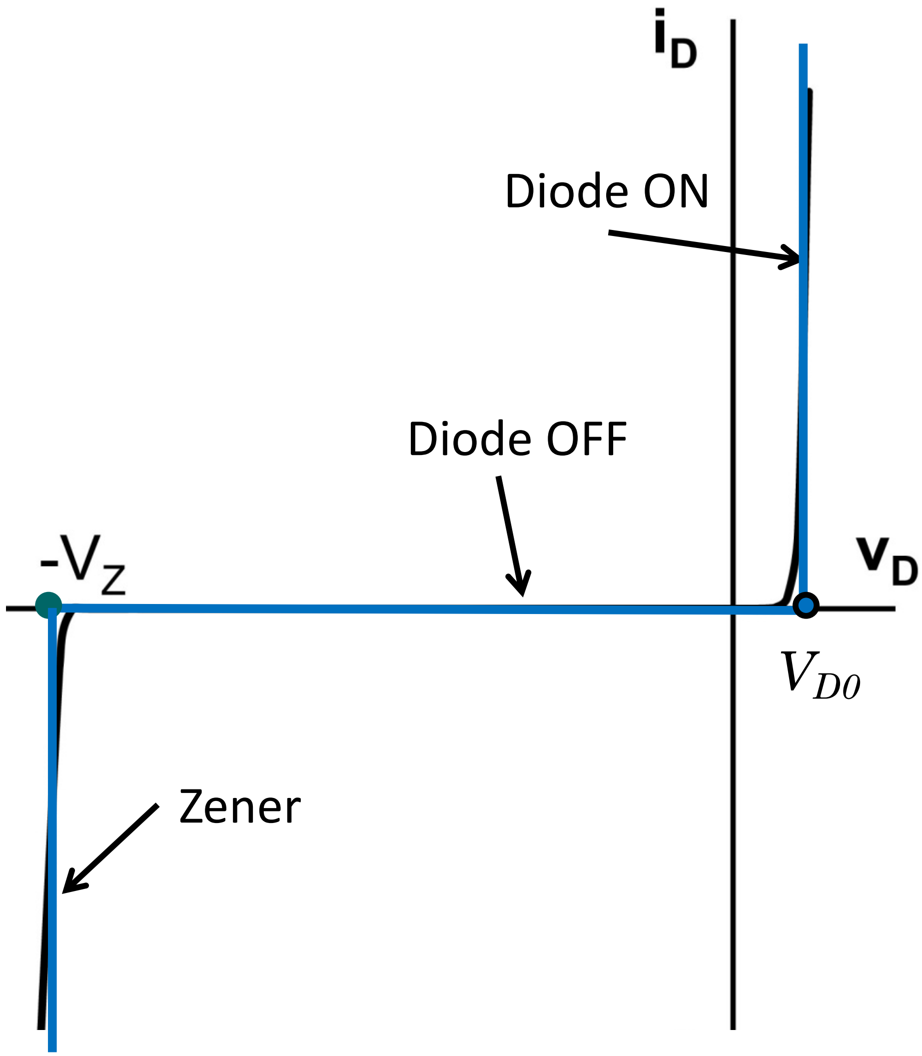
Zener Diode



Made specially to operate in the reverse breakdown region.

Useful as a “reference” voltage in many circuits.

Zener Diode piecewise-linear model



Diode ON: $v_D = V_{D0}$ and $i_D \geq 0$

Diode OFF: $i_D = 0$ and $-V_Z < v_D < V_{D0}$

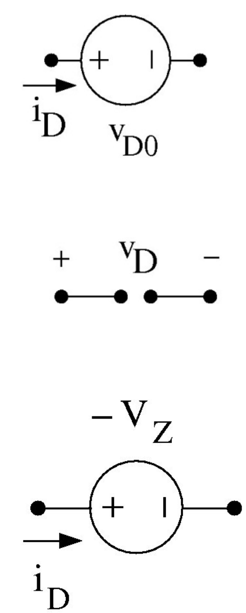
Zener: $v_D = -V_Z$ and $i_D \leq 0$

Circuit Models:

ON:

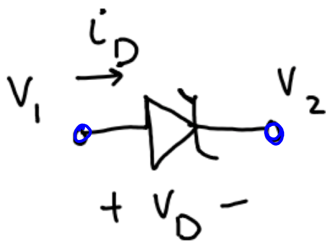
OFF:

Zener:



Zener Diode piecewise-linear model

Assume Zener diode with $V_D = 0.7$ V and $V_Z = 5$ V.



Ⓐ When $0 < V_1 - V_2 < 0.7$, diode is forward-biased, but it's not ON, yet. $\Rightarrow i_D = 0$

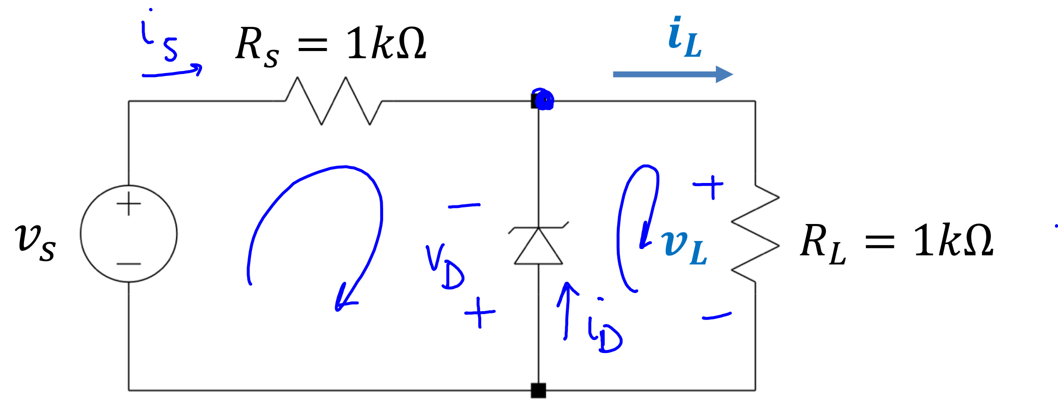
Ⓑ When $-5 < V_1 - V_2 < 0$, diode is reverse-biased, but it's not in the Zener region, so it's off. $\Rightarrow i_D = 0$

Ⓒ When $V_1 - V_2 = 0.7$, diode is forward-biased and it's ON $\Rightarrow i_D \geq 0$ and $V_D = V_{D_0} = 0.7$ V.

Ⓓ When $V_1 - V_2 = -5$ V, diode is in Zener region, it conducts, $\Rightarrow i_D \leq 0$ and $V_D = -V_Z = -5$ V

Example:

In the following circuit, find i_L and v_L for $v_s = 10\ V$. For what range of v_s and R_L the Zener diode will be in the Zener region and the circuit can operate as a voltage regulator? $(V_Z = 3\ V, V_{D0} = 0.7\ V)$



KCL:

$$\boxed{i_s + i_D - i_L = 0}$$

KVL:

$$\boxed{V_s = R_s i_s - V_D}$$

$$V_D + V_L = 0 \rightarrow \boxed{V_L = -V_D}$$

Assume the diode is in the Zener region:

$$\boxed{V_D = -V_Z}, \quad \boxed{i_D < 0}$$

$$\boxed{V_L = V_Z = 3V}$$

$$i_L = \frac{V_L}{R_L} = \frac{3V}{1k} = 3mA, \quad \boxed{i_L = 3mA}$$

$$i_s = \frac{V_s + V_D}{R_s} = \frac{10V - 3V}{1k}$$

$$\boxed{i_s = 7mA}$$

$$i_D = i_L - i_s = 3mA - 7mA$$

$$= -4mA < 0$$

when the diode is in the Zener region, $i_D \leq 0$.

$$i_D = i_L - i_s \leq 0 \longrightarrow \boxed{i_s \geq i_L}$$

$$V_L = V_Z \quad , \quad \boxed{i_L = \frac{V_L}{R_L} = \frac{V_Z}{R_L}}$$

$$\boxed{i_s = \frac{V_s - V_Z}{R_s}}$$

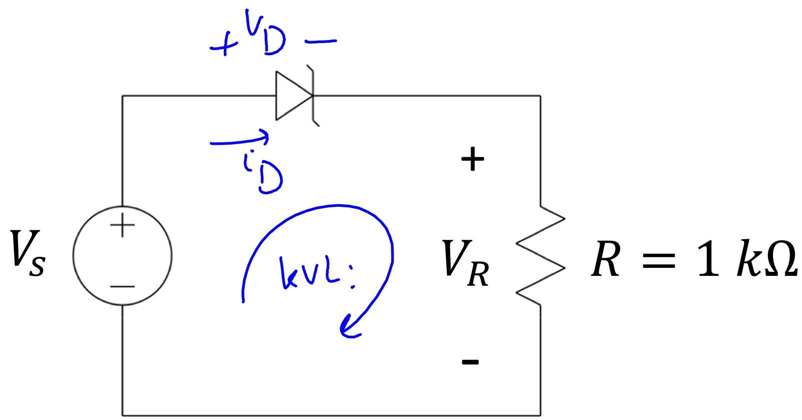
$$\boxed{\frac{V_s - V_Z}{R_s} \geq \frac{V_Z}{R_L}}$$

$$\frac{V_s}{R_s} \geq V_Z \left(\frac{1}{R_L} + \frac{1}{R_s} \right) \longrightarrow V_s \geq \underline{\underline{V_Z \left(1 + \frac{R_s}{R_L} \right)}}$$

$$\frac{V_s/V_Z - 1}{R_s} \geq \frac{1}{R_L} \longrightarrow R_L \geq \boxed{\frac{R_s}{V_s/V_Z - 1}}$$

Lecture 3 reading quiz

In the following circuit, find V_R for $V_s = +5\,V$ and $V_s = -5\,V$. Assume $V_Z = 3\,V$ and $V_{Do} = 0.7\,V$.



$\boxed{V_s = 5V}$

Assume diode is in Zener

$V_D = -V_Z$, $\boxed{i_D < 0}$

KVL: $V_s = V_D + R\, i_D$

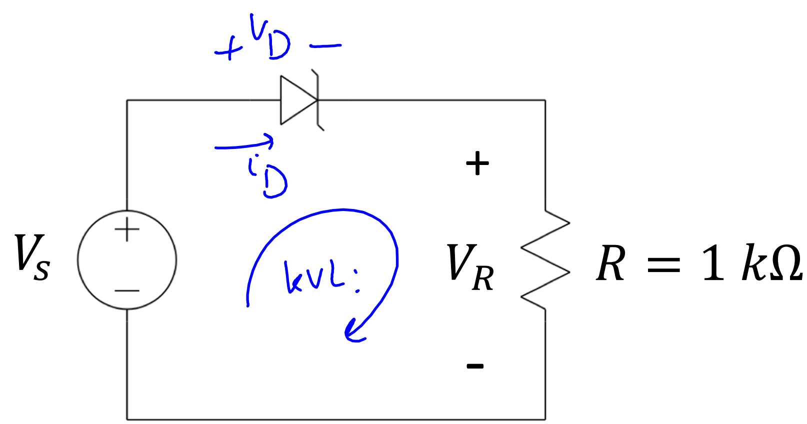
$5 = -3 + 1\,k\Omega \times i_D \longrightarrow i_D = 8mA > 0$

Assumption was wrong.

Lecture 3 reading quiz

In the following circuit, find V_R for $V_s = +5\ V$ and $V_s = -5\ V$. Assume $V_Z = 3\ V$ and $V_{Do} = 0.7\ V$.

$\boxed{V_s = 5\,V}$



Assume the diode is ON,

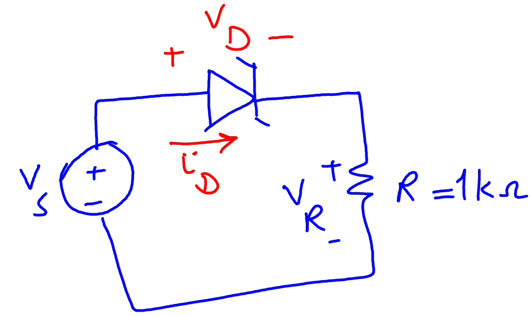
$V_D = V_{D_0}$ and $\boxed{i_D \geq 0}$

Assumption was correct

KVL : $V_s = V_D + Ri_D \longrightarrow 5 = 0.7 + 1k\Omega \times i_D \longrightarrow \boxed{i_D = 4.3\ mA > 0}$

$V_R = 1k\Omega \times i_D = 4.3\,V$

For $\boxed{V_s = -5\,V}$,



Assume diode is in Zener region:

$V_D = -V_Z$, $\boxed{i_D \leq 0}$

KVL: $V_s = V_D + 1k\Omega \times i_D$

$-5V = -3V + 1k\Omega \times i_D \longrightarrow i_D = -2mA < 0$

Assumption was correct and the diode is in the Zener region.

$V_R = 1k\Omega \times i_D = -2V$

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what if we assumed the diode was off for $V_s = -5V$

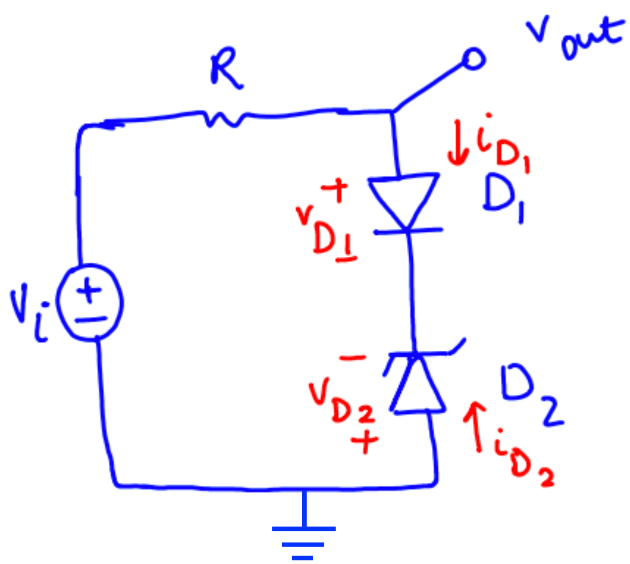
Diode off: $i_D = 0$, $-3V < V_D < 0.7V$

$V_s = V_D + R\,i_D \longrightarrow V_s = V_D = -5V < -3V$ ⟹ Assumption was wrong.

Discussion question 1.

In the below circuit find the range of v_i for which D_1 is ON and D_2 is in the Zener region. Calculate v_{out}.

Are there any other possible states at which D_1 and D_2 can operate? Assume $V_{D0} = 0.7\ V$ and $V_Z = 5\ V$.

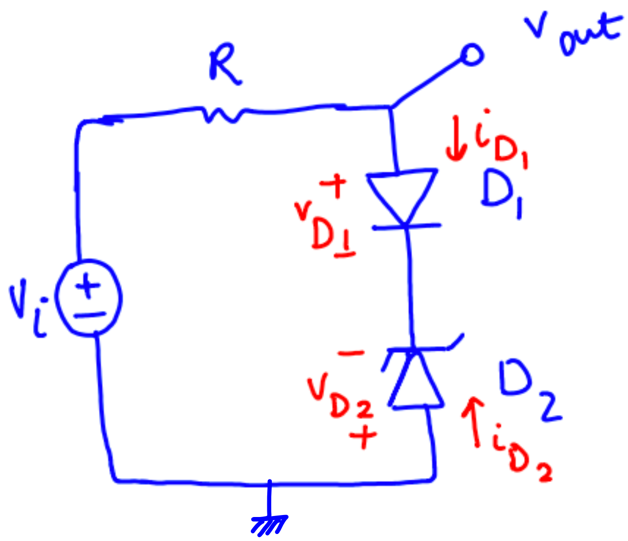


Extra activity: find v_{out} for all ranges of v_i (solve the circuit parametrically).

Discussion question 1.

$V_{D_0} = 0.7\,V$, $V_Z = 5V$

Solve the following circuit parametrically.



	D_1	D_2	
	ON	ON	✗
	ON	OFF	✗ Diodes are in series
A	ON	Zener	✓
	OFF	ON	✗ Diodes are in series
B	OFF	OFF	✓
	OFF	Zener	✗ Diode are in series

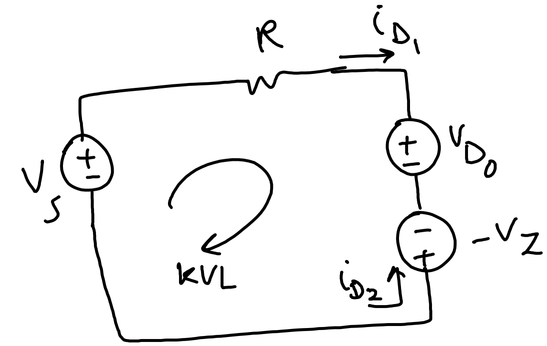
D_1 and D_2 cannot be forward biased and ON, because:

D_1 ON $\longrightarrow$ $i_{D_1} \geq 0$, $V_{D_1} = 0.7\ V$

D_2 ON $\longrightarrow$ $i_{D_2} \geq 0$, $V_{D_2} = 0.7V$

KCL: $i_{D_1} = -i_{D_2} \Longrightarrow$ both can't be ON at the same time.

(A) when D_1 is ON & D_2 is in zener :



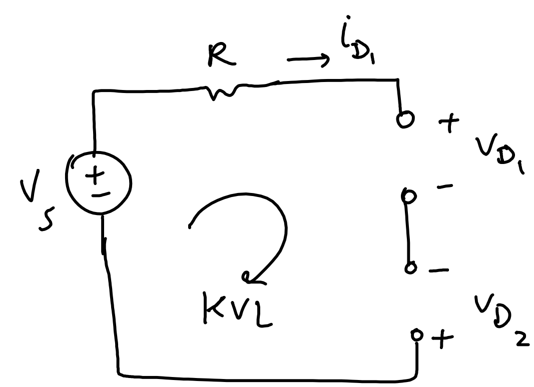
D_1 ON $\longrightarrow$ $i_{D_1} \geqslant 0$ & $V_{D_1} = V_{D_0} = 0.7V$

D_2 Zener $\longrightarrow$ $i_{D_2} \leqslant 0$ & $V_{D_2} = -V_Z = -5V$

KVL: $i_{D_1} = \dfrac{V_S - V_{D_0} - V_Z}{R} \geqslant 0 \longrightarrow V_S \geqslant V_Z + V_{D_0} \longrightarrow V_S \geqslant 5.7V$

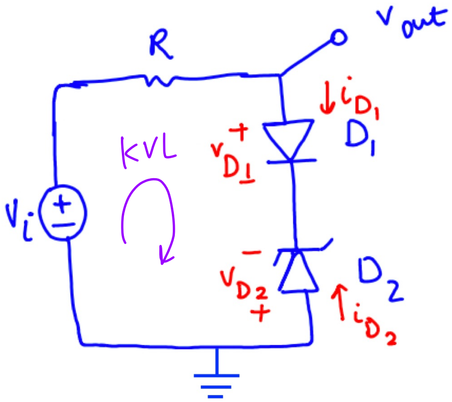
For $V_S \geqslant 5.7V$ $\longrightarrow$ D_1 is ON and D_2 is in Zener region

(B) when D_1 and D_2 are off:



D_1 off $\longrightarrow$ $i_{D_1} = 0$ & $V_{D_1} < V_{D_0}$

D_2 off $\longrightarrow$ $i_{D_2} = 0$ & $-V_Z < V_{D_2} < V_{D_0}$



when D_1 and D_2 are off:

D_1 off $\longrightarrow$ $i_{D_1}=0$ & $V_{D_1} < V_{D_0}$

D_2 off $\longrightarrow$ $i_{D_2}=0$ & $-V_Z < V_{D_2} < V_{D_0}$

KVL: $V_i = R \times i_{D_1} + V_{D_1} - V_{D_2} \Rightarrow V_i = V_{D_1} - V_{D_2}$

$-V_Z < V_{D_2} < V_{D_0} \longrightarrow -V_{D_0} < -V_{D_2} < V_Z$

also $V_{D_1} < V_{D_0}$. V_{D_1} in this range can have any value from $-\infty$ up to V_{D_0}.

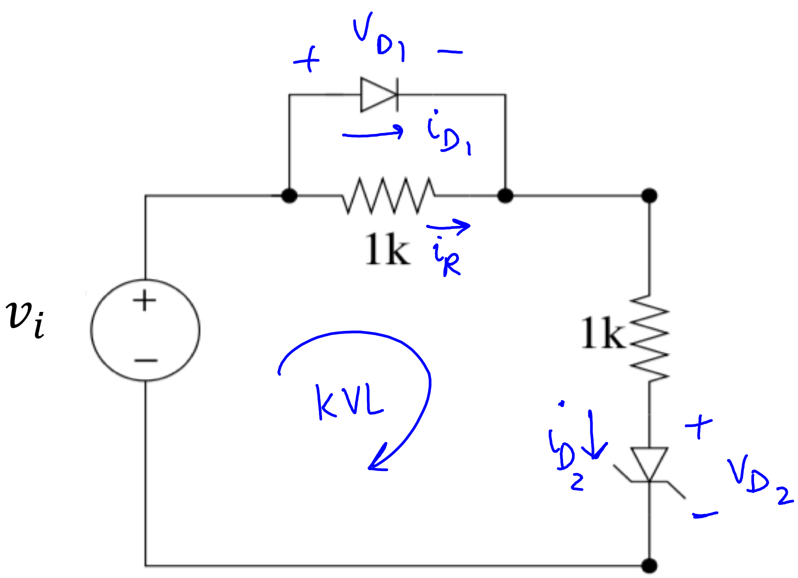
As a result, we can write $-\infty < V_{D_1} < V_{D_0}$

* note: this is a theoretical range. There is a limit on negative V_D values.

$$\Rightarrow \begin{matrix} -V_{D_0} < -V_{D_2} < V_Z \\ -\infty < V_{D_1} < V_{D_0} \end{matrix} \longrightarrow -\infty < \underbrace{\boxed{V_{D_1} - V_{D_2}}}_{V_i} < V_Z + V_{D_0} \quad \text{or} \quad V_i < V_Z + V_{D_0}$$

Clicker question 1:

What is the range of v_i for which both diodes are ON? Assume $V_Z = 4\ V$ and $V_{Do} = 0.7\ V$.



D_1 ON : $i_{D1} \geq 0$

$V_{D1} = V_{Do}$

D_2 ON : $i_{D2} \geq 0$

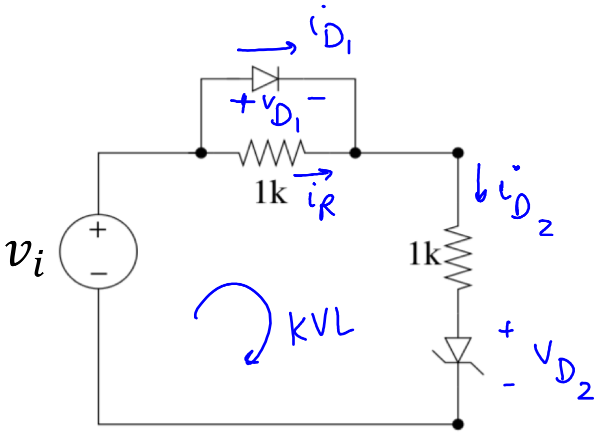
$V_{D2} = V_{Do}$

A. $v_i \geq 2.1$ V

B. $v_i \geq 1.4$ V

C. $v_i \geq 0.7$ V

D. Both diodes cannot be ON simultaneously.



KCL: $i_{D_2} = i_{D_1} + i_R$, $i_{D_1} \geq 0$ and $i_{D_2} \geq 0$

Both current inequalities must be true when D_1 and D_2 are ON.

$$i_R = \frac{V_{D_1}}{1k} = \frac{0.7\,V}{1k\Omega} = 0.7\,mA$$

$$i_{D_2} = i_{D_1} + 0.7\,mA$$

KVL: $V_i = V_{D_1} + 1k \times i_{D_2} + V_{D_2} \longrightarrow V_i = 0.7V + 1k\Omega \times (i_{D_1} + 0.7mA) + 0.7V$

$$V_i = 2.1\,V + 1k\Omega \times i_{D_1} \longrightarrow i_{D_1} = \frac{V_i - 2.1V}{1k\Omega} \geq 0 \longrightarrow V_i \geq 2.1V$$