3.6 Limiting and Clamping Circuits

Reading Assignment: *pp. 184-187 (i.e., neglect section 3.6.2)*

Another **application** of junction diodes →

Q: *What **is** a limiter?*

A: A 2-port device that **restricts** (i.e., limits) the voltage across a device to some specified region.

→

HO: Diode Limiters

Q:

A: HO: Steps for Analyzing Limiter Circuits

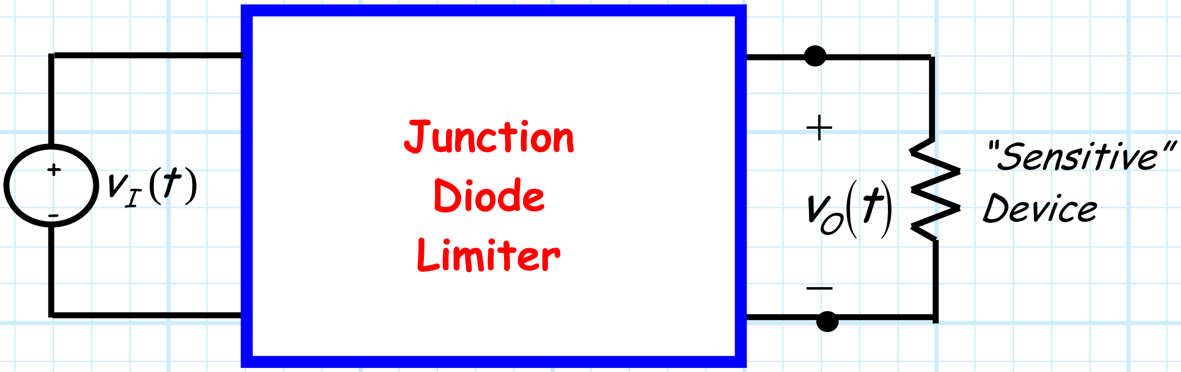
Example: A Diode Limiter

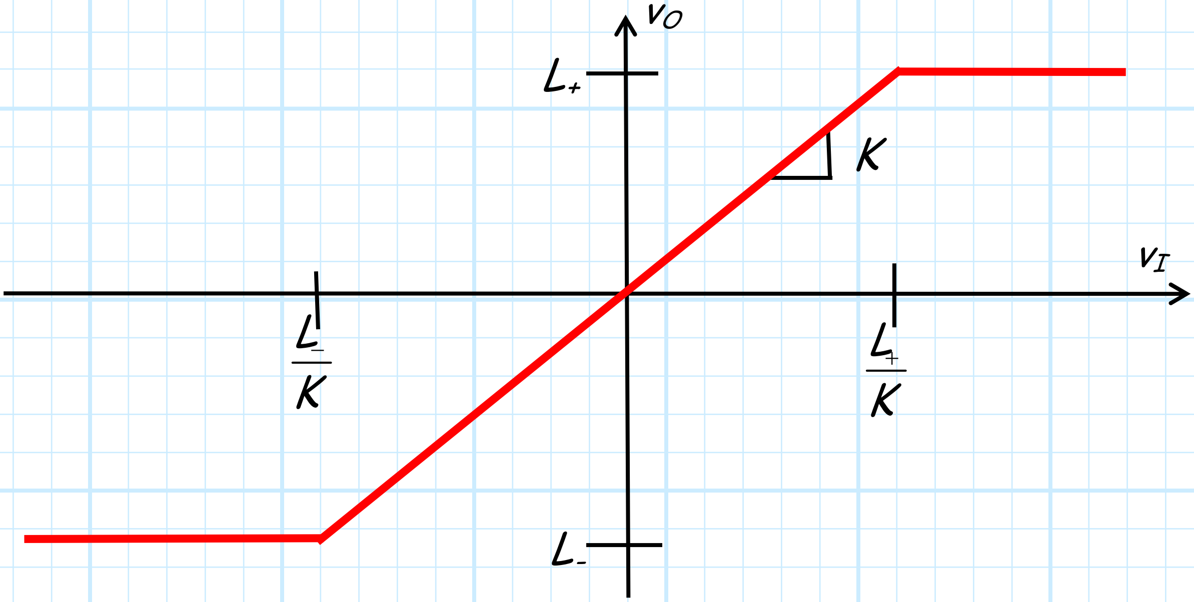
Diode Limiters

Often, a voltage source (either DC or AC) is used to supply an electronic device that is very **expensive** and/or very **sensitive**.

In this case, we may choose insert a **diode limiter** between the source and the device—this limiter will provide **over-voltage protection** !

To see how, we should first consider a typical **transfer function** for a junction diode limiter:





Note that this transfer function indicates that the **output** voltage v_O can **never** be more than a **maximum** voltage L_+ , nor less than a **minimum** voltage L_-.

* Thus, the device places some **limits** on the value of the **output** voltage:

$$L_- < v_O < L_+ \qquad \text{for any} \quad v_I$$

* The limits L_- and L_+ provide a **safe** operating value for v_O, the voltage across our "sensitive" electronic device.

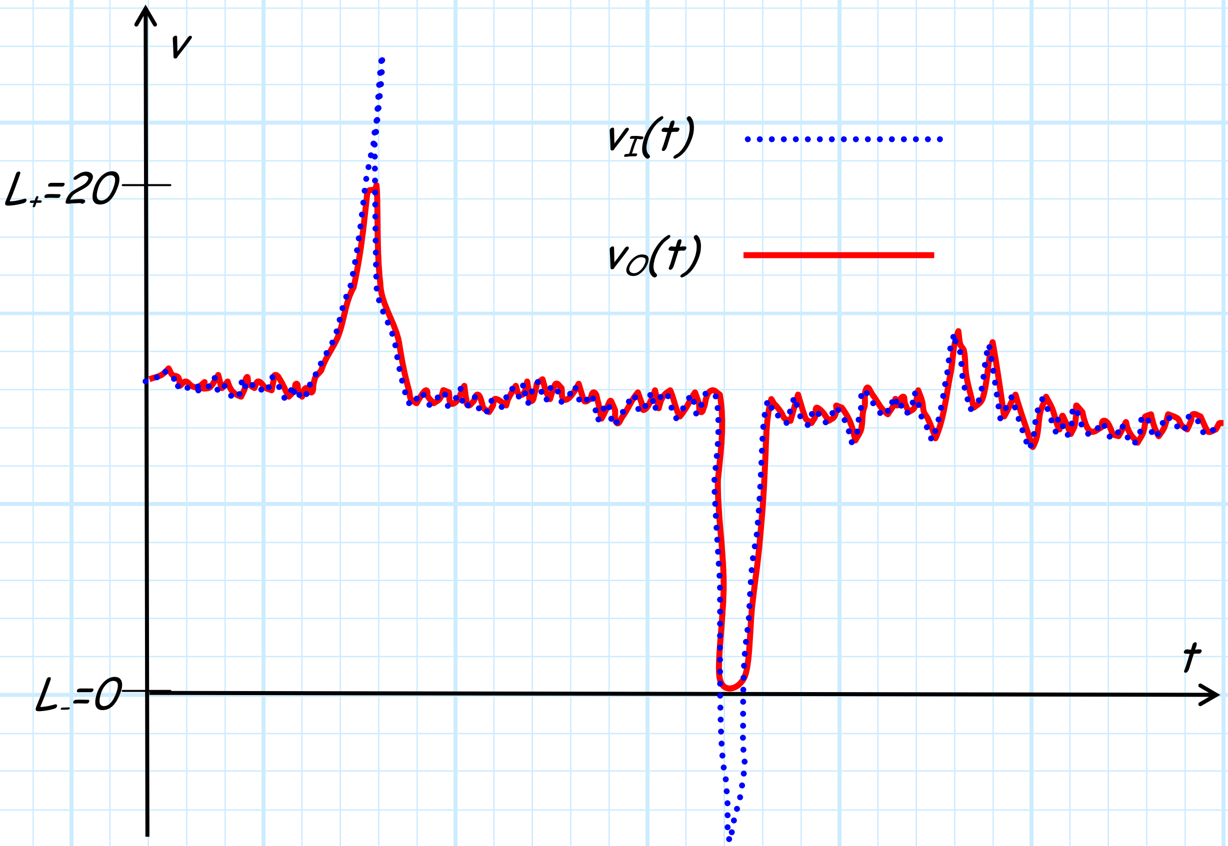
* Presumably, if **no limiter** were present, we might find that $v_O > L_+$ or $v_O < L_-$, resulting in **damage** to the device!

* Note although $L_+ > L_-$, the values of L_- and L_+ may be both **positive**, both **negative**, or even **zero**.

For example, a limiter with $\boldsymbol{L_- = 0}$ ($L_+ > 0$) would prevent the voltage from ever becoming **negative** (positive). We find that for many devices, the **wrong** voltage **polarity** can be **destructive**!

To illustrate, let's consider an **example** input voltage $v_I(t)$, and the resulting output voltage when passed through a **limiter** with values $L_-=0$ and $L_+=20$ V ($K=1$). I.E.:

$$v_O = \begin{cases} 0 & \text{if} \quad v_I < 0 \\ v_I & \text{if} \quad 0 < v_I < 20 \\ 20 & \text{if} \quad v_I > 20 \end{cases}$$



Note there are a couple of "**hiccups**" in the **input** voltage that take the voltage value **outside** the "safety" range of the sensitive device. However, the limiter does in fact **limit** these excursions, such that the voltage across the sensitive device **always** remains between 0 and 20 Volts.

Q: *Why would these "hiccups" occur?*

A: There are **many** possible reasons, including:

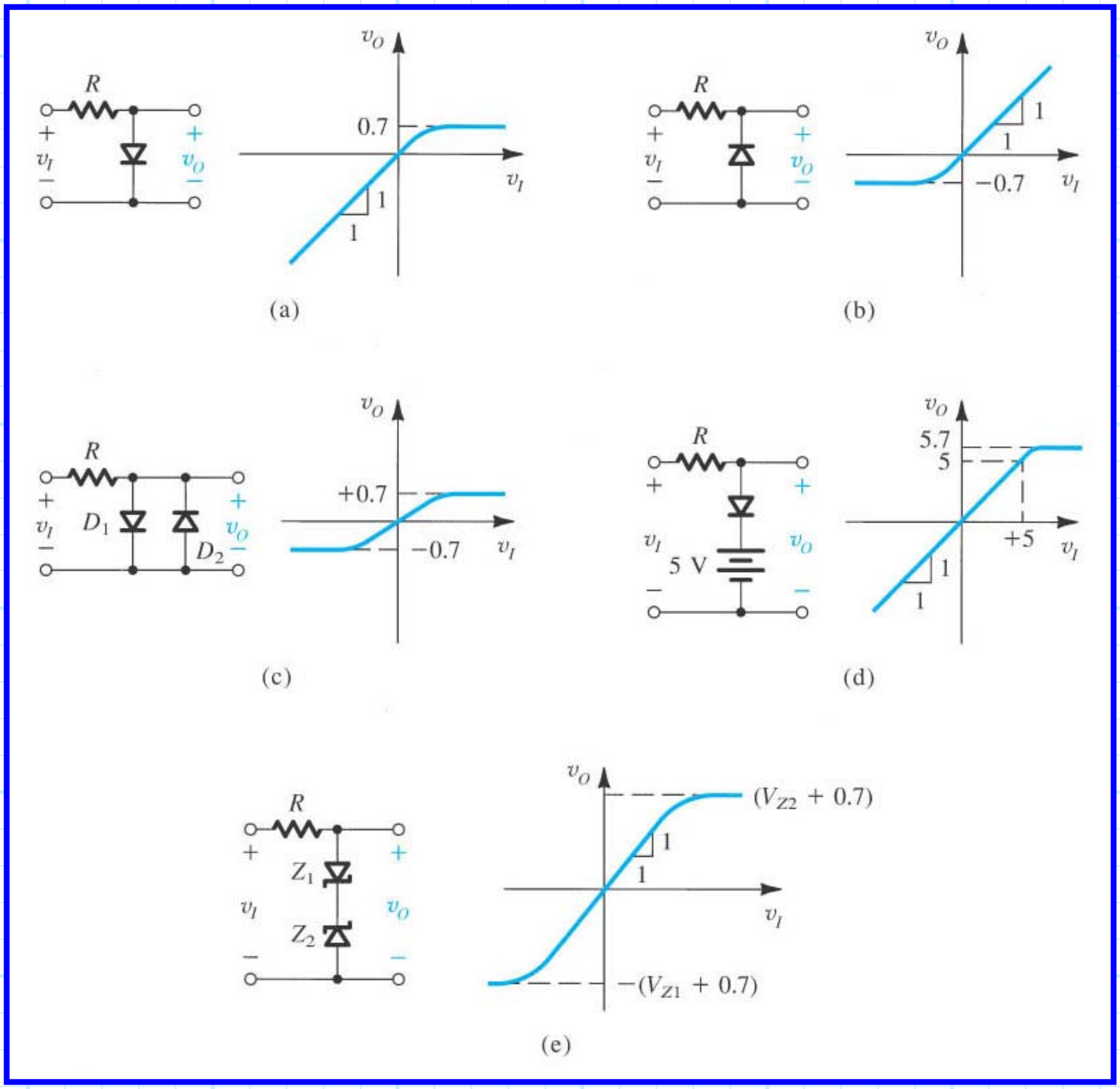
1. A power **surge** (e.g., lightning strike)
2. **Static** discharge
3. **Switching** transients (e.g., at power up or down).

Perhaps the most **prevalent** reason, however, is **operator error**.

→ Someone connects the **wrong** source to the sensitive device!

Thus, limiters are often used on expensive/sensitive devices to make them "**fool-proof**".

Your book has many **examples** of limiter circuits, including:



Steps for Analyzing Limiter Circuits

The junction diodes in most limiter circuits can/will be in forward bias, **or** reverse bias, **or** breakdown modes! Thus, the distinction between a Zener diode and a "normal" junction diode is essentially **meaningless**.

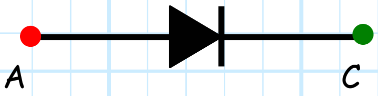
But, this presents us with a **big problem**—what diode **model** do we use to analyze a limiter? Recall that **none** of the diode models that we studied will provide accurate estimates for **all three** junction diode modes!

The **solution** we will use is to **change** the diode model we implement, as we consider **each** of the possible junction diode modes. Specifically:

Junction Diode Mode	*Junction Diode Model*
Forward Bias	**CVD model** with ideal diode f.b.
Reverse Bias	**Ideal diode** model with ideal diode r.b
Breakdown	**Zener CVD model** with ideal diode f.b.

Step 1:

Assume that the limiter diode is **forward biased**, so replace



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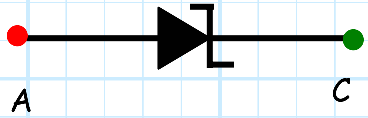
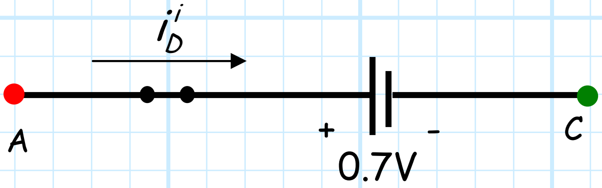


with a **CVD model**, where the **ideal** diode is **forward biased**:



Now, using this model, **determine**:

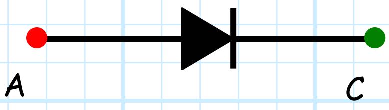
1. The **output voltage** v_O in terms of input voltage v_I .

2. The **ideal diode current** i_D^i in terms of input voltage v_I.

Finally, we solve the **inequality** $i_D^i > 0$ for v_I, thus determining **when** (i.e., for what values of v_I) this assumption, and thus the derived expression for output voltage v_O, is true.

Step 2:

Assume that the limiter diode is in **breakdown**, so replace



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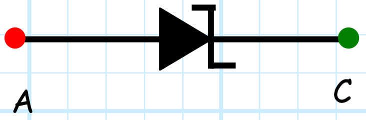
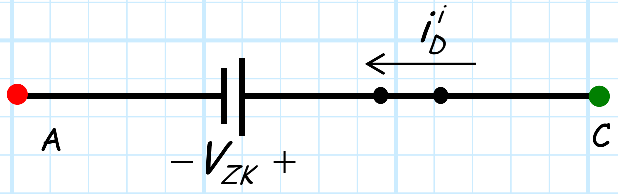


with a **Zener CVD model**, where the **ideal** diode is **forward biased**:



Now, using this model, **determine**:

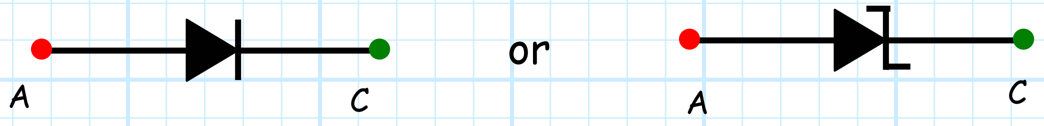
1. The **output voltage** v_O in terms of input voltage v_I .

2. The **ideal diode current** i_D^i in terms of input voltage v_I.

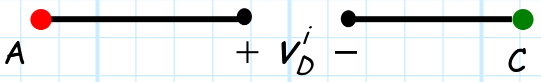
Finally, we solve the **inequality** $i_D^i > 0$ for v_I, thus determining **when** (i.e., for what values of v_I) this assumption, and thus the derived expression for output voltage v_O, is true.

Step 3:

Assume that the limiter diode is **reverse biased**, so replace



with an **Ideal Diode model**, where the ideal diode is **reversed biased**:



Now, using this model, determine the **output voltage** v_O in terms of input voltage v_I.

Q: *What about v_D^i? Don't we need to* ***likewise*** *determine its value, and then determine* ***when*** $v_D^i < 0$*?*

A: Actually, **no**. If the junction diode is **not** forward biased and it is **not** in breakdown, then it **must** be reverse biased! As **obvious** as this statement is, we can use it determine **when** the junction diode is reverse biased—it's **when** the junction diode is **not** in forward bias **and when** it is **not** in reverse bias.

For **example**, say that we find that the junction diode is **forward biased** when:

$$v_I > 20 \text{ V},$$

and that the junction diode is **in breakdown** when:

$$v_I < -15 \text{ V}.$$

We can thus **conclude** that the junction diode is **reverse biased** when:

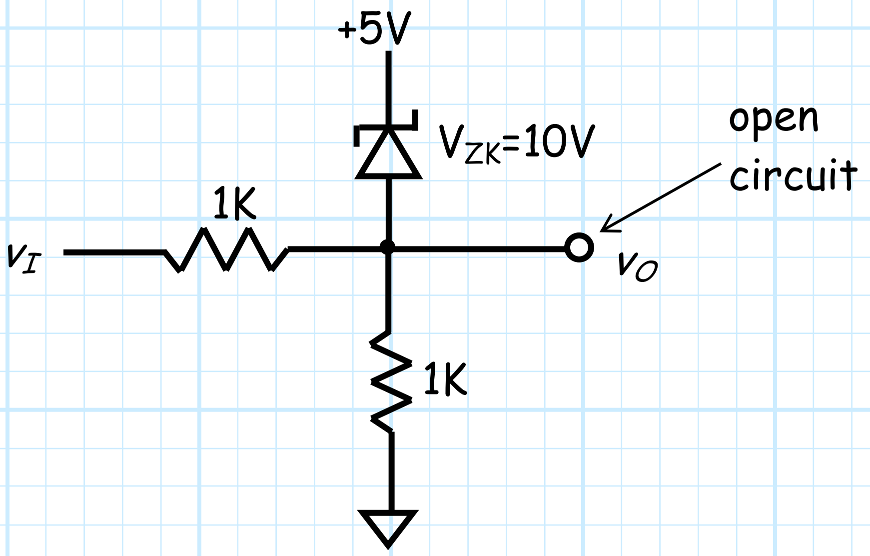
$$-15 \text{ V} < v_I < 20 \text{ V}$$

Step 4:

We take the result of the **previous 3 steps** and form a continuous, piecewise linear **transfer function** (make sure it's **continuous**, and that it's a **function**!).

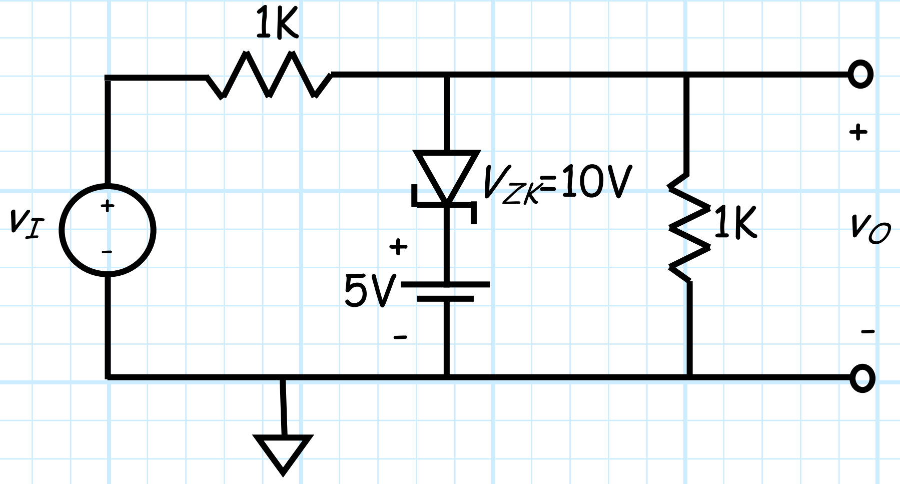
Example: A Diode Limiter

Consider the following **junction** diode circuit:



This circuit is a junction **diode limiter**!

Perhaps that would be clearer if we **redrew** this circuit as:

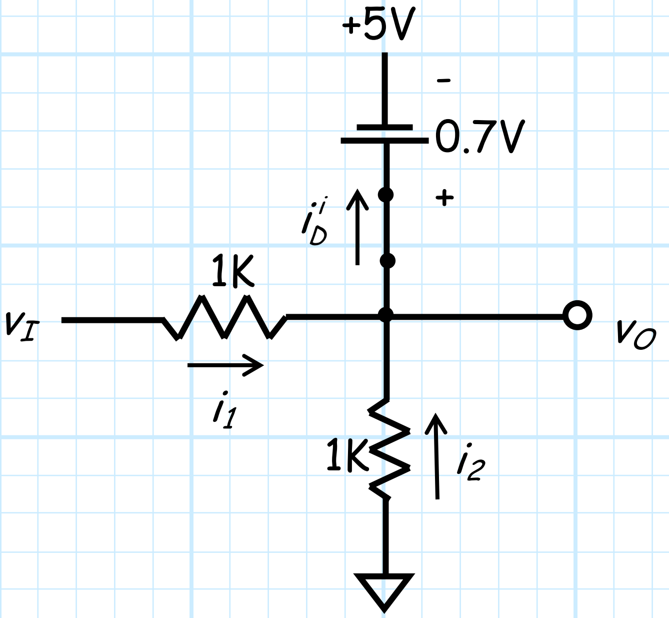


This is the **same** circuit as above!

Now, let's determine the **transfer function** of this limiter. To do this, we must follow the **4 steps** detailed in the previous handout!

Step1: Assume junction diode is **forward biased**

Replace the junction diode with a **CVD model**. ASSUME the **ideal** diode is forward biased, ENFORCE $v_D^i = 0$.



We find that the **output voltage** is simply:

$$v_O = 5.0 + 0.7 = 5.7 \text{ V}$$

while the **ideal** diode current is more difficult to determine.

From KCL:

$$i_D^i = i_1 + i_2$$

where from Ohm's Law:

$$i_1 = \frac{v_I - 5.7}{1} = v_I - 5.7$$

and:

$$i_2 = \frac{0 - 5.7}{1} = -5.7$$

Thus, the **ideal** diode current is:

$$\begin{aligned} i_D^i &= i_1 + i_2 \\ &= v_I - 5.7 - 5.7 \\ &= v_I - 11.4 \end{aligned}$$

Now, for our assumption to be correct, this current must be **positive** (i.e., $i_D^i > 0$). Thus, we solve this **inequality** to determine **when** our assumption is true:

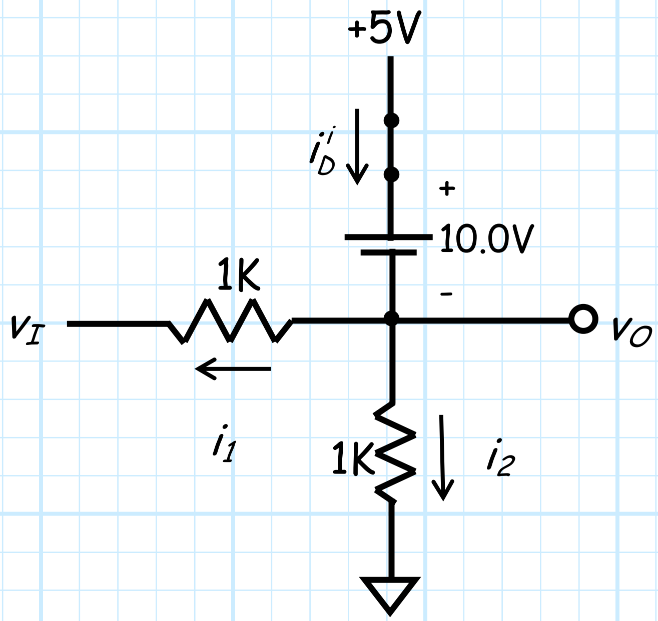
$$\begin{aligned} v_I - 11.4 &> 0 \\ v_I &> 11.4 \text{ V} \end{aligned}$$

So, from this step we find:

$$v_O = 5.7 \text{ V} \quad when \quad v_I > 11.4 \text{ V}$$

Step2: Assume the **junction** diode is in **breakdown**

Replace the junction diode with a **Zener CVD** model. ASSUME the **ideal** diode is forward biased, ENFORCE $v_D^i = 0$.



We find that the **output voltage** is simply:

$$v_O = 5 - 10 = -5.0\,V$$

while the **ideal** diode current is more difficult to determine.

From KCL:

$$i_D^i = i_1 + i_2$$

where from Ohm's Law:

$$i_1 = \frac{-5 - V_I}{1} = -v_I - 5.0$$

and:

$$i_2 = \frac{0 - 5.0}{1} = -5.0\,V$$

Thus, the **ideal** diode current is:

$$\begin{aligned} i_D^i &= i_1 + i_2 \\ &= -v_I - 5.0 - 5.0 \\ &= -v_I - 10.0 \end{aligned}$$

Now, for our assumption to be correct, this current must be **positive** (i.e., $i_D^i > 0$). Thus, we solve this **inequality** to determine **when** our assumption is true:

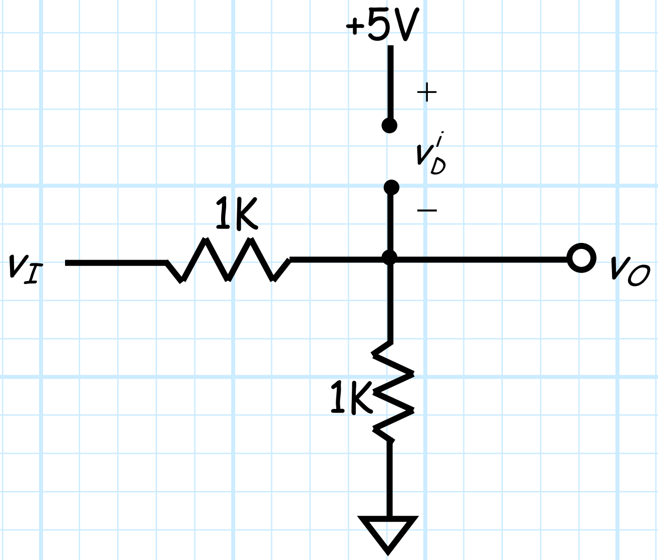
$$\begin{aligned} -v_I - 10.0 &> 0 \\ -v_I &> 10.0 \text{ V} \\ v_I &< -10.0 \text{ V} \end{aligned}$$

So, from this step we find:

$$v_O = -5.0 \text{ V} \quad \textit{when} \quad v_I < -10.0 \text{ V}$$

Step 3: Assume the **junction** diode is **reverse** biased

Replace the junction diode with the **Ideal Diode** model. ASSUME the **ideal** diode is **reverse** biased, ENFORCE $i_D^i = 0$.



A **voltage divider**!

Thus the **output voltage** is:

$$\begin{aligned} v_O &= \frac{v_I(1)}{1+1} \\ &= \frac{v_I}{2} \end{aligned}$$

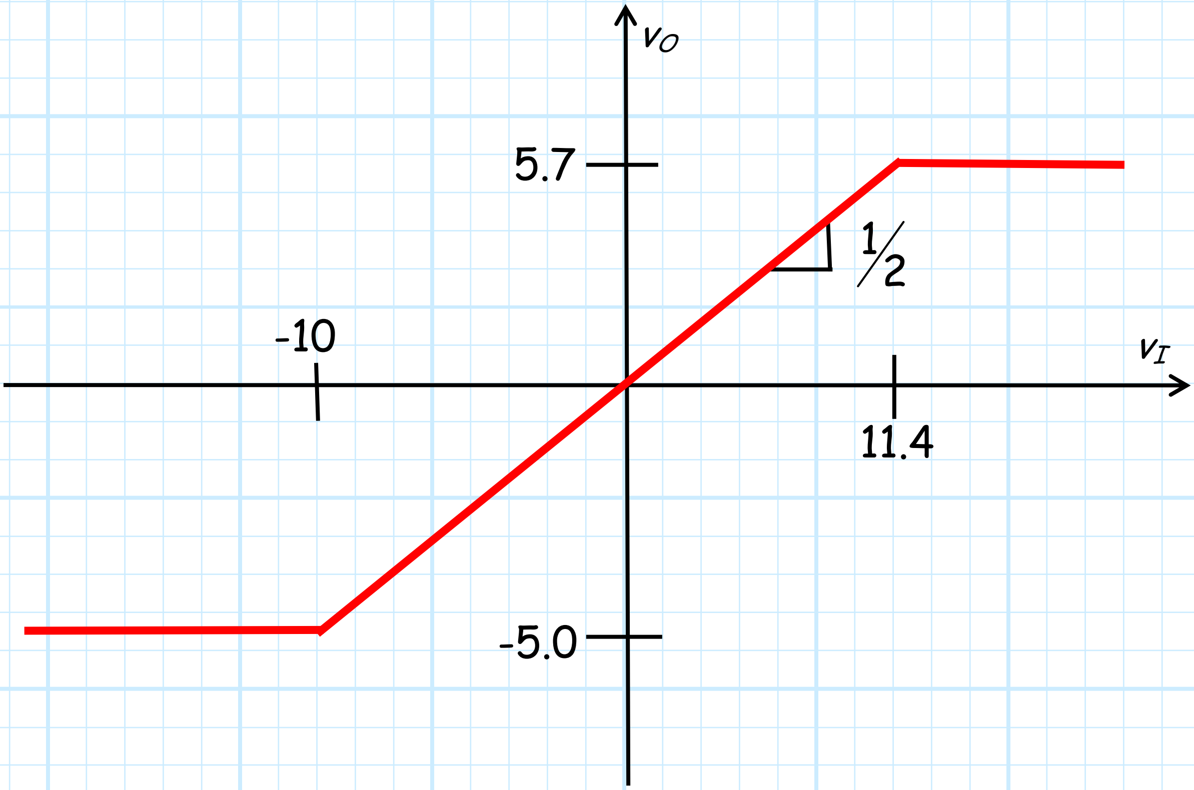
This output voltage is true **when** the junction diode is neither forward biased nor in breakdown. Thus, using the results from the first two steps, we can **infer** that it is true when:

$$-10.0 < v_I < 11.4$$

Step 4: Determine the continuous **transfer function**

Combining the results of the previous 3 steps, we get the following **continuous**, piece-wise linear **transfer function**:

$$v_O = \begin{cases} 5.7 \text{ V} & \text{if} \quad v_I > 11.4 \text{ V} \\ v_I/2 & \text{if} \quad -10.0 < v_I < 11.4 \text{ V} \\ -5.0V & \text{if} \quad v_I < -10.0 \text{ V} \end{cases}$$



Note that at $v_I = -10$:

$$v_O = \frac{v_I}{2} = \frac{-10}{2} = -5.0 \text{ V}$$

and at $v_I = 11.4$:

$$v_O = \frac{v_I}{2} = \frac{11.4}{2} = 5.7 \text{ V}$$

Thus, this function **is** continuous!