3.4 Operation in the Reverse Breakdown Region — Zener Diodes *(pp. 167-171)*

A Zener Diode →

The 3 technical differences between a junction diode and a Zener diode:

1.

2.

3.

The practical difference between a Zener diode and "normal" junction diodes:

➔

∴ 1.

2.

3.

HO: Zener Diode Notation

A. Zener Diode Models

Q: How do we analyze zener diodes circuits?

A: Same as junction diode circuits—

Big problem ->

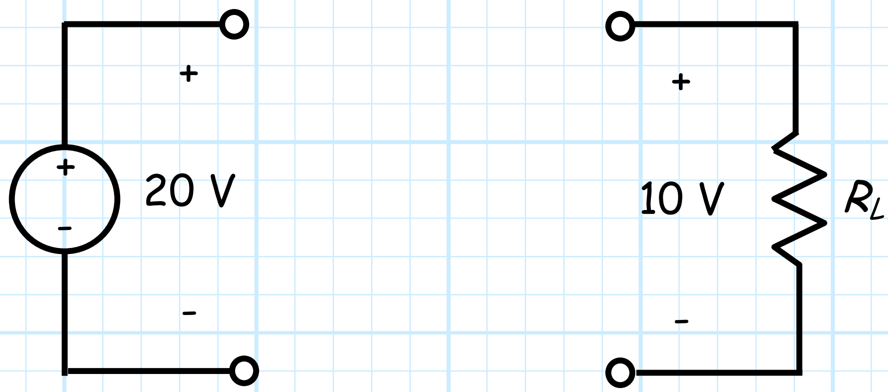
Big solution ->

HO: Zener Diode Models

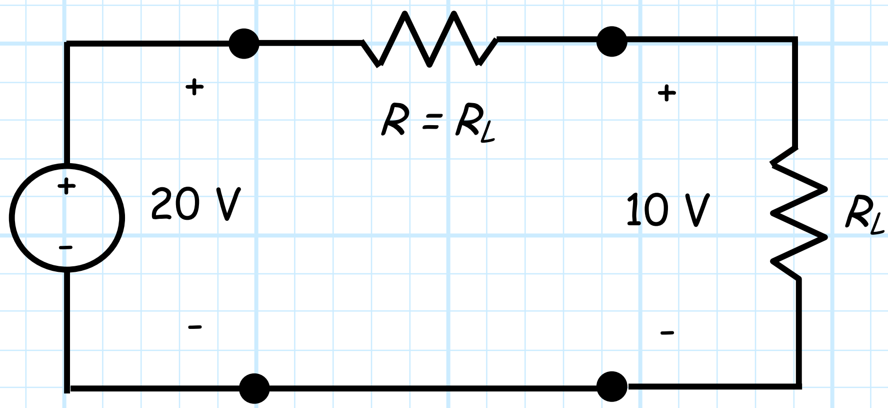
Example: Zener Circuit Analysis

B. Voltage Regulation

Say that we have a 20 V supply but need to place 10 V across some load:



The solution seems easy! →



This, in fact is a very bad solution—

HO: The Shunt Regulator

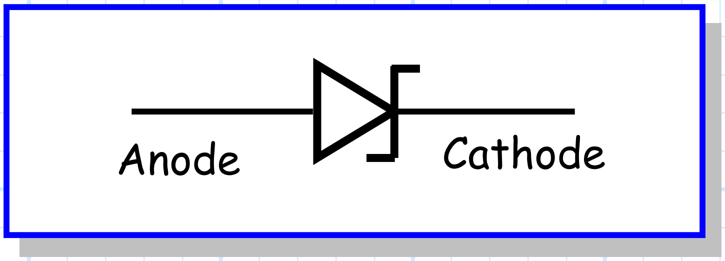
HO: Line Regulation

HO: Load Regulation

Example: The Shunt Regulator

Zener Diode Notation

To distinguish a **zener** diode from conventional junction diodes, we use a modified diode **symbol**:



Generally speaking, a **zener** diode will be operating in either **breakdown** or **reverse bias** mode.

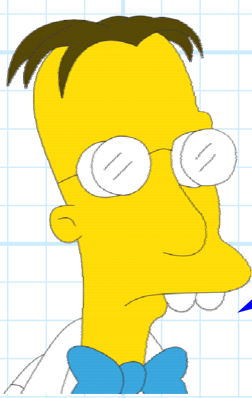
For both these **two** operating regions, the cathode **voltage** will be greater than the anode voltage, i.e.,:

$$v_D < 0 \quad \text{(for r.b. and bd)}$$

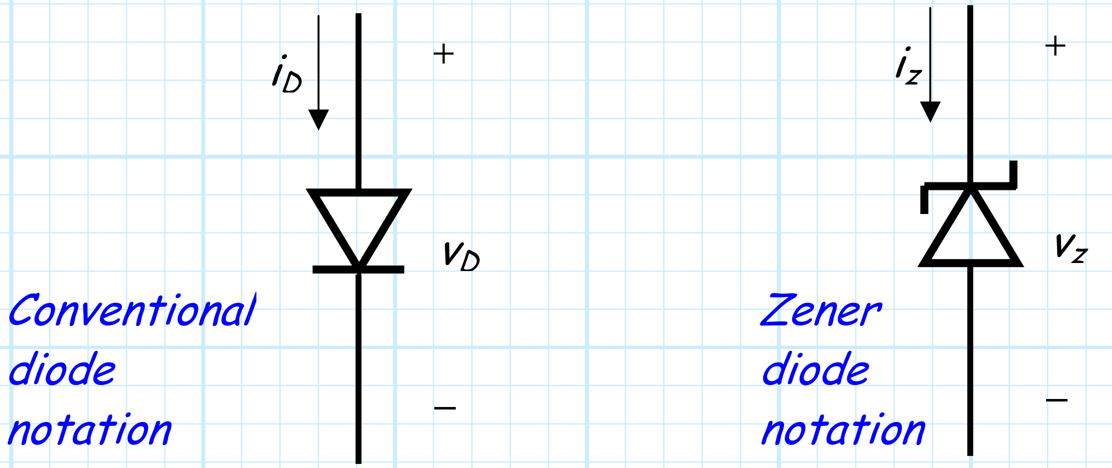
Likewise, the diode **current** (although often tiny) will flow from cathode to anode for these two modes:

$$i_D < 0 \quad \text{(for r.b. and bd)}$$

Q: *Yikes! Won't the the numerical values of both i_D and v_D be **negative** for a zener diode (assuming only rb and b.d. modes).*



A: *With the standard diode notation, this is true. Thus, to avoid **negative** values in our circuit computations, we are going to **change** the definitions of diode current and voltage!*

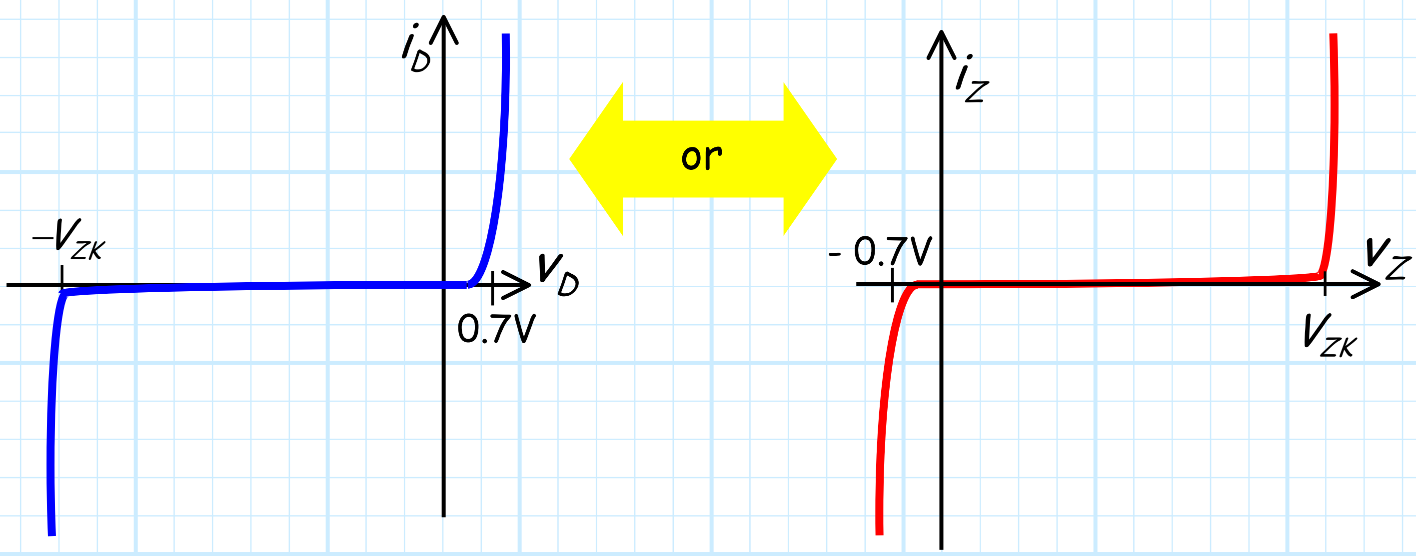


* In other words, for a Zener diode, we denote current flowing from **cathode to anode** as positive.

* Likewise, we denote diode voltage as the potential at the **cathode** with respect to the potential at the **anode**.

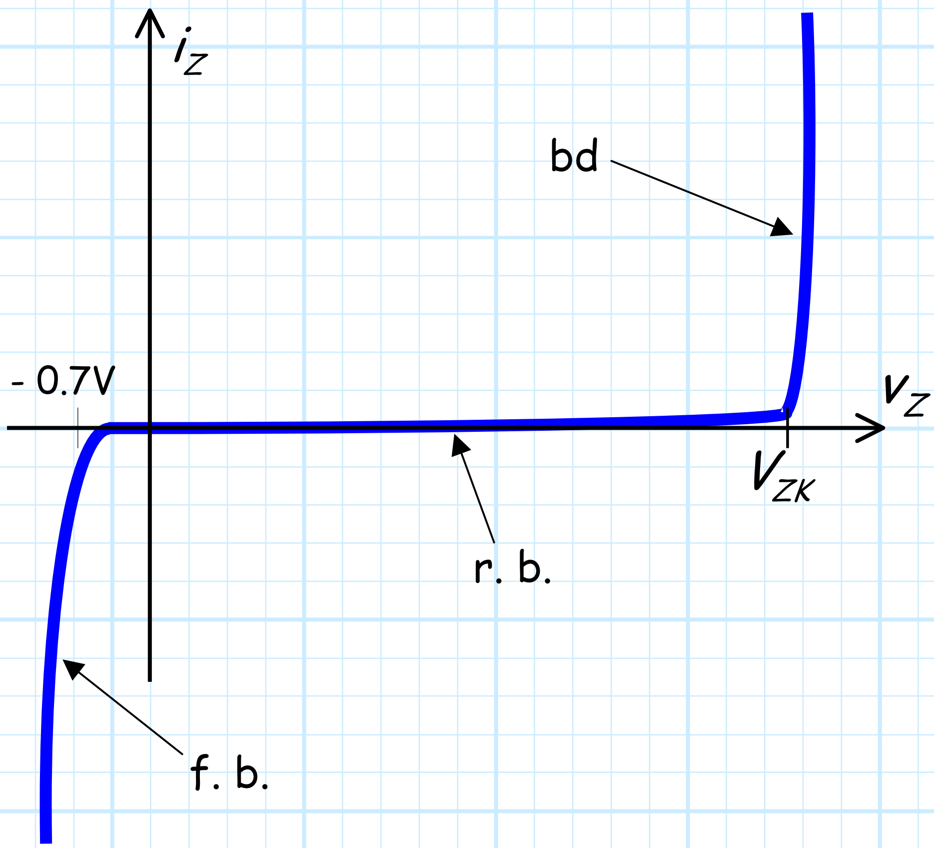
Note that each of the above two statements are precisely **opposite** to the "conventional" junction diode notation that we have used thus far:

$$v_Z = -v_D \quad \text{and} \quad i_Z = -i_D$$



Two ways of expressing the **same** junction diode curve.

The i_Z versus v_Z curve for a zener diode is therefore:



Thus, in **forward bias** (as unlikely as this is):

$$i_Z = -I_s \, exp\left(\frac{-v_Z}{nV_T}\right)$$

or approximately:

$$v_Z \approx -0.7 \text{ V} \;\; \text{and} \;\; i_Z < 0$$

Likewise, in **reverse bias**:

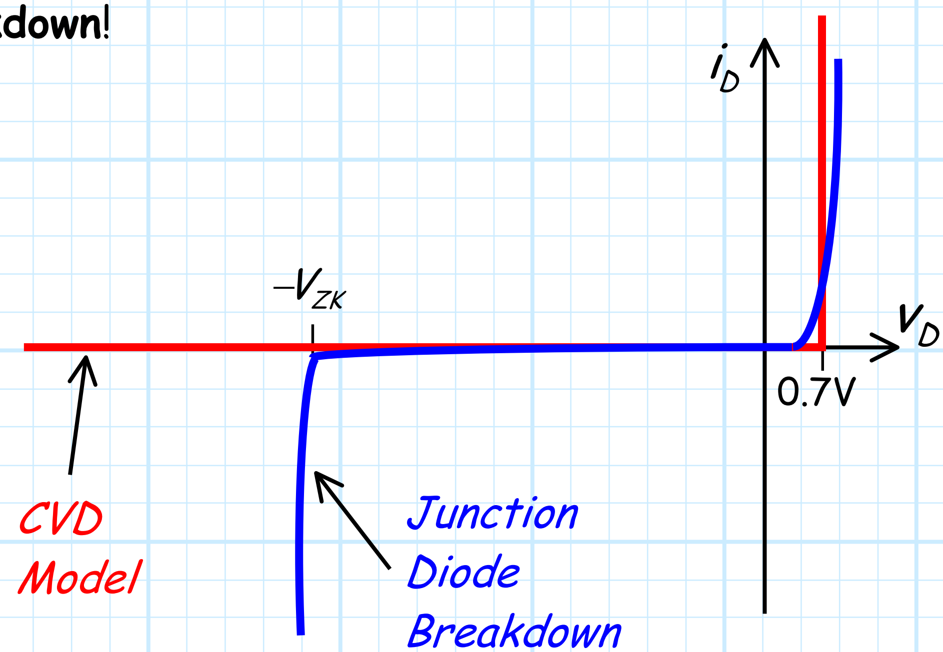
$$i_Z \approx I_s \quad \text{and} \quad 0 < v_Z < V_{ZK}$$

And finally, for **breakdown**:

$$i_Z > 0 \quad \text{and} \quad v_Z \approx V_{ZK}$$

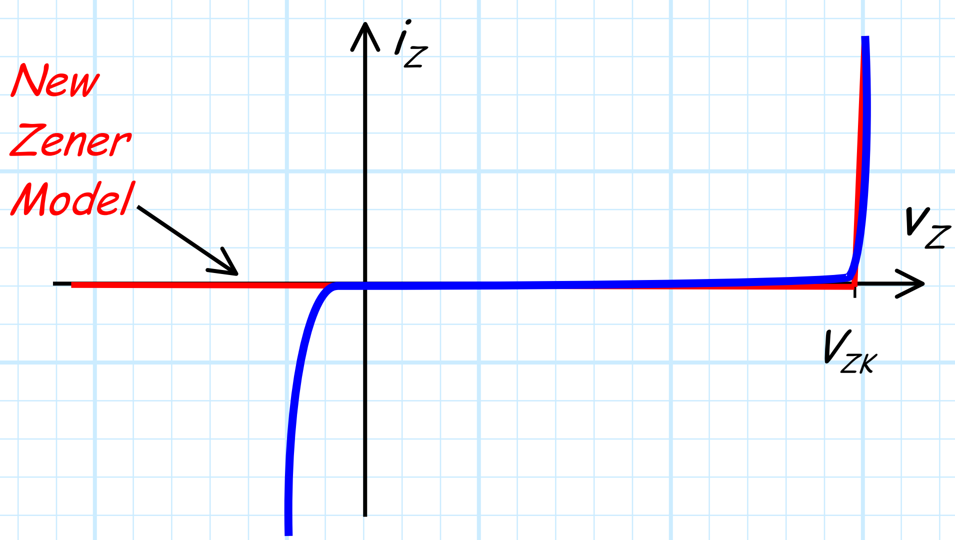
Zener Diode Models

The conventional diode models we studied earlier were based on junction diode behavior in the **forward** and **reverse** bias regions—they did **not** "match" the junction diode behavior in **breakdown**!



However, we assume that **Zener** diodes most often operate in **breakdown**—we need **new** diode models!

Specifically, we need models that match junction/Zener diode behavior in the **reverse bias** and **breakdown** regions.



We will study **two** important zener diode models, each with **familiar** names!

1. The Constant Voltage Drop (CVD) Zener Model
2. The Piece-Wise Linear (PWL) Zener Model

The Zener CVD Model

Let's see, we know that a Zener Diode in **reverse** bias can be described as:

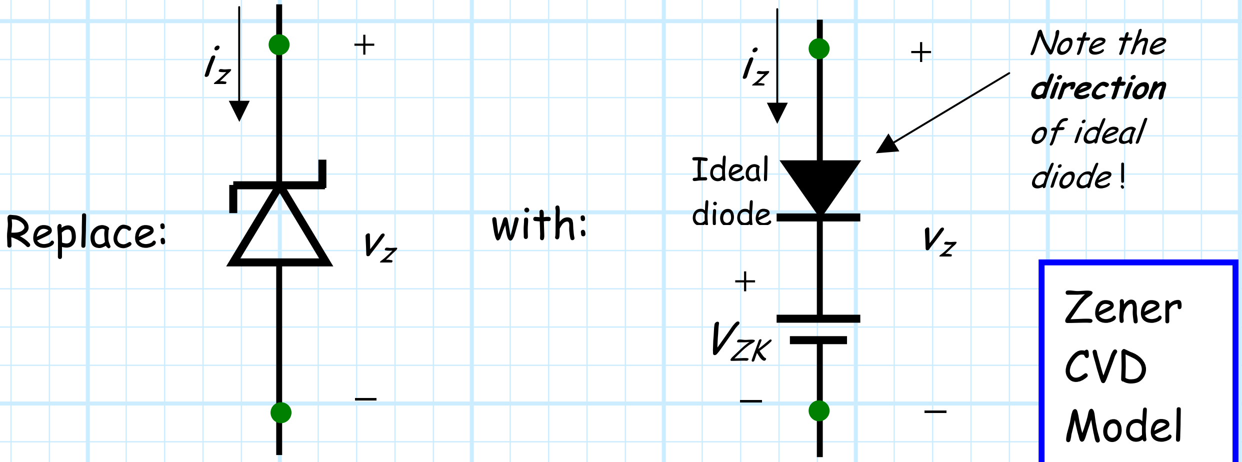
$$i_Z \approx I_s \approx 0 \quad \text{and} \quad v_Z < V_{ZK}$$

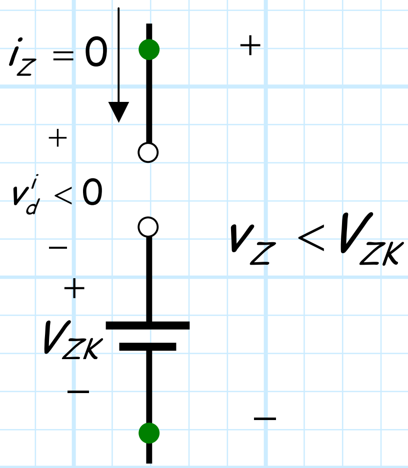
Whereas a Zener in **breakdown** is approximately stated as:

$$i_Z > 0 \quad \text{and} \quad v_Z \approx V_{ZK}$$

Q: *Can we construct a **model** which behaves in a **similar** manner??*

A: Yes! The **Zener CVD model** behaves precisely in this way!





Analyzing this Zener CVD model, we find that **if** the model voltage v_Z is less than V_{ZK} (i.e., $v_Z < V_{ZK}$), then the **ideal** diode will be in **reverse** bias, and thus the model current i_Z will equal **zero**. In other words:

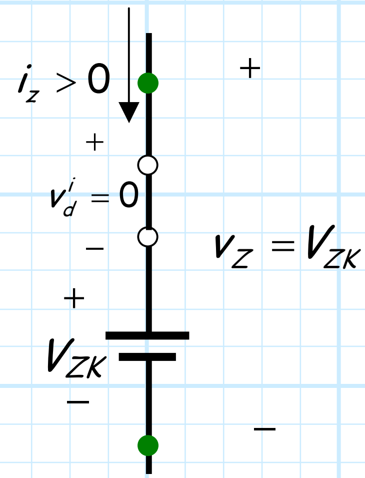
$$i_Z = 0 \quad \text{and} \quad v_Z < V_{ZK}$$

Just like a **Zener** diode in **reverse bias**!

Likewise, we find that **if** the model current is positive (i_Z>0), then the **ideal** diode must be **forward** biased, and thus the model voltage must be $v_Z = V_{ZK}$. In other words:

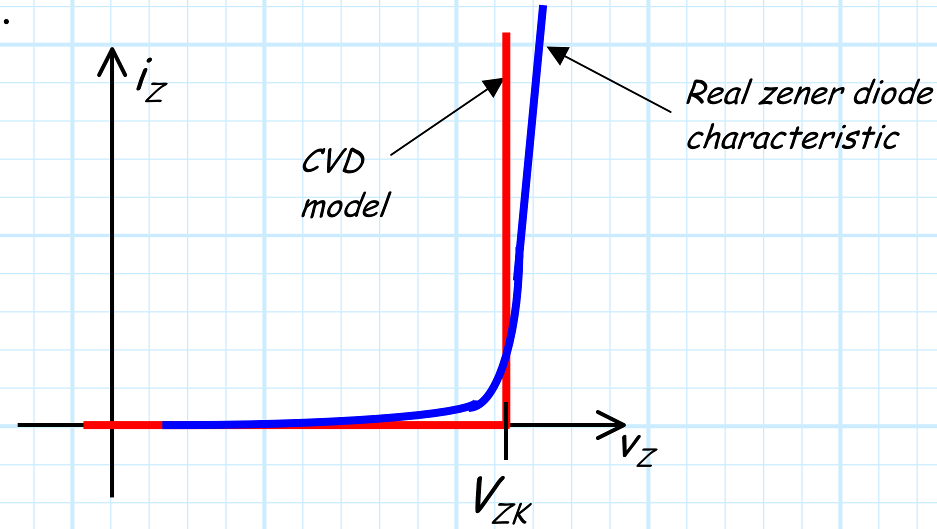
$$i_Z > 0 \quad \text{and} \quad v_Z = V_{ZK}$$

Just like a **Zener** diode in **breakdown**!



Problem: The voltage across a zener diode in breakdown is NOT EXACTLY equal to V_{ZK} for all $i_z > 0$. The CVD is an **approximation**.

In **reality**, v_Z **increases** a very small (tiny) amount as i_Z increases.

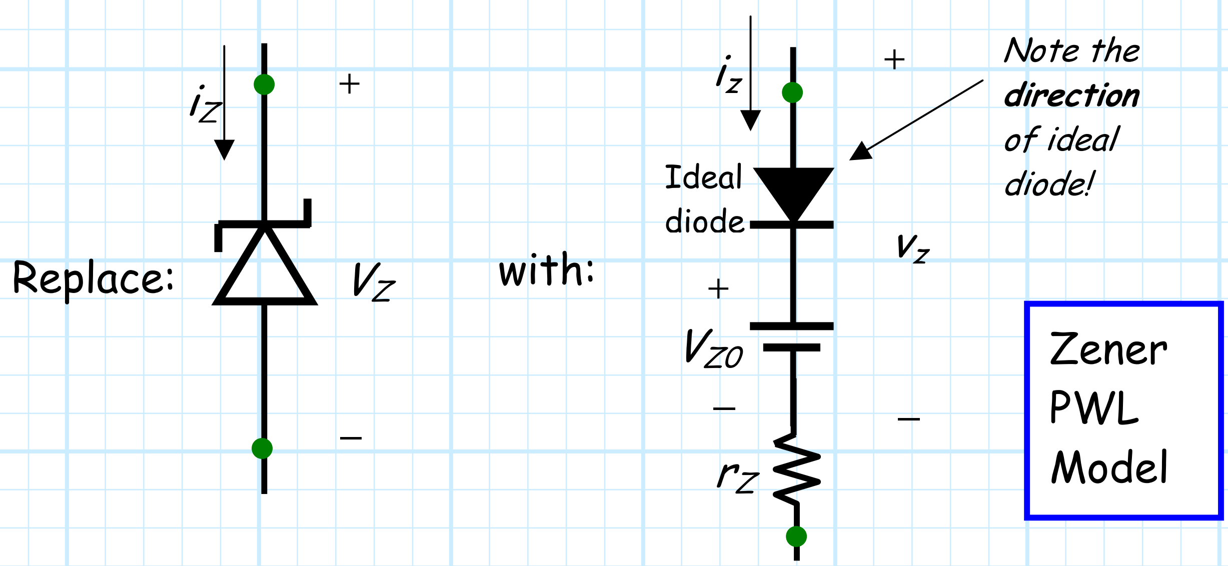


Thus, the CVD model causes a **small** error, usually acceptable—but for some cases **not**!

For these cases, we require a **better** model:

→ The Zener (PWL) Piece-Wise Linear model.

The Zener Piecewise Linear Model

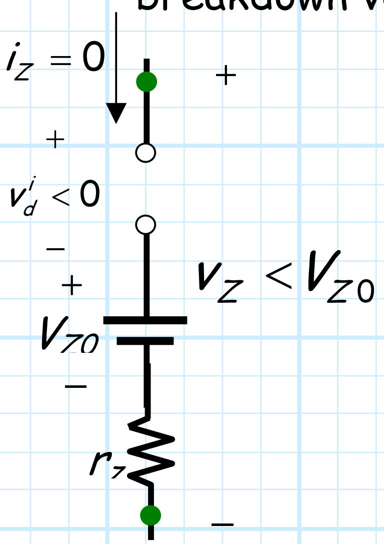


Please Note:

* The PWL model includes a **very small** series resistor, such that the voltage across the model v_z **increases slightly** with increasing i_z.

* This small resistance r_Z is called the **dynamic resistance**.

* The voltage source V_{Z0} is **not** equal to the zener breakdown voltage V_{ZK}, however, it is typically **very close**!



Analyzing this Zener PWL model, we find that **if** the model voltage v_Z is less than V_{Z0} (i.e., $v_Z < V_{Z0}$), then the **ideal** diode will be in **reverse** bias, and the model current i_Z will equal zero. In other words:

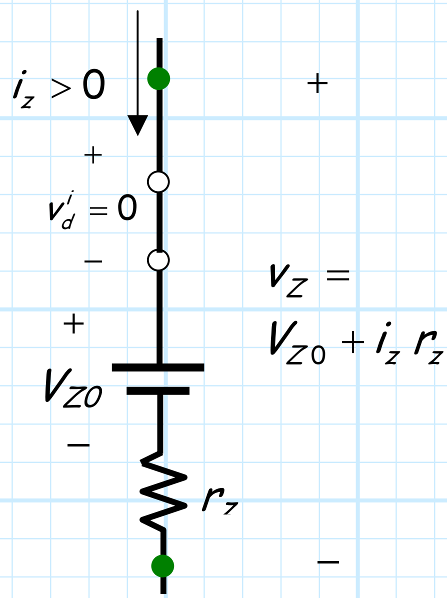
$i_Z = 0$ and $v_Z < V_{Z0} \approx V_{ZK}$

Just like a **Zener** diode in **reverse bias**!

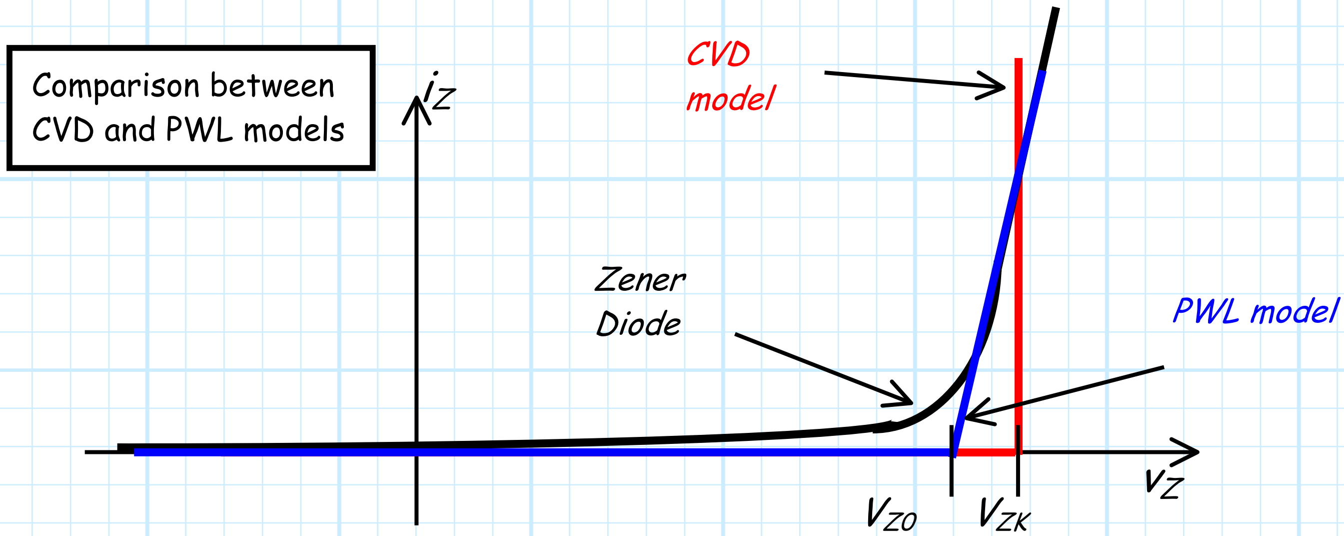
Likewise, we find that **if** the model current is positive ($i_Z > 0$), then the **ideal** diode must be **forward** biased, and thus:

$i_Z > 0$ and $v_Z = V_{Z0} + i_Z r_Z$

Note that the model voltage v_Z will be near V_{ZK}, but will increase **slightly** as the model current increases.

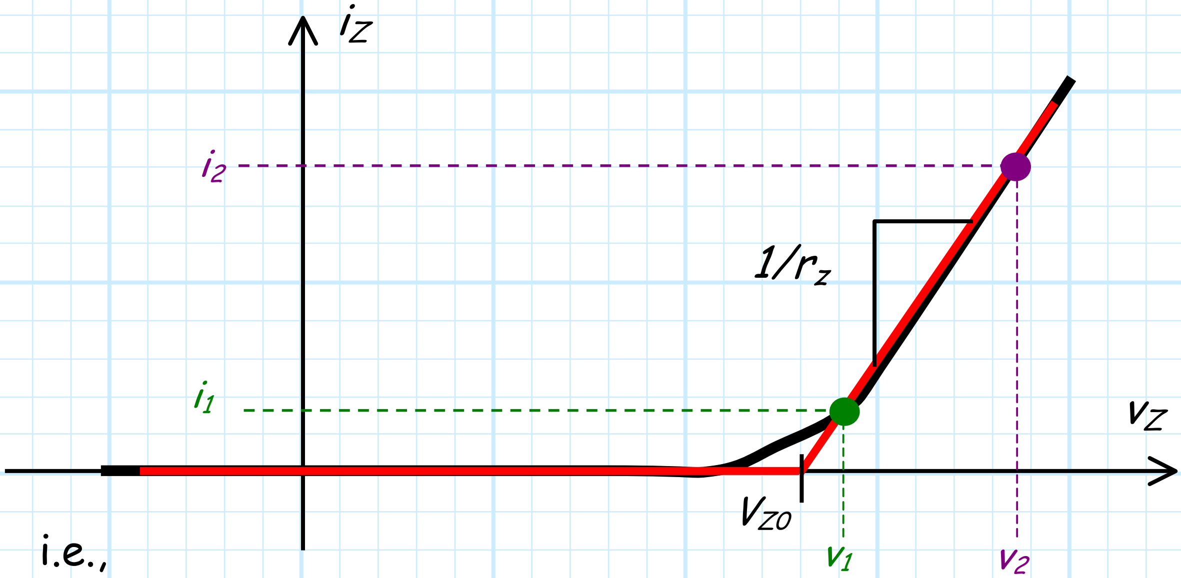


Just like a **Zener** diode in **breakdown**!



Q: *How do we **construct** this PWL model (i.e., find V_{Z0} and r_z)?*

A: Pick **two points** on the zener diode curve (v_1, i_1) and (v_2, i_2), and then select r_z and V_{Z0} so that the PWL model line **intersects** them.



i.e.,

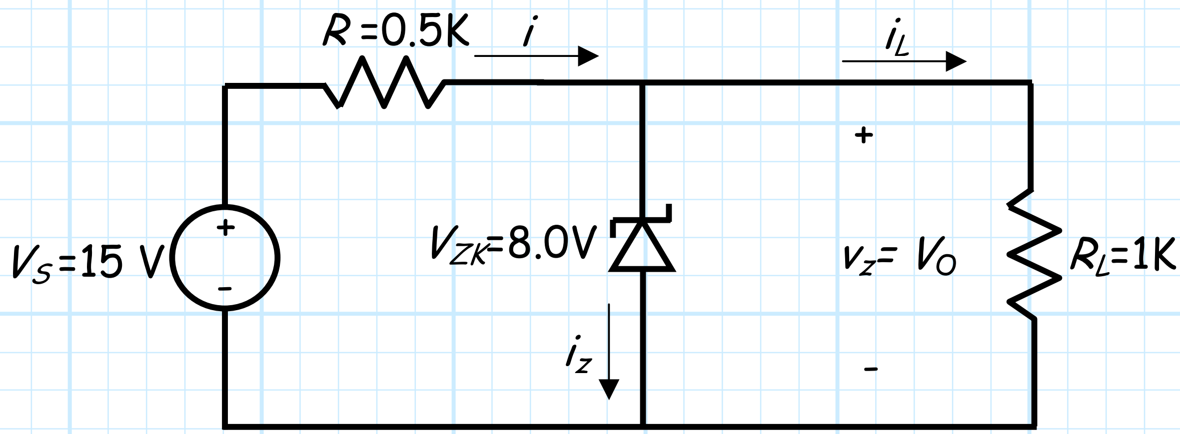
$$r_z = \frac{v_2 - v_1}{i_2 - i_1}$$

and

$$V_{z0} = v_1 - i_1 r_z \qquad \text{or} \qquad V_{z0} = v_2 - i_2 r_z$$

Example: Zener Diode Circuit Analysis

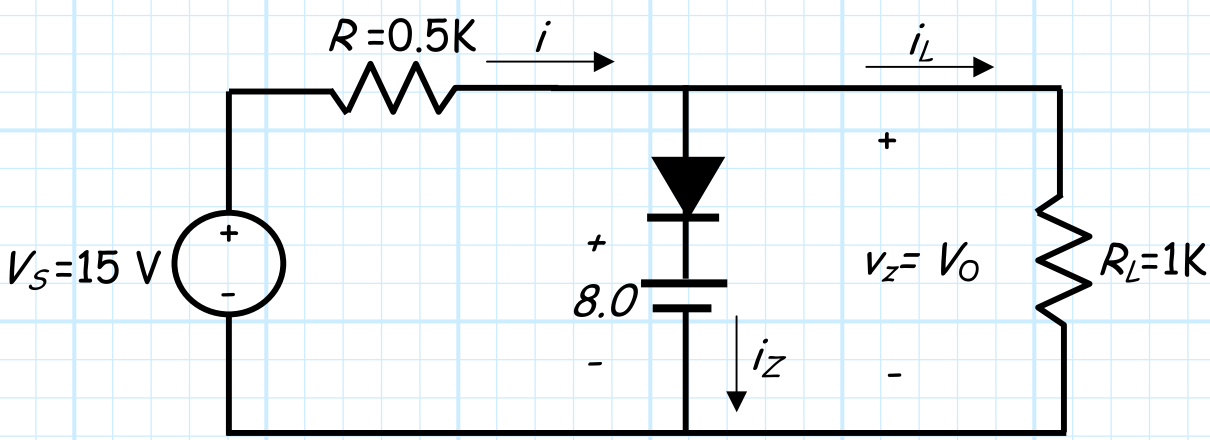
Consider the circuit below:



Note that the load resistor R_L is in **parallel** with the Zener diode, so that the voltage V_O across this load resistor is **equal** to the Zener diode voltage v_Z.

Q: *So just what is the value of voltage V_O?*

A: Let's **replace** the Zener diode with a **Zener CVD model** and find out!



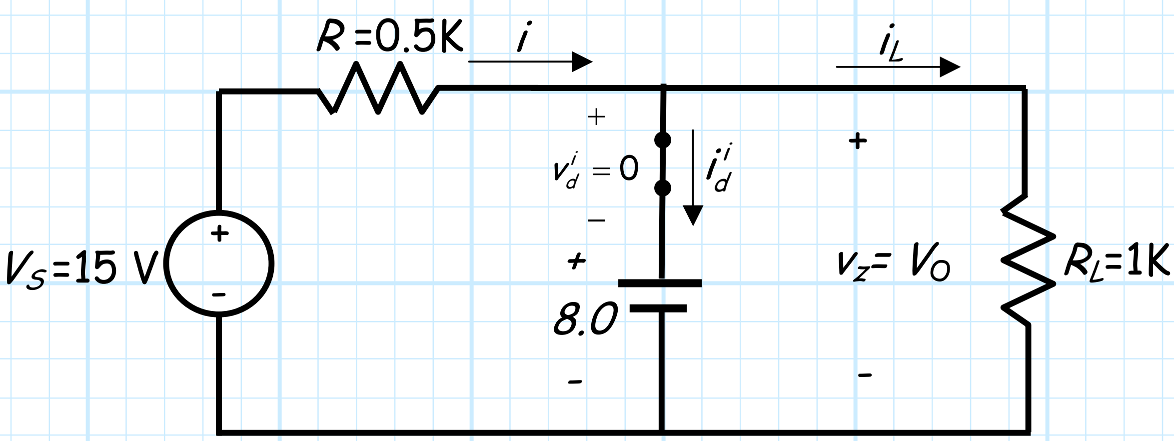
Q: *Yikes! We have an **IDEAL** diode circuit!*

A: Yes! We analyze it **precisely** like we did in section 3.1—remember, there are **no** Zener diodes in the circuit above!

ASSUME: IDEAL diode is **forward biased**.

ENFORCE: $v_d^i = 0$

ANALYZE:



From KVL:

$$v_Z = V_O = v_D^i + 8.0 = 0 + 8.0 = 8.0 \text{ V}$$

From KCL:

$$i = i_D^i + i_L$$

where from Ohm's Law:

$$i = \frac{15 - 8.0}{0.5} = 14 \text{ mA}$$

and:

$$i_L = \frac{8.0}{1} = 8.0 \text{ mA}$$

Therefore:

$$\begin{aligned} i_D^i &= i - i_L \\ &= 14 - 8 \\ &= 6 \text{ mA} \end{aligned}$$

CHECK:

$$i_D^i = 6mA > 0 \quad \checkmark$$

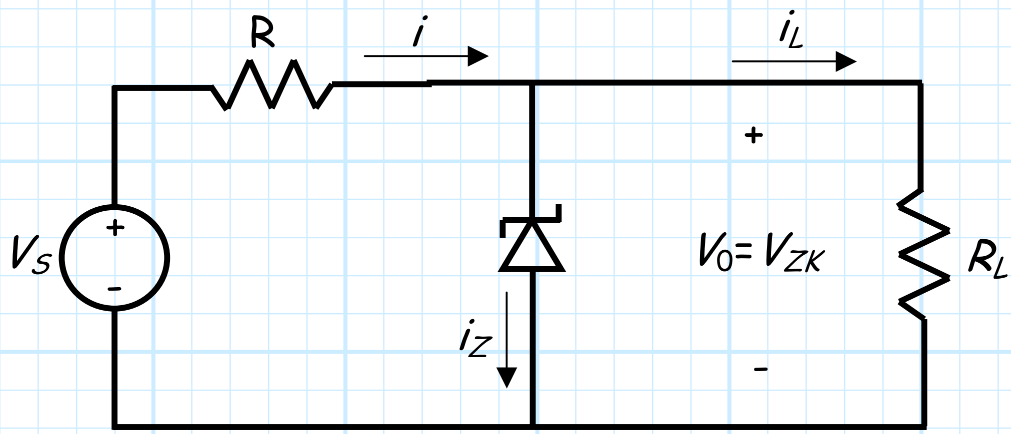
Look at what this means!

→ The voltage across load resistor R_L is equal to the Zener breakdown voltage V_{ZK}—**regardless** of the value of load resistor R_L or source voltage V_S (provided, of course, that the Zener diode is in breakdown)!

This is an example of a primary **application** of Zener diodes—**voltage regulation.**

We call this particular regulator circuit the **shunt regulator**.

The Shunt Regulator



The shunt regulator is a ***voltage regulator***. That is, a device that keeps the voltage across some load resistor (R_L) ***constant***.

Q: *Why would this voltage **not** be a constant?*

A: Two reasons:

(1) the **source voltage** V_s may vary and **change** with time.

(2) The **load** R_L may also vary and **change** with time. In other words, the **current** i_L delivered to the load may change.

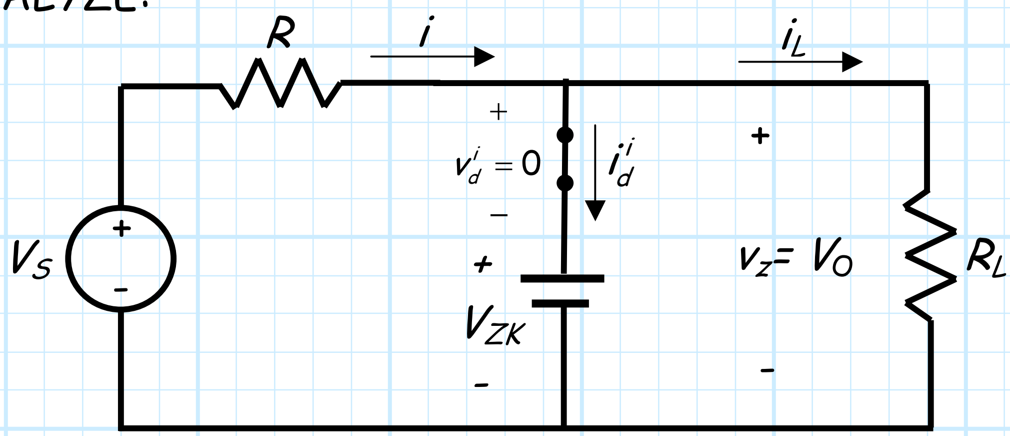
What can we do to keep load voltage V_O **constant**?

$\Rightarrow$ Employ a **Zener diode** in a **shunt regulator** circuit!

Let's **analyze** the shunt regulator circuit in terms of Zener breakdown voltage V_{ZK}, source voltage V_S , and load resistor R_L.

Replacing the Zener diode with a **Zener CVD model**, we ASSUME the ideal diode is **forward** biased, and thus ENFORCE $v_D^i = 0$.

ANALYZE:



From KVL:

$$v_Z = V_O = v_D^i + V_{ZK} = V_{ZK}$$

From KCL:

$$i = i_D^i + i_L$$

where:

$$i = \frac{V_S - V_{ZK}}{R}$$

and:

$$i_L = \frac{V_{ZK}}{R_L}$$

Therefore:

$$\begin{aligned} i_D^i &= i - i_L \\ &= \frac{V_S - V_{ZK}}{R} - \frac{V_{ZK}}{R_L} \\ &= \frac{V_S}{R} - \frac{V_{ZK}\left(R + R_L\right)}{RR_L} \end{aligned}$$

CHECK:

Note we find that ideal diode is forward biased **if**:

$$i_D^i = \frac{V_S}{R} - \frac{V_{ZK}\left(R + R_L\right)}{RR_L} > 0$$

or therefore:

$$\frac{V_S}{R} - \frac{V_{ZK}\left(R + R_L\right)}{RR_L} > 0$$

$$\frac{V_S}{R} > \frac{V_{ZK}\left(R + R_L\right)}{RR_L}$$

$$V_S \frac{R_L}{R + R_L} > V_{ZK}$$

Hence, the Zener diode may **not** be in breakdown (i.e., the ideal diode may not be f.b.) **if** V_S or R_L are too small, or shunt resistor R is too large!

Summarizing, we find that **if**:

$$V_S \frac{R_L}{R + R_L} > V_{ZK}$$

then:

1. The Zener diode is in breakdown.

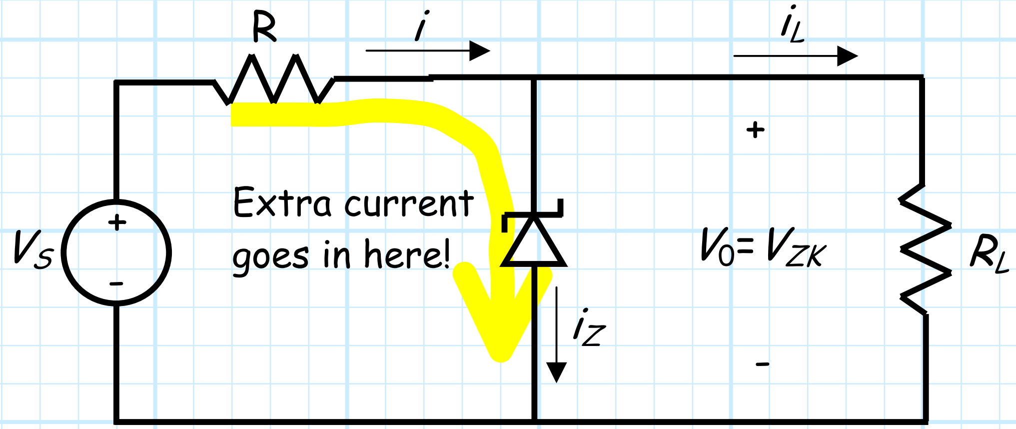
2. The load voltage $V_O = V_{ZK}$.

3. The load current is $i_L = V_{ZK} / R_L$.

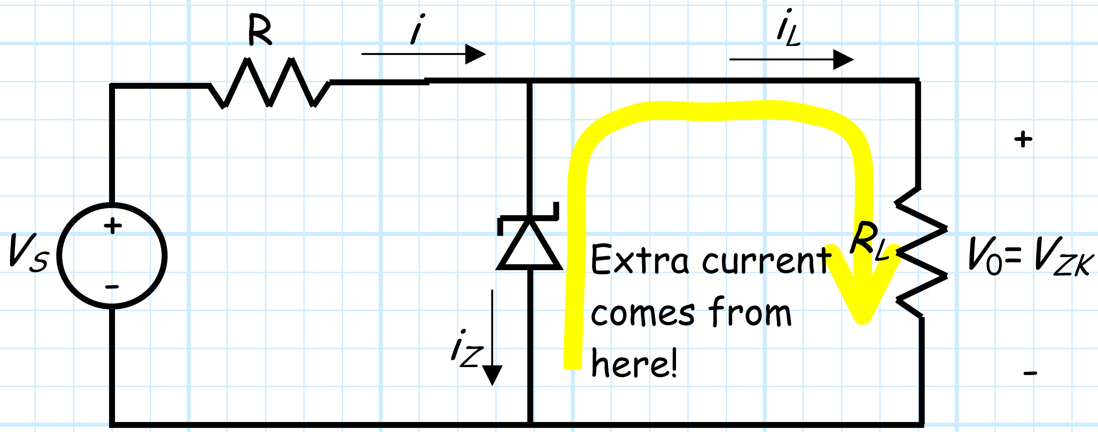
4. The current through the shunt resistor R is $i = (V_S - V_{ZK}) / R$.

5. The current through the Zener diode is $i_Z = i - i_L > 0$.

We find then, that if the **source voltage** V_S **increases**, the current i through shunt resistor R will likewise increase. However, this extra current will result in an **equal** increase in the **Zener diode current** i_Z—thus the load current (and therefore load voltage V_O) will remain **unchanged**!



Similarly, if the **load current** i_L **increases** (i.e., R_L decreases), then the Zener current i_Z will decrease by an **equal** amount. As a result, the current through shunt resistor R (and therefore the load voltage V_O) will remain **unchanged**!



Q: You mean that V_O stays **perfectly constant**, regardless of source voltage V_S or load current i_L??

A: Well, V_O remains **approximately** constant, but it **will** change a **tiny** amount when V_S or i_L changes.

To determine precisely how **much** the load voltage V_O changes, we will need to use a more **precise** Zener diode model (i.e., the Zener **PWL**)!

Line Regulation

Since the Zener diode in a shunt regulator has some small (but non-zero) dynamic resistance r_Z, we find that the load voltage V_O will have a **small** dependence on source voltage V_S.

In other words, if the source voltage V_S **increases** (decreases), the load voltage V_O will **likewise** increase (decrease) by some very small amount.

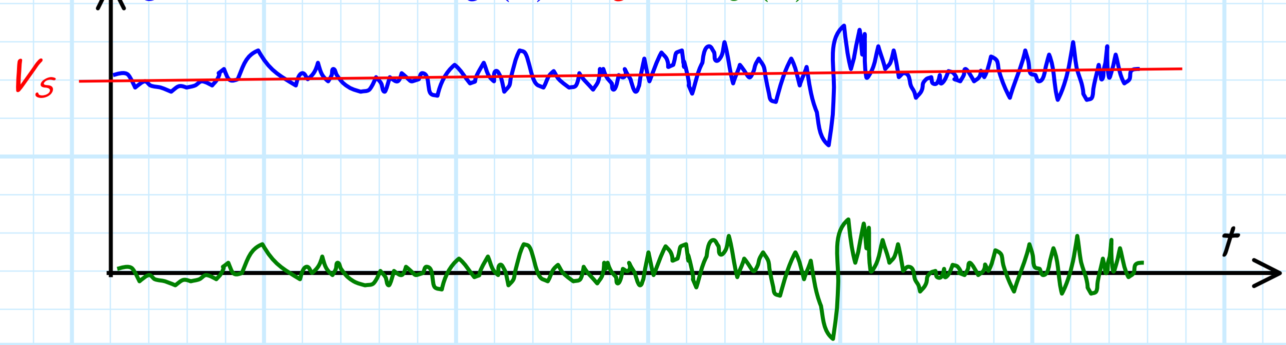
Q: ***Why*** *would the source voltage V_S ever change?*

A: There are **many** reasons why V_S will not be a perfect constant with time. Among them are:

1. Thermal **noise**
2. Temperature **drift**
3. Coupled **60 Hz** signals (or digital clock signals)

As a result, it is more appropriate to represent the **total** source voltage as a time-varying signal ($v_s(t)$), consisting of both a **DC** component (V_S) and a **small-signal** component ($\Delta v_s(t)$):

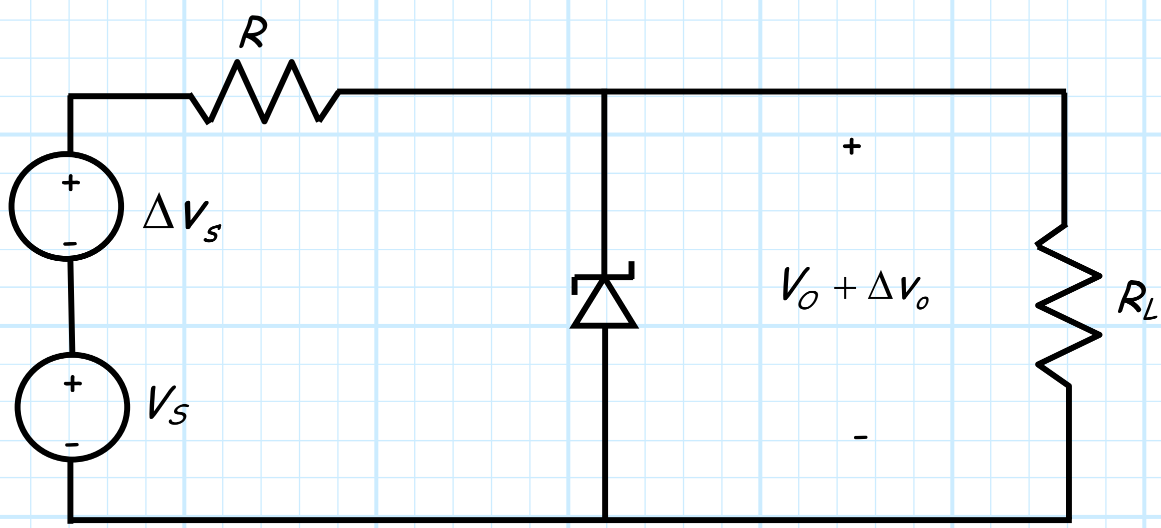
$$v_S(t) = V_S + \Delta v_s(t)$$



As a result of the small-signal source voltage, the total **load** voltage is likewise time-varying, with both a DC (V_O) and small-signal (Δv_o) component:

$$v_O(t) = V_O + \Delta v_o(t)$$

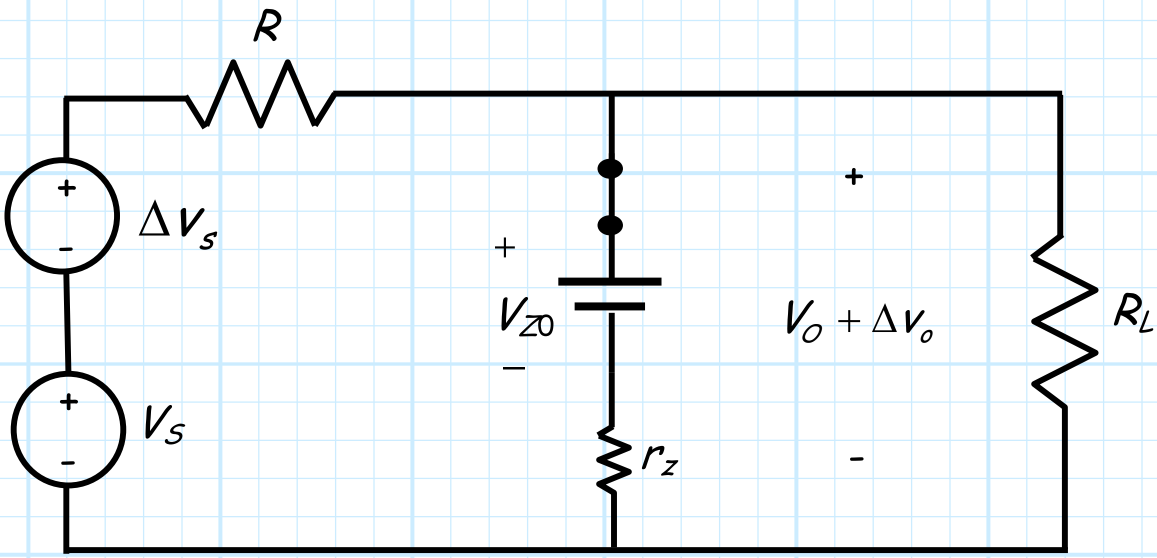
So, we know that the DC source V_S produces the DC load voltage V_O, whereas the small-signal **source** voltage Δv_s results in the small-signal **load** voltage Δv_o.



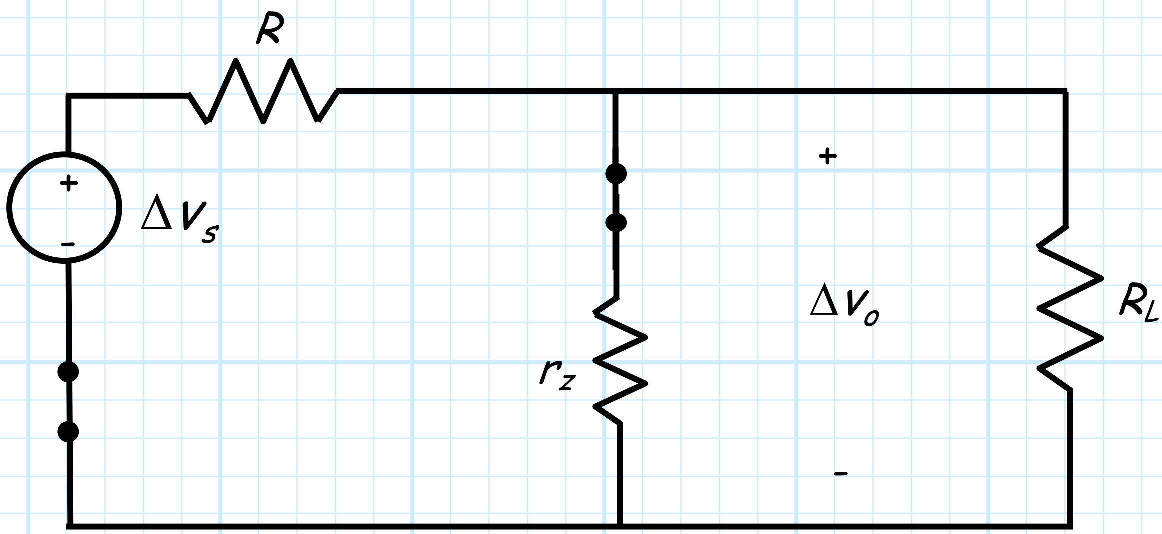
Q: *Just how are Δv_s and Δv_o **related**? I mean, if Δv_s equals, say, **500 mV**, what will value of Δv_o be?*

A: Determining this answer is **easy**! We simply need to perform a **small-signal analysis**.

In other words, we first replace the Zener diode with its **Zener PWL model**.



We then turn **off** all the **DC** sources (including V_{ZO}) and analyze the remaining **small-signal circuit**!



From **voltage division**, we find: $\Delta v_o = \Delta v_s \left(\dfrac{r_Z \| R_L}{R + r_Z \| R_L} \right)$

However, recall that the value of a Zener dynamic resistance r_Z is **very small**. Thus, we can assume that $r_Z >> R_L$, and therefore $r_Z \| R_L \approx r_Z$, leading to:

$$\Delta v_o = \Delta v_s \left(\frac{r_Z \| R_L}{R + r_Z \| R_L} \right)$$
$$\approx \Delta v_s \left(\frac{r_Z}{r_Z + R} \right)$$

Rearranging, we find:

$$\boxed{\frac{\Delta v_o}{\Delta v_s} = \frac{r_Z}{r_Z + R} \doteq \textit{line regulation}}$$

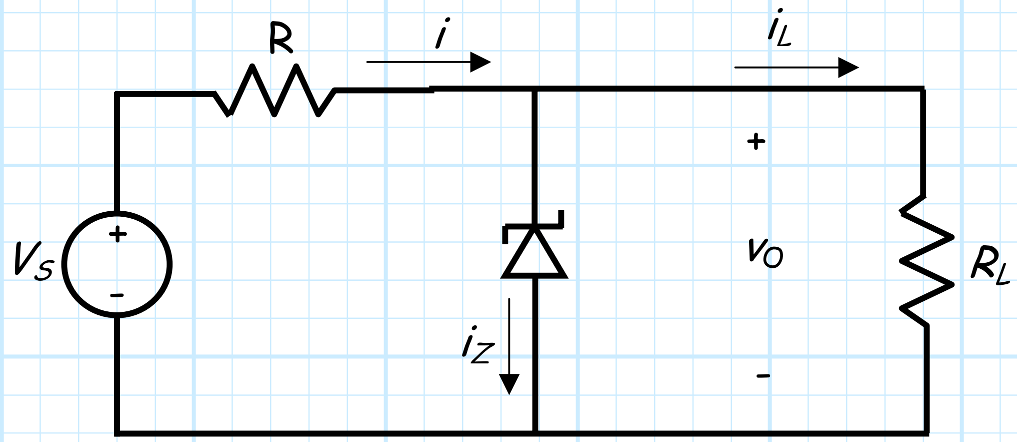
This equation describes an important performance parameter for shunt regulators. We call this parameter the **line regulation.**

* Line regulation allows us to determine the **amount** that the load voltage changes (Δv_o) when the source voltage changes (Δv_s).

* For example, if line regulation is 0.002, we find that the load voltage will increase 1 mV when the source voltage increases 500mV
(i.e., $\Delta v_o = 0.002 \Delta v_s = 0.002(0.5) = 0.001\text{ V}$).

* **Ideally**, line regulation is **zero**. Since dynamic resistance r_Z is typically very small (i.e., $r_Z \ll R$), we find that the line regulation of most shunt regulators is likewise **small** (this is a **good** thing!).

Load Regulation



For voltage regulators, we typically define a **load** R_L in terms of its **current** i_L, where:

$$i_L = \frac{v_O}{R_L}$$

Note that since the load (i.e., regulator) voltage v_O is a constant (approximately), specifying i_L is **equivalent** to specifying R_L, and vice versa!

Now, since the Zener diode in a shunt regulator has some small (but non-zero) dynamic resistance r_Z, we find that the load voltage v_O will also have a **very small** dependence on load resistance R_L (or equivalently, **load current** i_L).

In fact, if the load current i_L **increases** (decreases), the load voltage v_O will actually **decrease** (increase) by some small amount.

Q: ***Why*** *would the load current i_L ever change?*

A: You must realize that the load resistor R_L simply **models** a more **useful** device. The "load" may in fact be an amplifier, or a component of a cell phone, or a circuit board in a digital computer.

These are all **dynamic** devices, such that they may require **more** current at some times than at others (e.g., the computational load increases, or the cell phone begins to transmit).

As a result, it is more appropriate to represent the **total** load current as a time-varying signal ($i_L(t)$), consisting of both a **DC** component (I_L) and a **small-signal** component ($\Delta i_l(t)$):

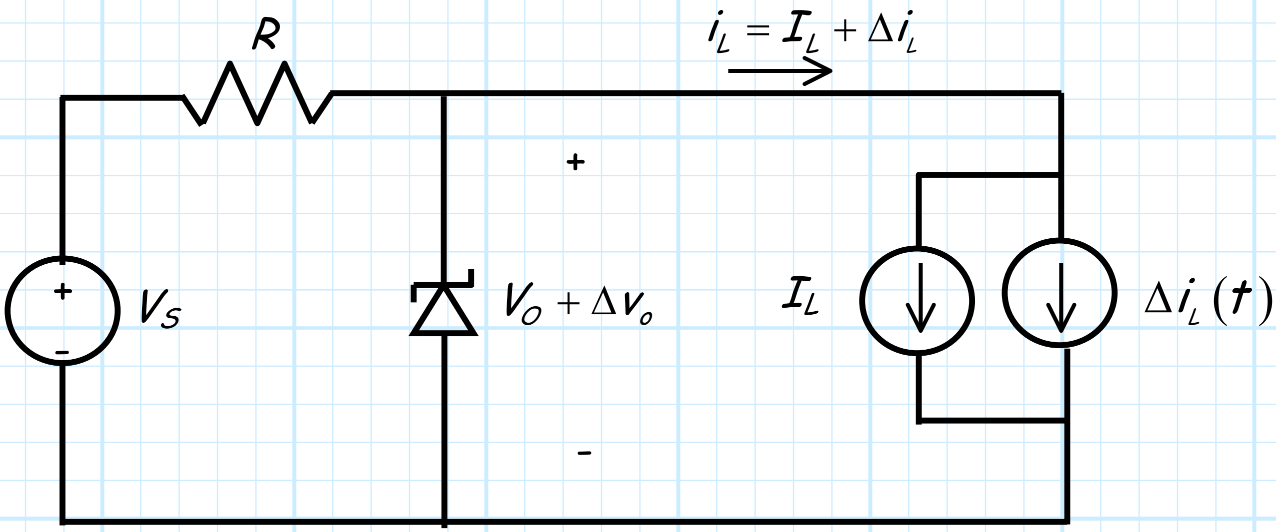
$$i_L(t) = I_L + \Delta i_l(t)$$

This small-signal load current of course leads to a load voltage that is **likewise** time-varying, with both a DC (V_O) and small-signal (Δv_o) component:

$$v_O(t) = V_O + \Delta v_o(t)$$

So, we know that the DC load current I_L produces the DC load voltage V_O, whereas the small-signal **load current** $\Delta i_l(t)$ results in the small-signal **load** voltage Δv_o.

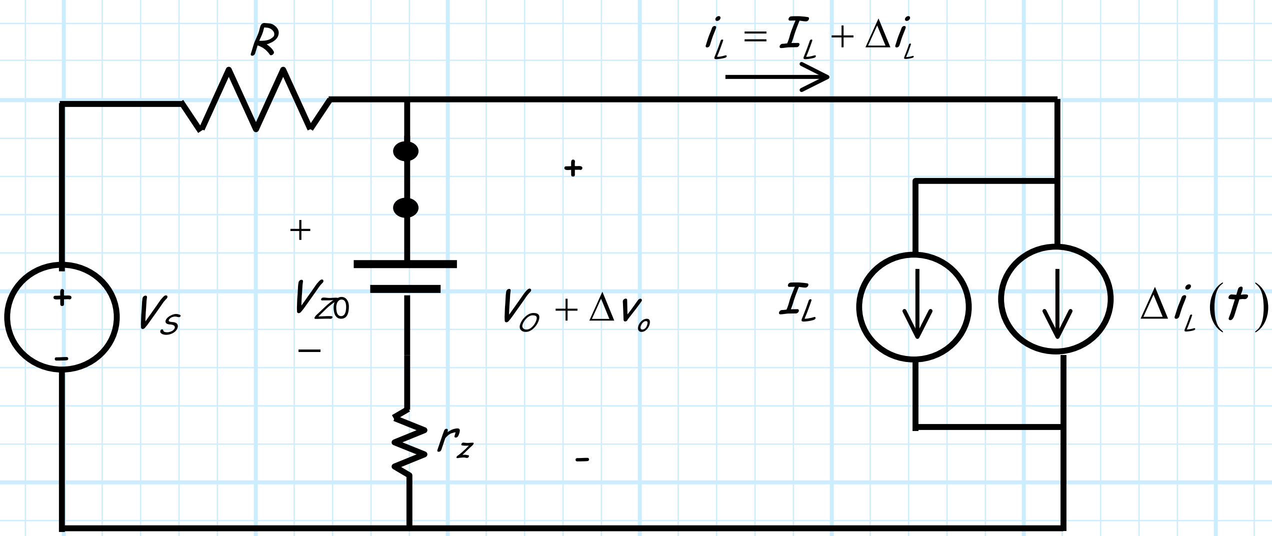
We can **replace** the load resistor with **current sources** to represent this load current:



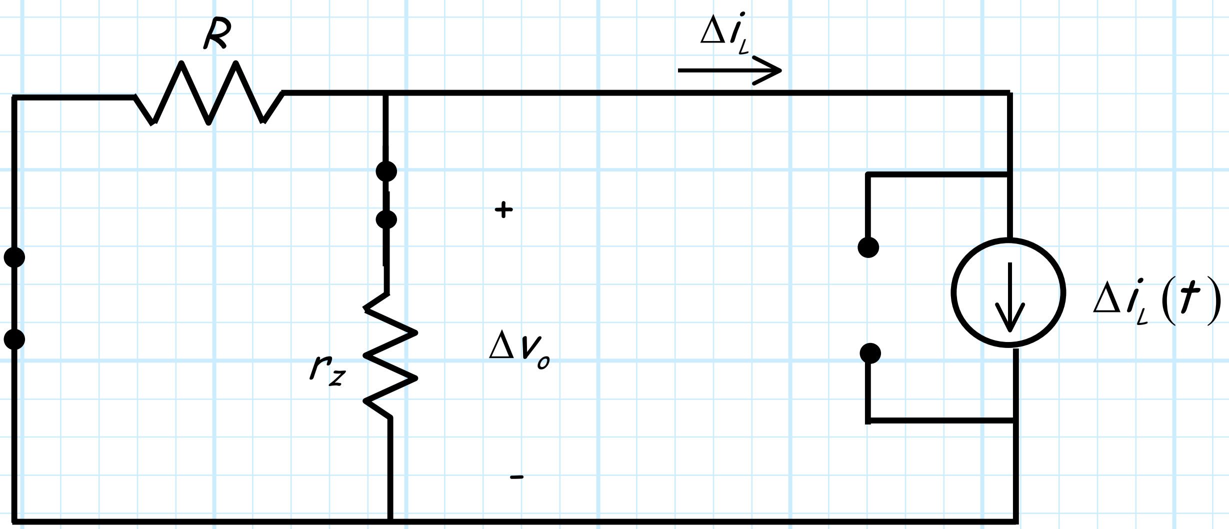
Q: *Just how are Δv_s and Δv_o **related**? I mean, if Δi_L equals, say, **50 mA**, what will value of Δv_o be?*

A: Determining this answer is **easy**! We simply need to perform a **small-signal analysis**.

In other words, we first replace the Zener diode with its **Zener PWL model**.



We then turn **off** all the **DC** sources (including V_{ZO}) and analyze the remaining **small-signal circuit**!



From **Ohm's Law,** it is evident that:

$$\begin{aligned}\Delta v_o &= -\Delta i_L \left(r_Z \| R \right) \\ &= -\Delta i_L \left(\frac{r_Z R}{r_Z + R} \right)\end{aligned}$$

Rearranging, we find:

$$\boxed{\text{load regulation} \doteq \frac{\Delta v_o}{\Delta i_L} = -\frac{r_Z R}{r_Z + R} = -r_Z \| R \approx -r_z \qquad [Ohms]}$$

This equation describes an important performance parameter for shunt regulators. We call this parameter the **load regulation.**

* Note load regulation is expressed in units of **resistance** (e.g., Ω).

* Note also that load regulation is a **negative** value. This means that **increasing** i_L leads to a **decreasing** v_O (and vice versa).

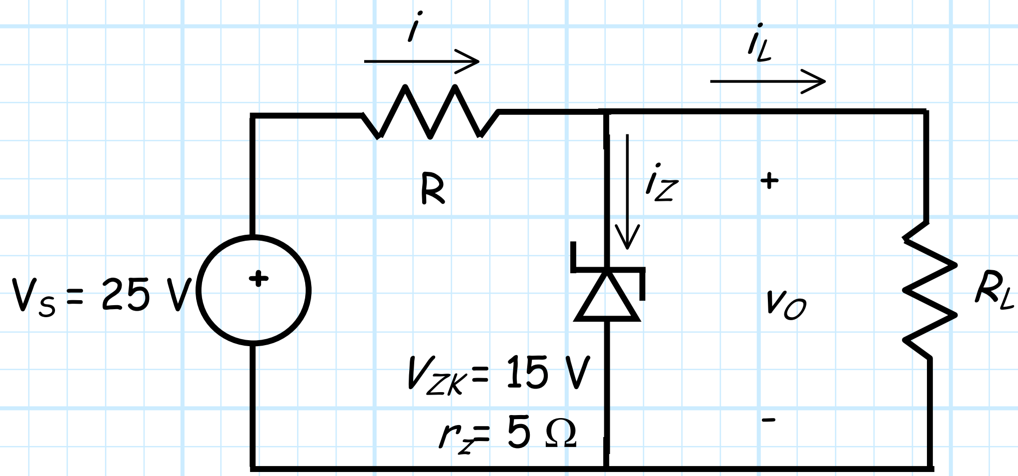
* Load regulation allows us to determine the **amount** that the load voltage changes (Δv_o) when the load current changes (Δi_L).

* For example, if load regulation is -0.0005 KΩ, we find that the load voltage will **decrease** 25 mV when the load current **increases** 50mA
(i.e.,$\Delta v_o = -0.0005\, \Delta i_L = -0.0005(50) = -0.025\text{ V}$).

* **Ideally**, load regulation is **zero**. Since dynamic resistance r_Z is typically very small (i.e., $r_Z \ll R$), we find that the load regulation of most shunt regulators is likewise **small** (this is a **good** thing!).

Example: The Shunt Regulator

Consider the **shunt regulator**, built using a zener diode with V_{ZK}=15.0 V and incremental resistance r_z = 5Ω:



1. **Determine R** if the largest possible value of i_L is 20 mA.

2. Using the value of R found in part 1 **determine** i_Z **if** R_L=1.5 K.

3. Determine the **change in** v_O if V_S increases one volt.

4. Determine the **change in** v_O if i_L increases 1 mA.

Part 1:

From KCL we know that $i = i_Z + i_L$.

We also know that for the diode to remain in breakdown, the zener current must be **positive**.

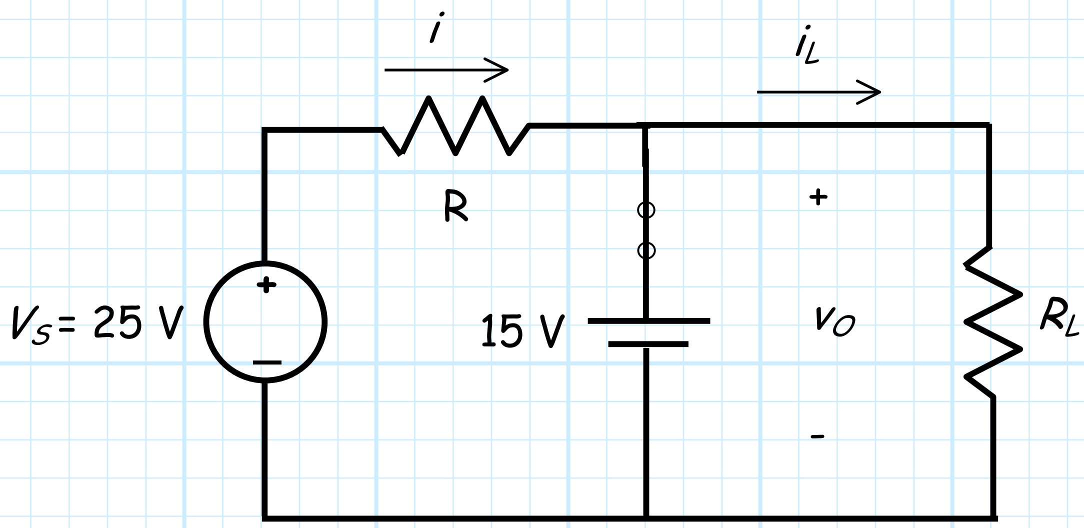
i.e., $i_Z = i - i_L > 0$

Therefore, if i_L can be as large as 20 mA, then i must be greater than 20 mA for i_Z to remain greater than zero.

i.e. $\boldsymbol{i > 20\text{mA}}$

Q: *But, what* ***is*** *i ??*

A: Use the zener CVD model to analyze the circuit.



Therefore from Ohm's Law:

$$i = \frac{V_S - V_{ZK}}{R} = \frac{25 - 15}{R} = \frac{10}{R}$$

and thus $i > 20mA$ **if**:

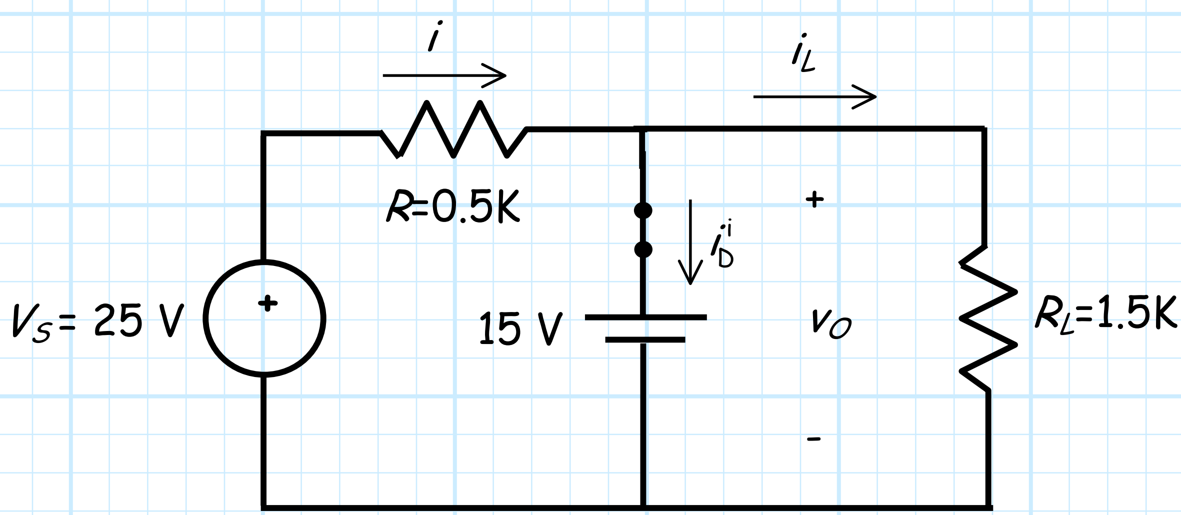
$$R < \frac{10}{20} = 0.5 \text{ K} = 500\ \Omega$$

Note we want R to be as large as possible, as large R improves both **line** and **load** regulation.

Therefore, set $R = 500\ \Omega = 0.5$ K

Part 2:

Again, use the zener **CVD model**, and enforce $v_D^i = 0$:



Analyzing, from KCL:

$$i_D^i = i - i_L$$

and from Ohm's Law:

$$i = \frac{V_s - V_{ZK}}{R} = \frac{25.0 - 15.0}{0.5} = 20.0\ mA$$

$$i_L = \frac{V_{ZK}}{R_L} = \frac{15.0}{1.5} = 10.0\ mA$$

Therefore $i_D^i = i - i_L = 20 - 10 = 10.0\ mA$ $\left(\therefore i_D^i = 10 > 0 \checkmark \right)$

And thus we **estimate** $i_Z = i_D^i = 10.0$ mA

Part 3:

The shunt regulator **line regulation** is:

$$\text{Line Regulation} = \frac{r_z}{R + r_z} = \frac{5}{500+5} = 0.01$$

Therefore if $\Delta v_s = 1$ V, then $\Delta v_o = (0.01)\ \Delta v_s =$ **0.01 V**

Part 4:

The shunt regulator **load regulation** is:

$$\text{Load Regulation} = \frac{-R\ r_z}{R + r_z} = \frac{-(500)5}{500+5} = -4.95\ \Omega$$

Therefore if $\Delta i_L = 1$ mA, then $\Delta v_o = -(4.95)\Delta i_L =$ **-4.95 mV**