3.4 Operation in the Reverse Breakdown Region — Zener Diodes

Reading Assignment: pp. 167-171

A **Zener** Diode →

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

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2.

3.

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

➔ Manufacturer **assumes** diode will be operated in **breakdown** region. Therefore:

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A Zener Diode is a junction diode!

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→ Manufacturer **assumes** diode will be operated in **breakdown** region. Therefore:

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: Fun with Zener Diodes

1. Manufacturer <u>exactly</u> specifies V_{ZK}

2. ____

3. ____

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Big solution ->

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Q: *How do we **analyze** zener diodes circuits?*

A: **Same** as junction diode circuits—with diode <u>models</u>!

Big problem -> Our current models do <u>not</u> match diode behavior in breakdown!

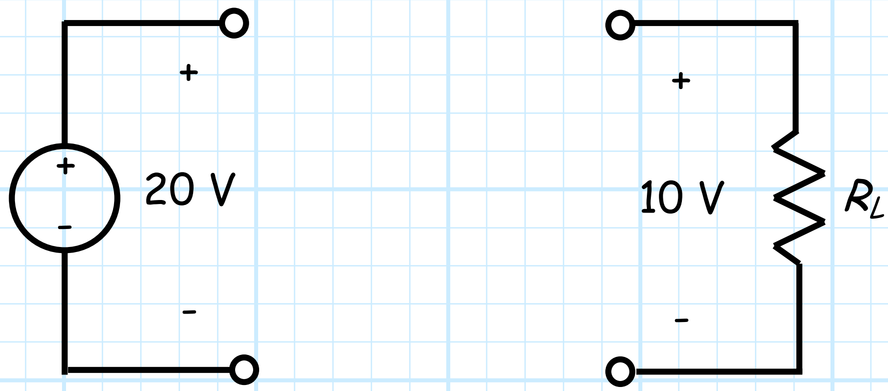
Big solution -> Create new diode models!

<u>HO: Zener Diode Models</u>

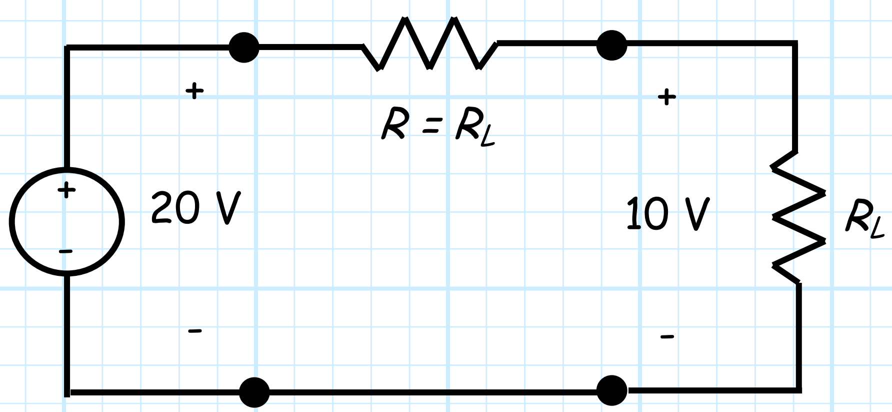
<u>Example: Fun with Zener Diodes</u>

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

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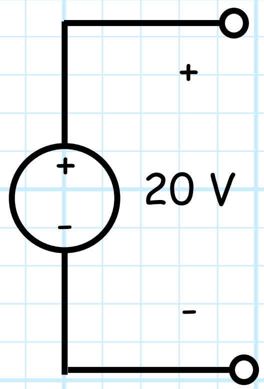
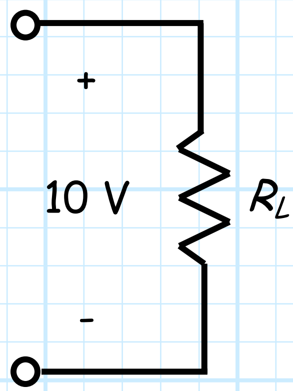
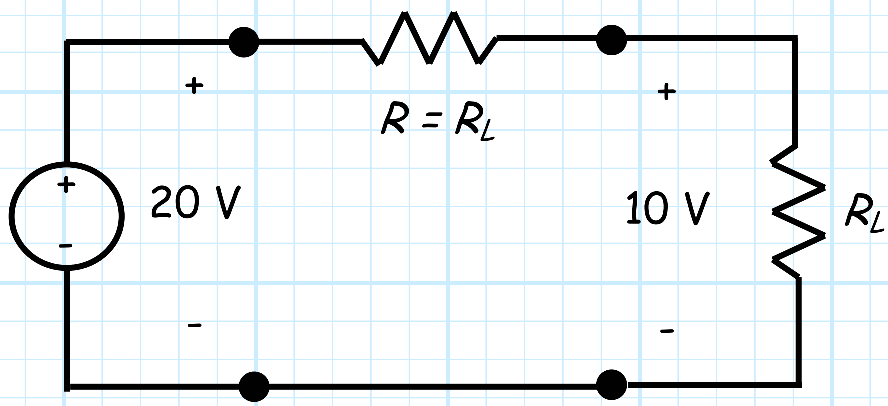




The solution **seems** easy! → insert a resistor $R=R_L$ and form a voltage divider (?):



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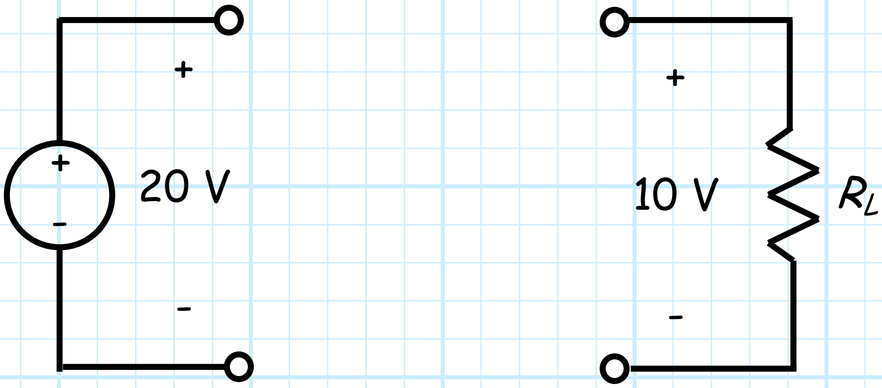

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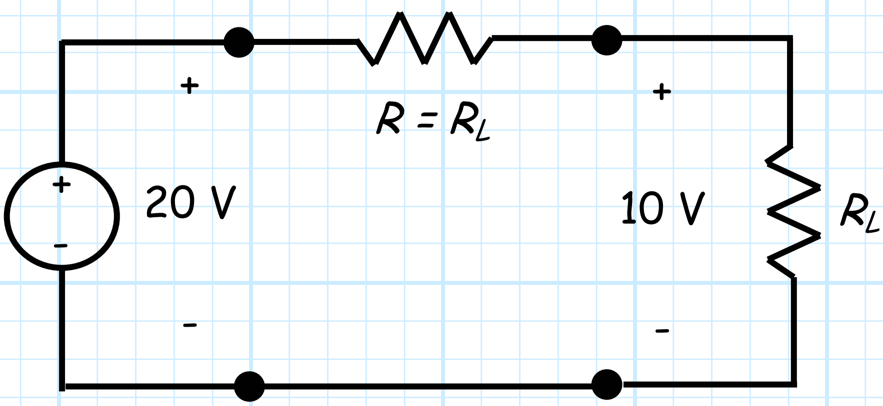


This, in fact is a **very bad** solution—we need a Zener diode to regulate the voltage!

HO: The Shunt Regulator

Two primary **measures** of voltage regulator effectiveness are **line regulation** and **load regulation.**

HO: Line Regulation

HO: Load Regulation

Example: The Shunt Regulator

Another important aspect of voltage regulation is power efficiency!

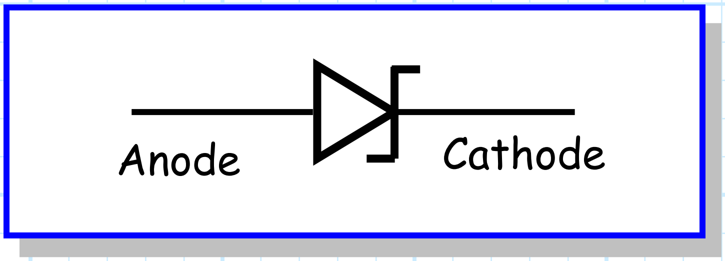
Regulator Power and Efficiency

One last point; voltage regulation can (and is) achieved by **other** means.

Voltage Regulators

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.

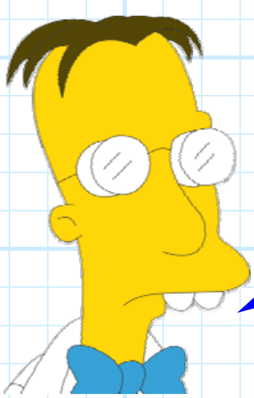
For both these **two** operating regions, the cathode **voltage** will be greater than the anode voltage, i.e.,:

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

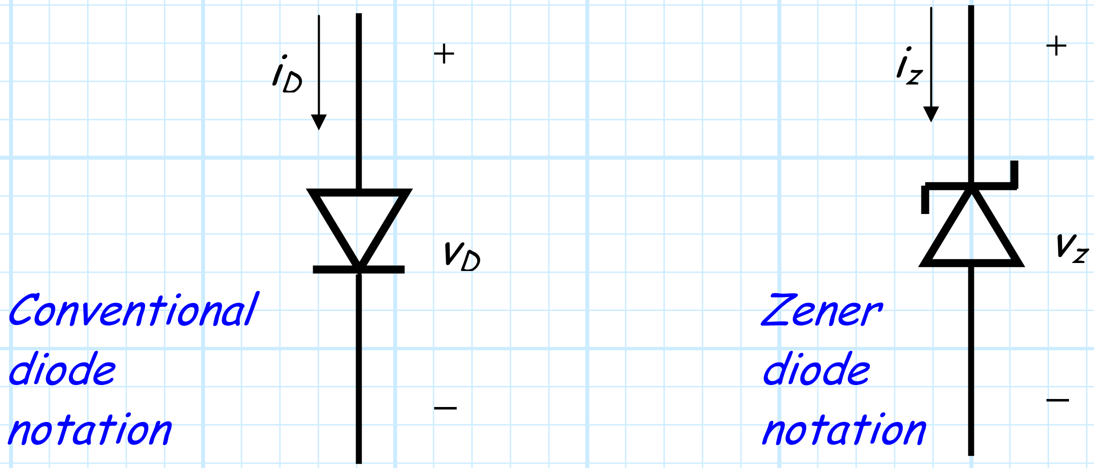
Likewise, the diode **current** (although often tiny) will flow from cathode to anode for these two modes:

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

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!*

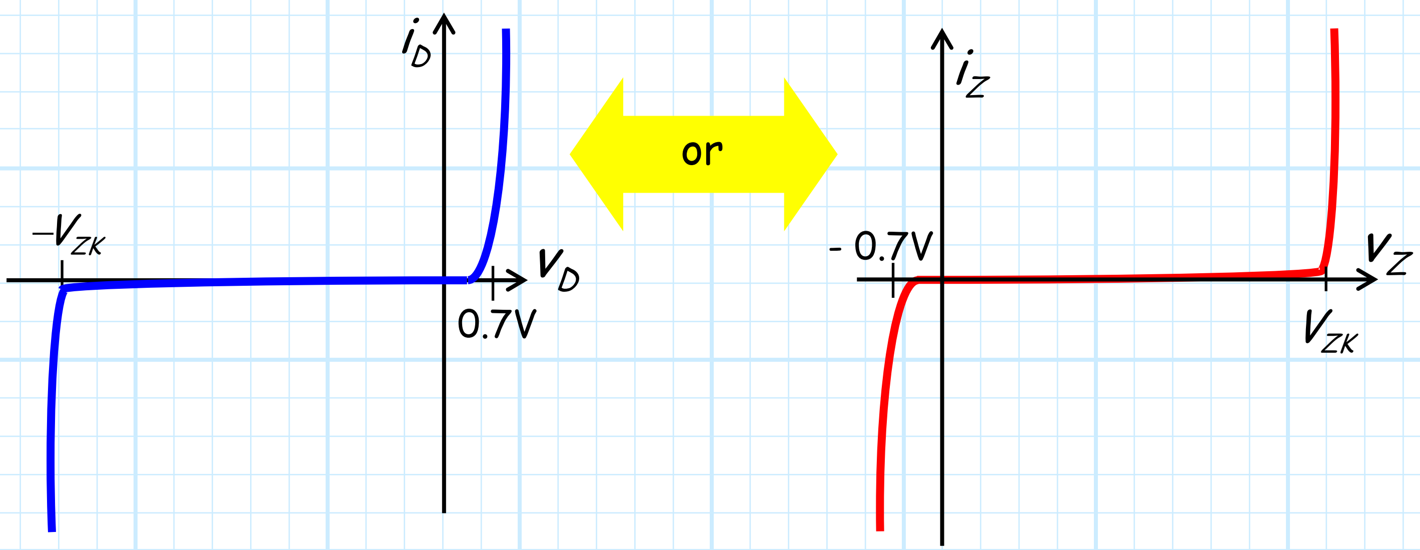


* In other words, for a Zener diode, we denote current flowing from **cathode to anode** as positive.

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

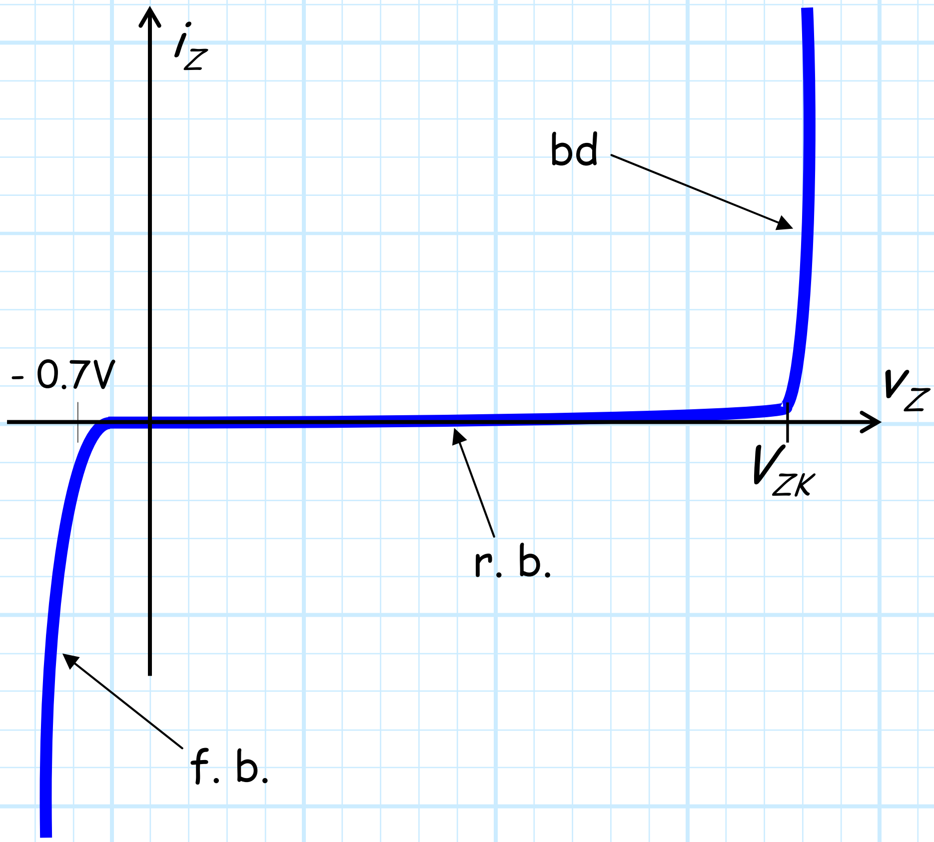
Note that each of the above two statements are precisely **opposite** to the "conventional" junction diode notation that we have used thus far:

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



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:

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

Likewise, in **reverse bias**:

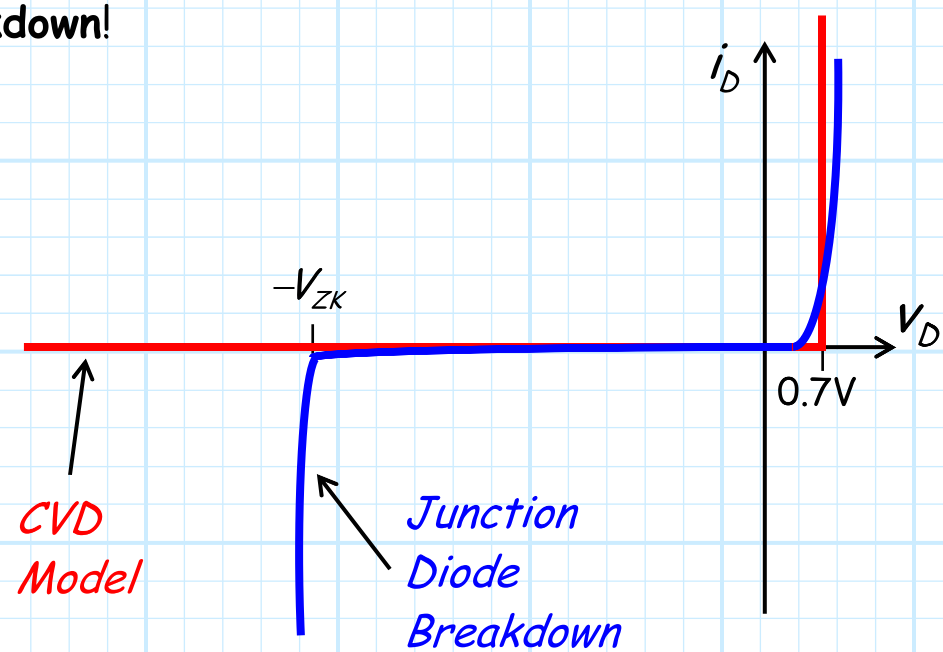
$$i_Z \approx I_s \quad \text{and} \quad 0 < v_Z < V_{ZK}$$

And finally, for **breakdown**:

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

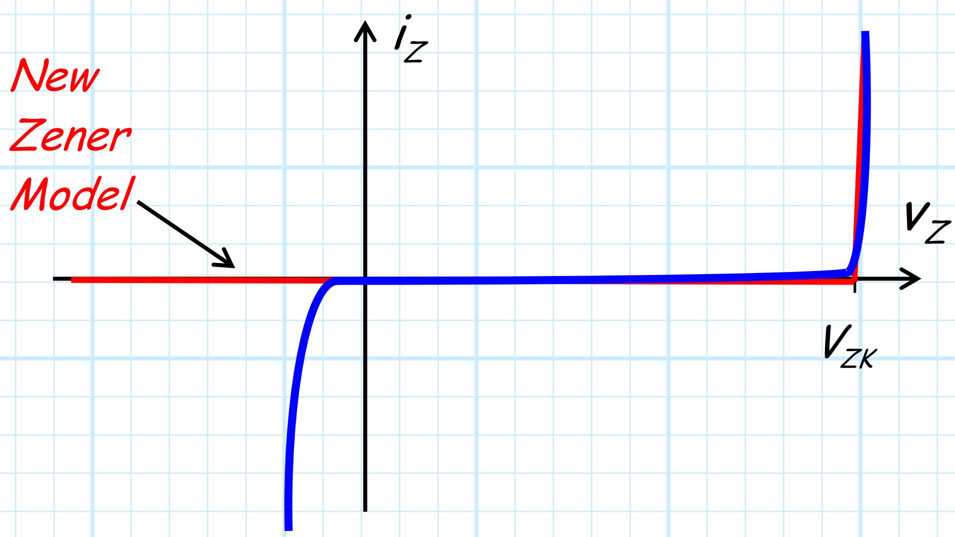
Zener Diode Models

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:

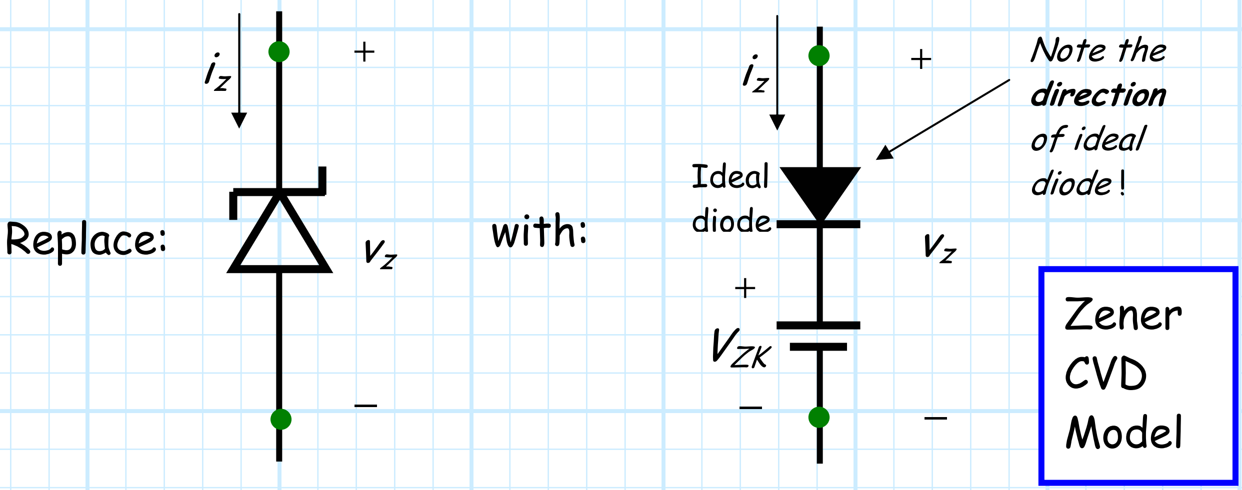
$$i_Z \approx I_s \approx 0 \quad \text{and} \quad v_Z < V_{ZK}$$

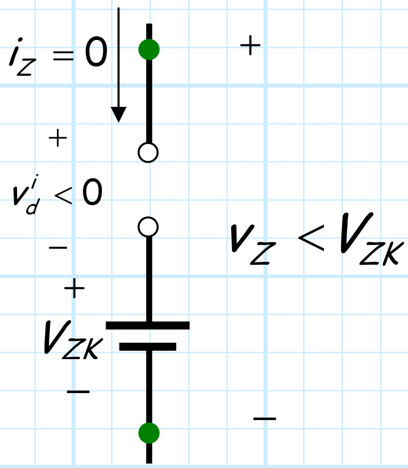
Whereas a Zener in **breakdown** is approximately stated as:

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

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:

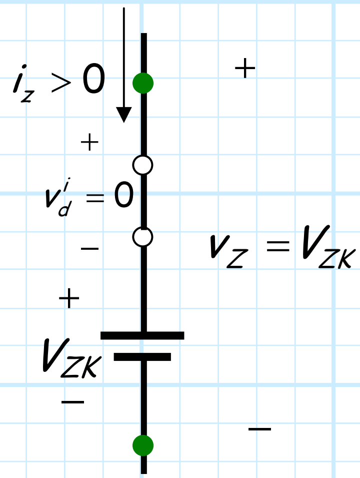
$$i_Z = 0 \quad \text{and} \quad v_Z < V_{ZK}$$

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:

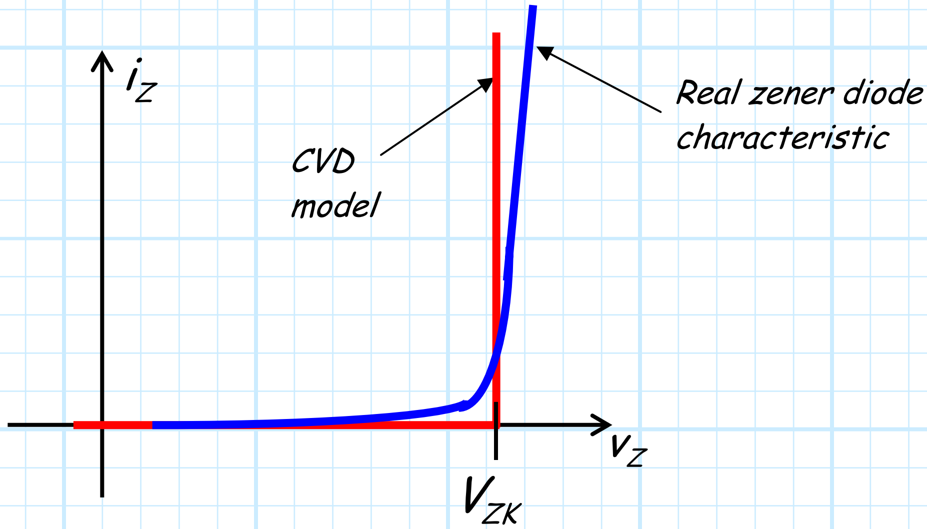
$$i_Z > 0 \quad \text{and} \quad v_Z = V_{ZK}$$

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.

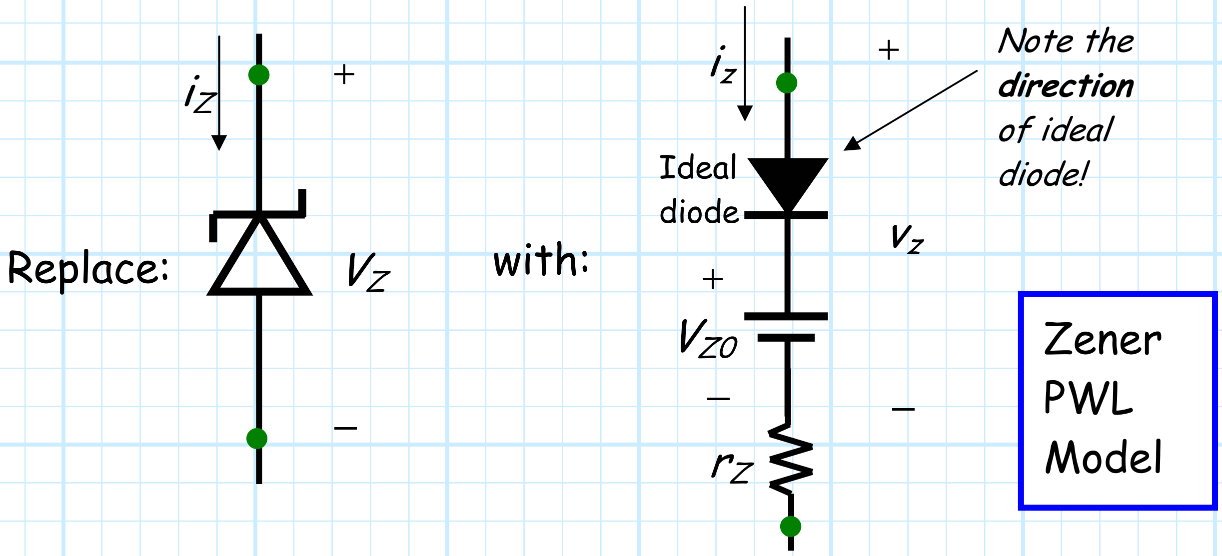


Thus, the CVD model causes a **small** error, usually acceptable—but for some cases **not**!

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

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

The Zener Piecewise Linear Model

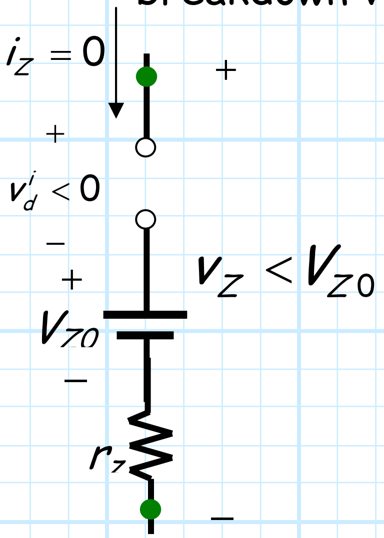


Please Note:

* 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**.

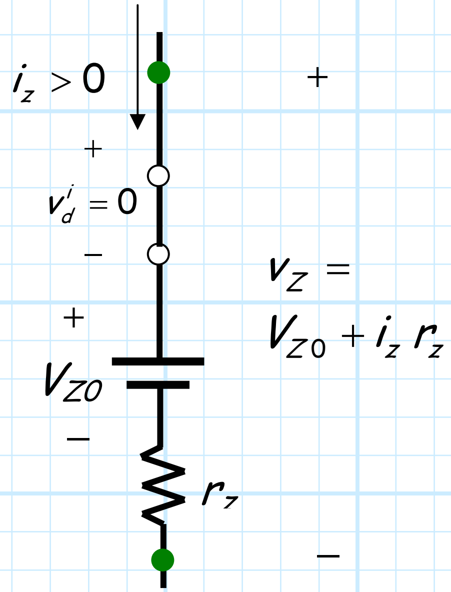
* The voltage source V_{Z0} is **not** equal to the zener breakdown voltage V_{ZK}, however, it is typically **very close**!



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**!

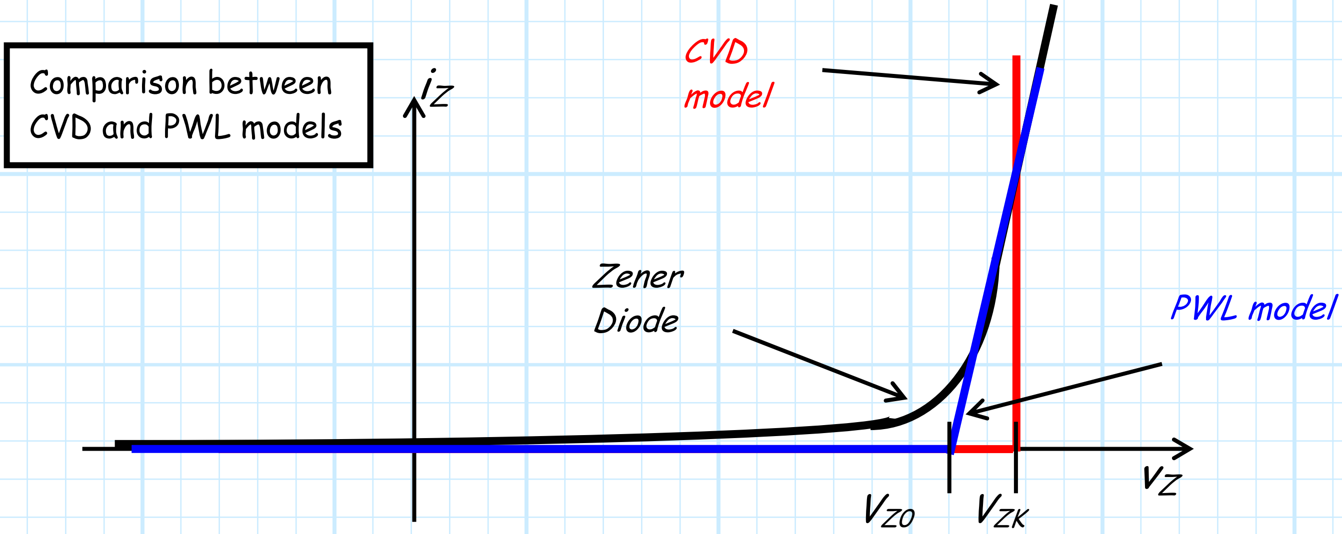


Likewise, we find that **if** the model current is positive ($i_Z > 0$), then the **ideal** diode must be **forward** biased, and thus:

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

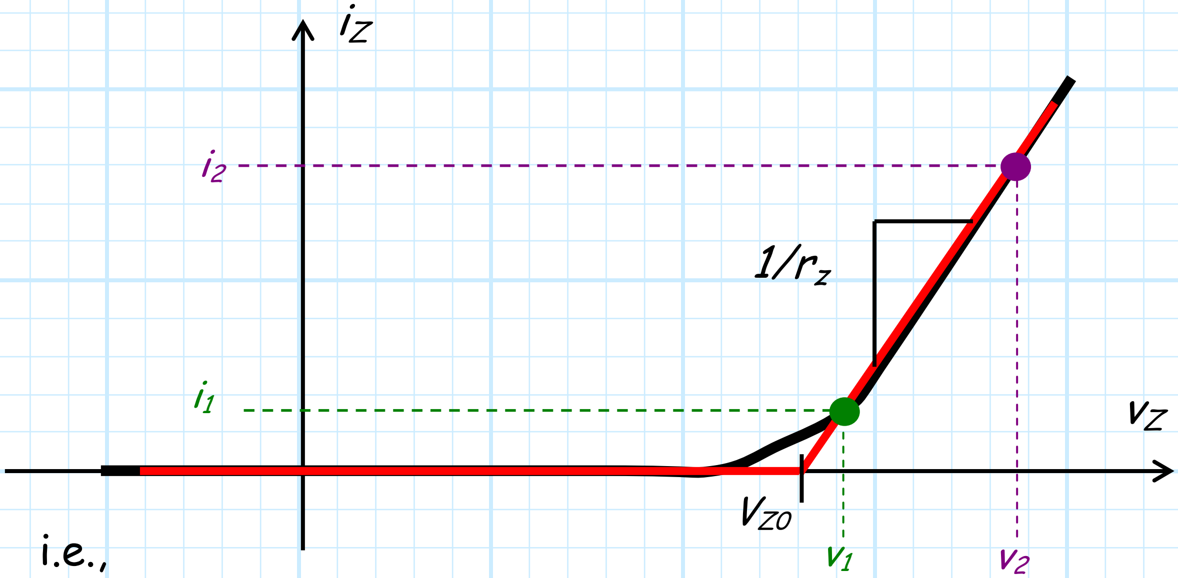
Note that the model voltage v_Z will be near V_{ZK}, but will increase **slightly** as the model current increases.

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.,

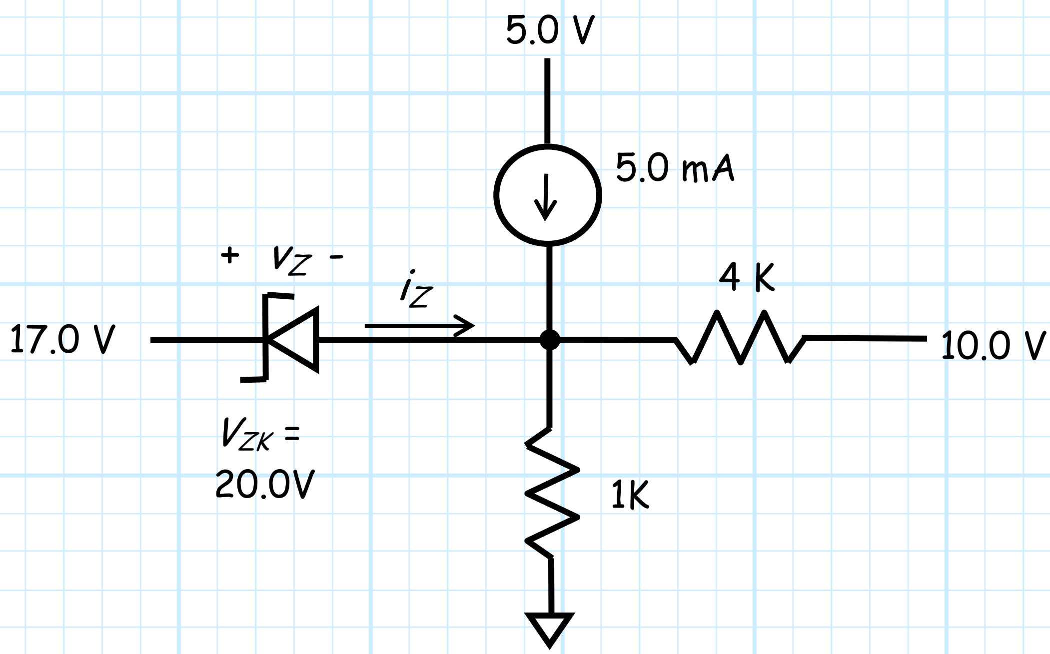
$$r_z = \frac{v_2 - v_1}{i_2 - i_1}$$

and

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

Example: Fun with Zener Diode Models

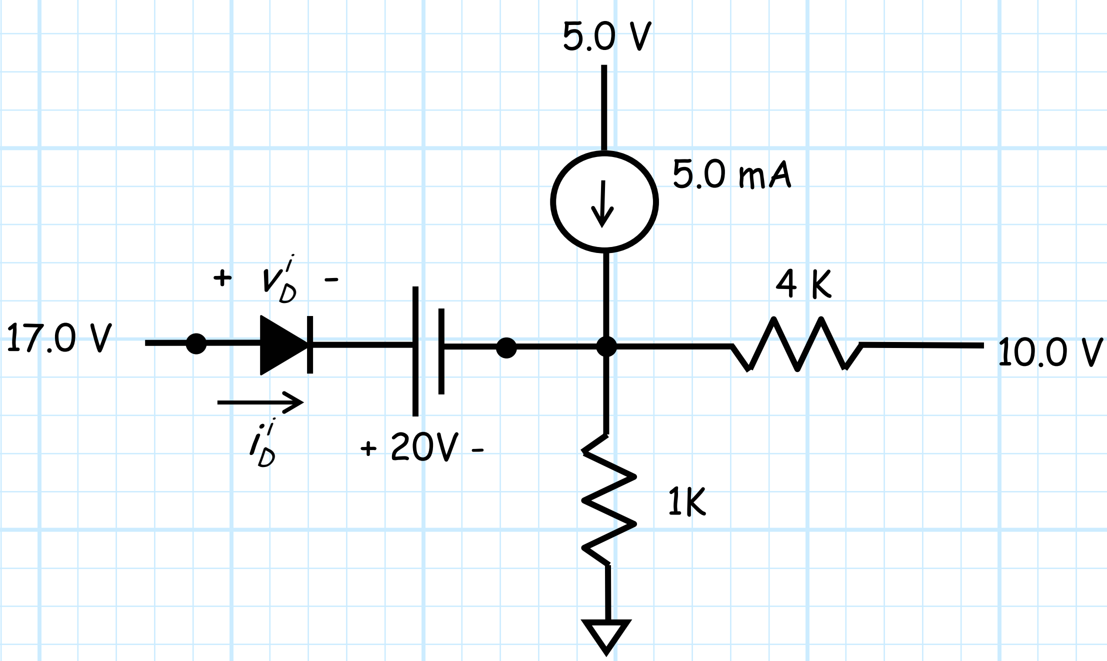
Consider **this** circuit, which includes a **zener** diode:



Let's see if we can determine the **voltage** across and **current** through the zener diode!

First, we must replace the zener diode with an appropriate model. Assuming that the zener will either be in breakdown or reverse bias, a good choice would be the **zener CVD model.**

Carefully replacing the zener diode with this model, we find that we are left with an **IDEAL** diode circuit:



Since this is an **IDEAL** diode circuit, we know how to analyze it!

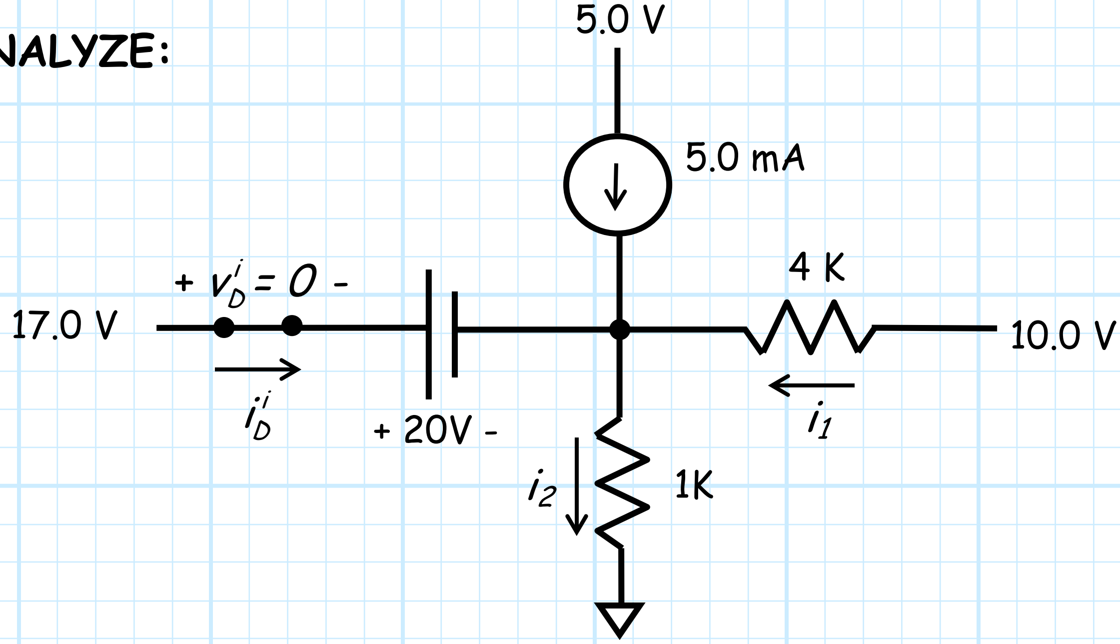
Q: *But wait! The ideal diode in this circuit is part of a **zener** diode model. Don't we need to thus **modify** our ideal diode circuit analysis procedure in some way? In order to account for the zener diode behavior, shouldn't we alter what we assume, or what we enforce, or what we check?*

A: **NO!** There are **no zener diodes** in the circuit above! We must analyze this **ideal** diode circuit in **precisely** the same way as we have **always** analyzed ideal diode circuits (i.e., section 3.1).

ASSUME: Ideal diode is forward biased.

ENFORCE: $v_D^i = 0$

ANALYZE:



From KVL:

$$17 - v_D^i - 20 - i_2(1) = 0$$

$$\therefore \quad i_2 = \frac{17 - 0 - 20}{1} = -3.0 \; mA$$

Likewise from KVL:

$$17 - v_D^i - 20 + i_1(4) = 10$$

$$i_1 = \frac{10 + 20 + 0 - 17}{4} = 3.25 \; mA$$

Now from KCL:

$$i_D^i = i_2 - i_1 - 5.0$$
$$= -3.0 - 3.25 - 5.0 = -11.25\ mA$$

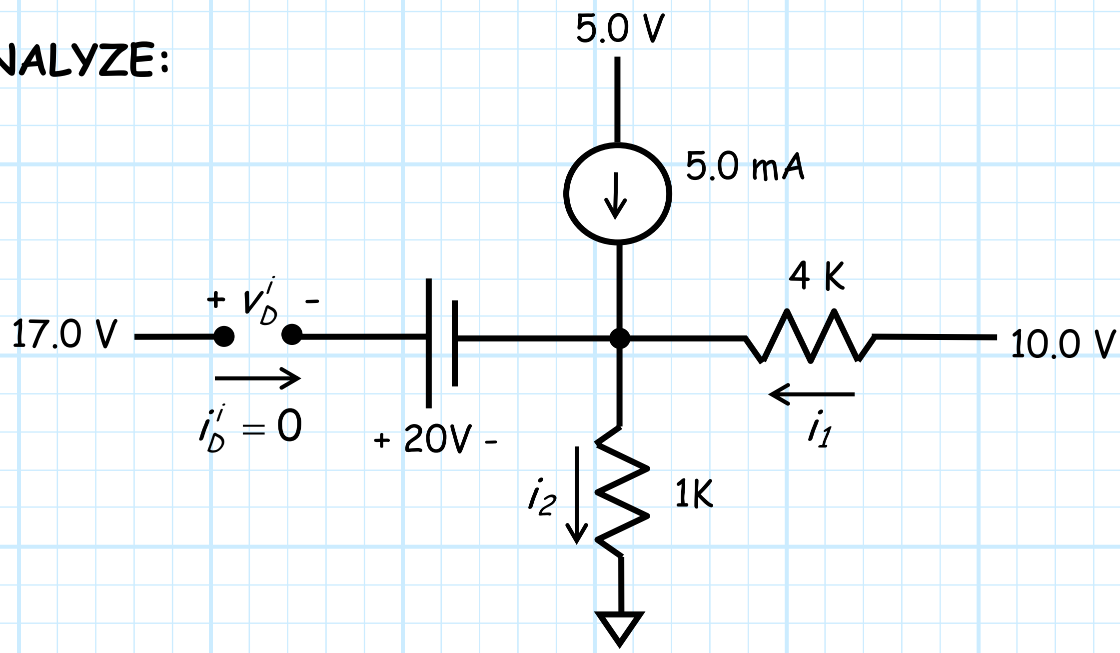
CHECK: $i_D^i = -11.25\ mA < 0$ ✗

Yikes! We must change our **ideal** diode assumption and try again.

ASSUME: Ideal diode is reverse biased.

ENFORCE: $i_D^i = 0$

ANALYZE:



From KCL:

$$i_2 = i_1 + 5$$

From KVL:

$$10.0 - i_1(4) - i_2(1) = 0$$

$$\therefore\ 10.0 - i_1(4) - (i_1 + 5)(1) = 0$$

$$\therefore\ i_1 = \frac{10-5}{4+1} = 1\ mA$$

Now, again using KVL:

$$17 - v_D^i - 20 + i_1(4) = 10$$

$$v_D^i = 17 - 20 + (1)(4) - 10$$
$$= -11.0\ V$$

CHECK: $v_D^i = -11.0\,V < 0$ ✓

Q: *Our assumption is **good**! Since our analysis is **complete**, can we move on to something else?*

A: Not so fast! Remember, we are attempting to find the voltage across, and current through, the **zener diode**.

To (approximately) determine these values, we find the voltage across, and current through, the zener diode **model**.

So,

$$v_Z = v_D^i + V_{ZK}$$
$$= -11 + 20$$
$$= 9.0\ V$$

and

$$i_Z = i_D^i = 0$$

We're done!

Q: *Wait! Don't we have to somehow CHECK these values?*

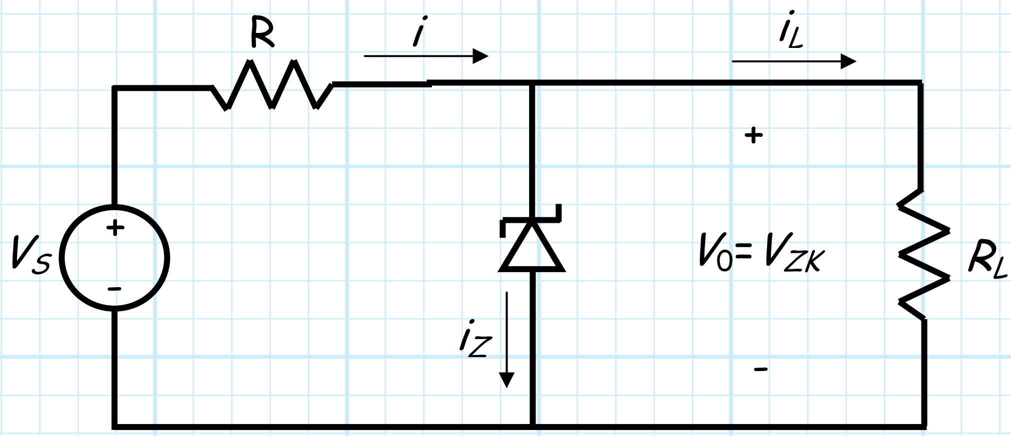
A: **NO!** We assumed **nothing** about the zener diode, we enforced **nothing** about the zener diode, and thus there is **nothing** to explicitly check in regards to the zener diode solutions.

However—like all engineering analysis—we should perform a **"sanity check"** to see if our answer makes physical sense.

So, let **me** ask you the question **Q:**Does this answer make physical sense?

A:

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.

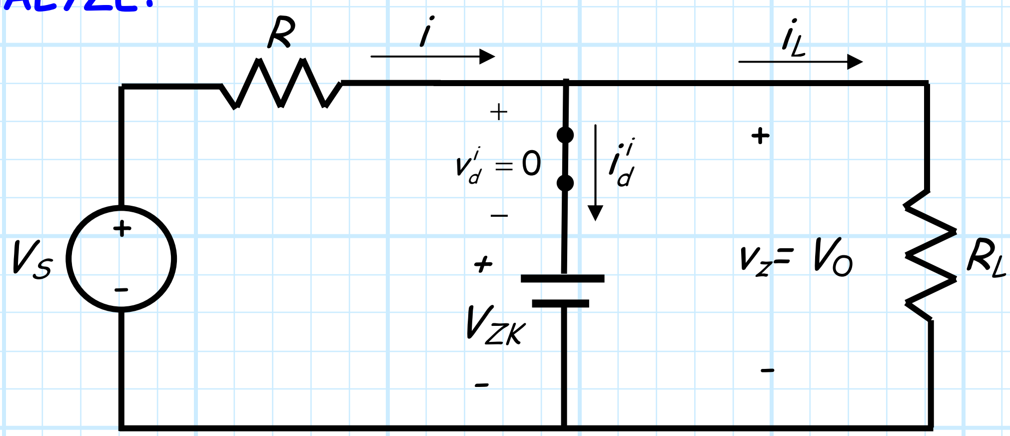
What can we do to keep load voltage V_O **constant**?

$\Rightarrow$ 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 from Ohm's Law:

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

and also :

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

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.

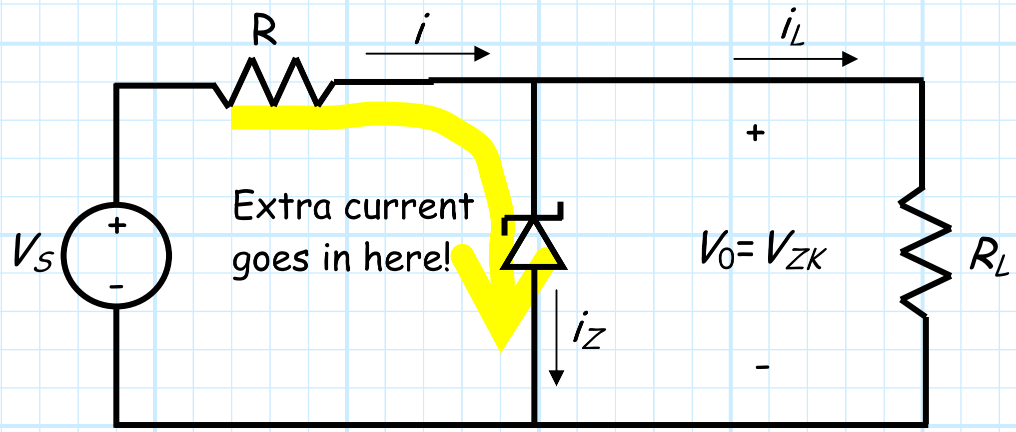
2. The load voltage $V_O = V_{ZK}$.

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

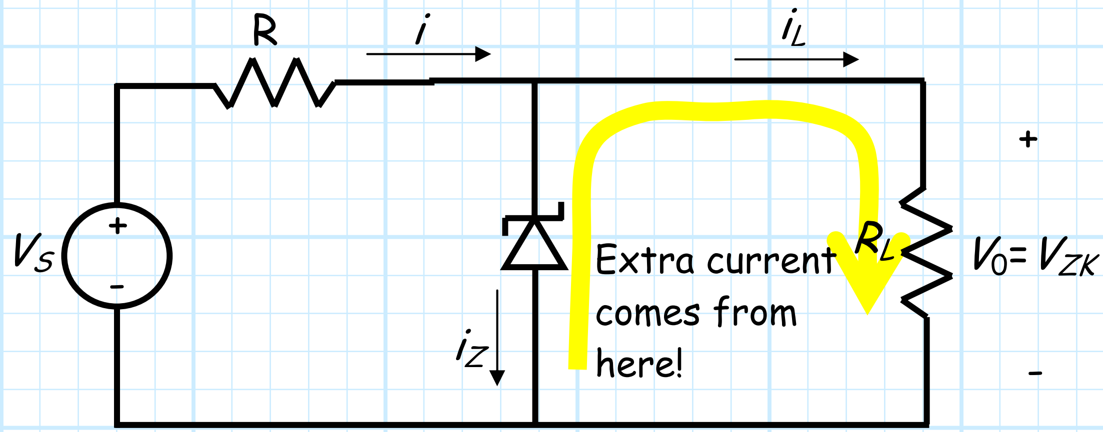
4. The current through the shunt resistor R is $i = (V_S - V_{ZK})/R$.

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.

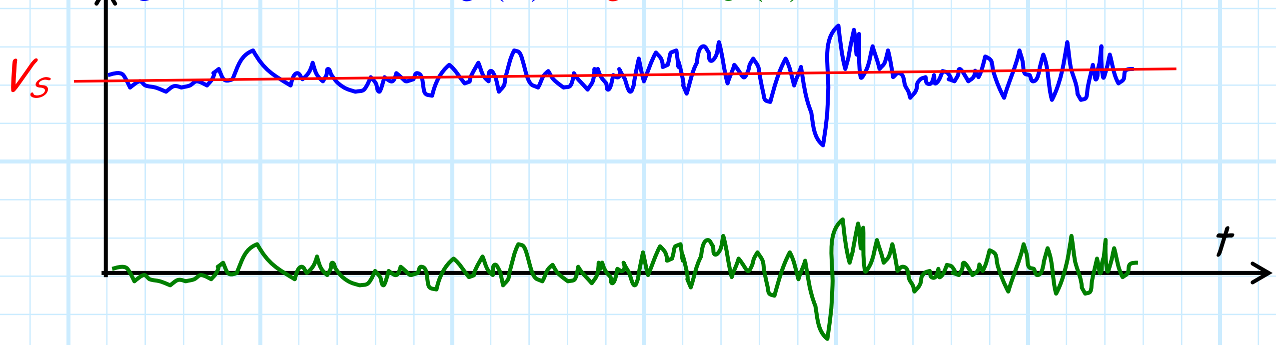
Q: ***Why** would the source voltage V_S ever change?*

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 ($\Delta v_s(t)$):

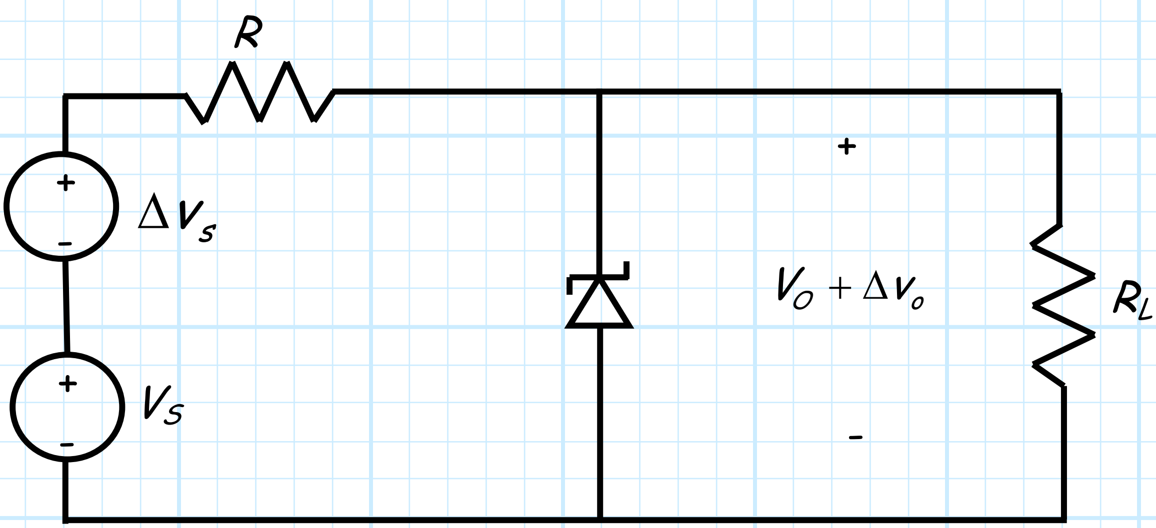
$$v_S(t) = V_S + \Delta v_s(t)$$



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:

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

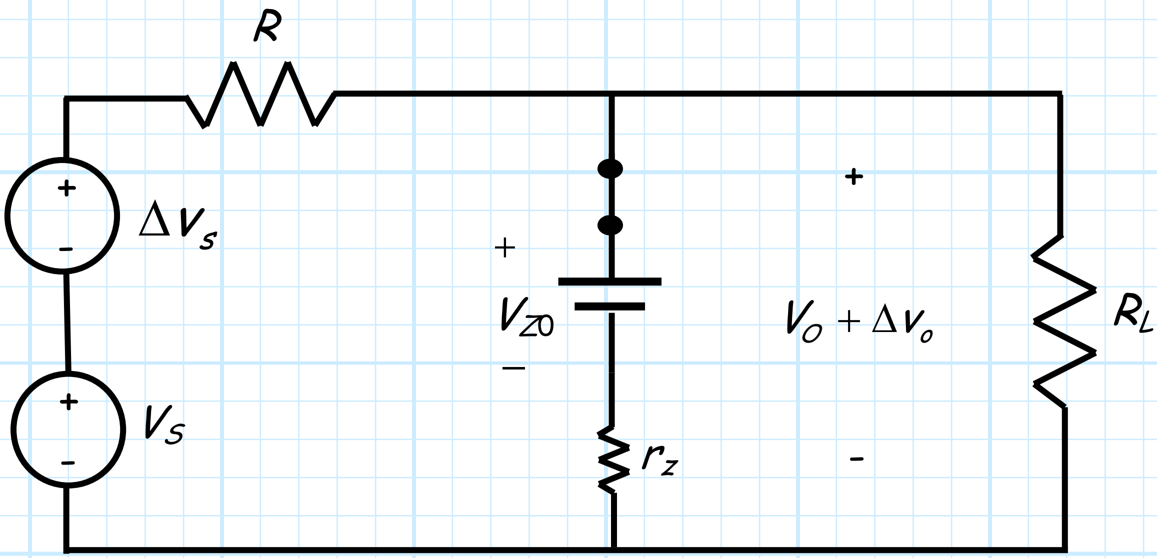
So, we know that the DC source V_S produces the DC load voltage V_O, whereas the small-signal **source** voltage Δv_s results in the small-signal **load** voltage Δv_o.



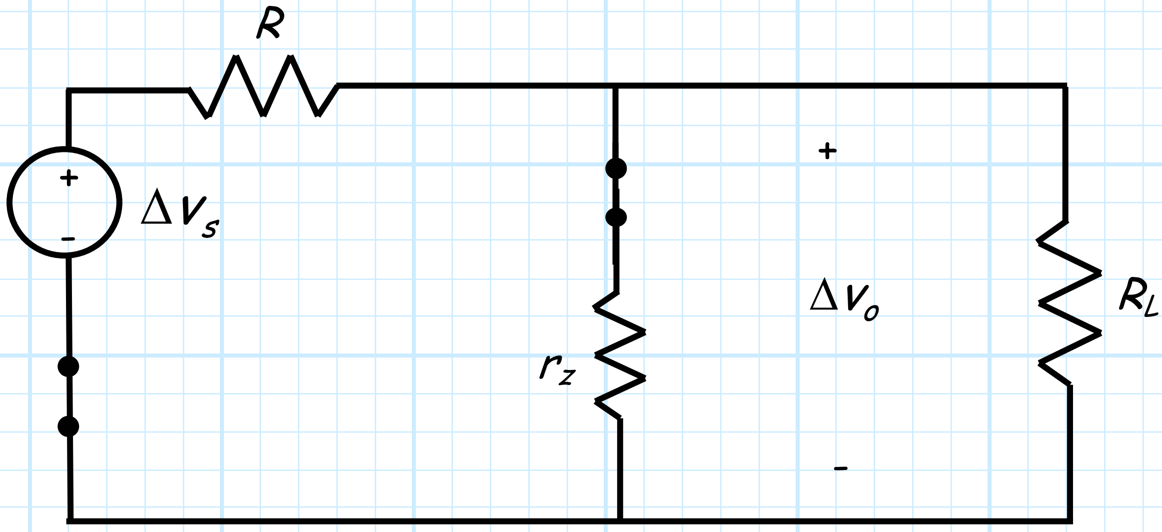
Q: *Just how are Δv_s and Δv_o* ***related****? I mean, if Δv_s equals, say,* ***500 mV****, what will value of Δv_o be?*

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

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:

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

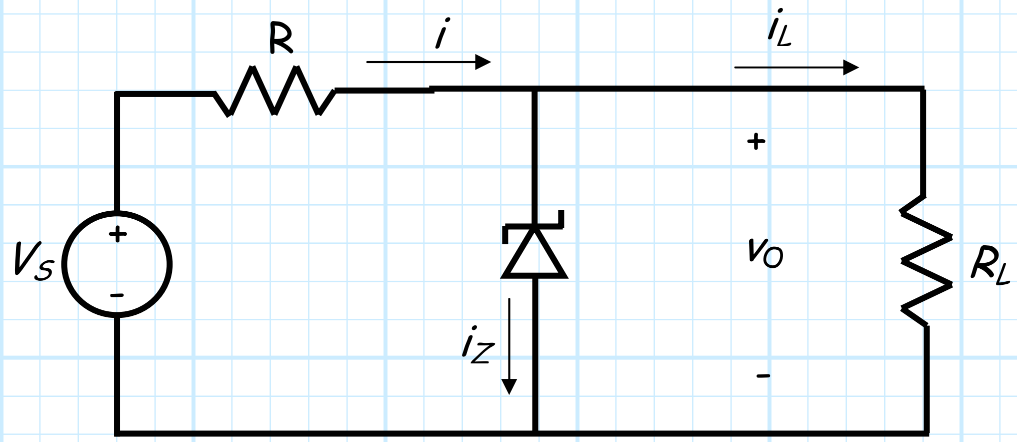
This equation describes an important performance parameter for shunt regulators. We call this parameter the **line regulation.**

* 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 ($\Delta i_l(t)$):

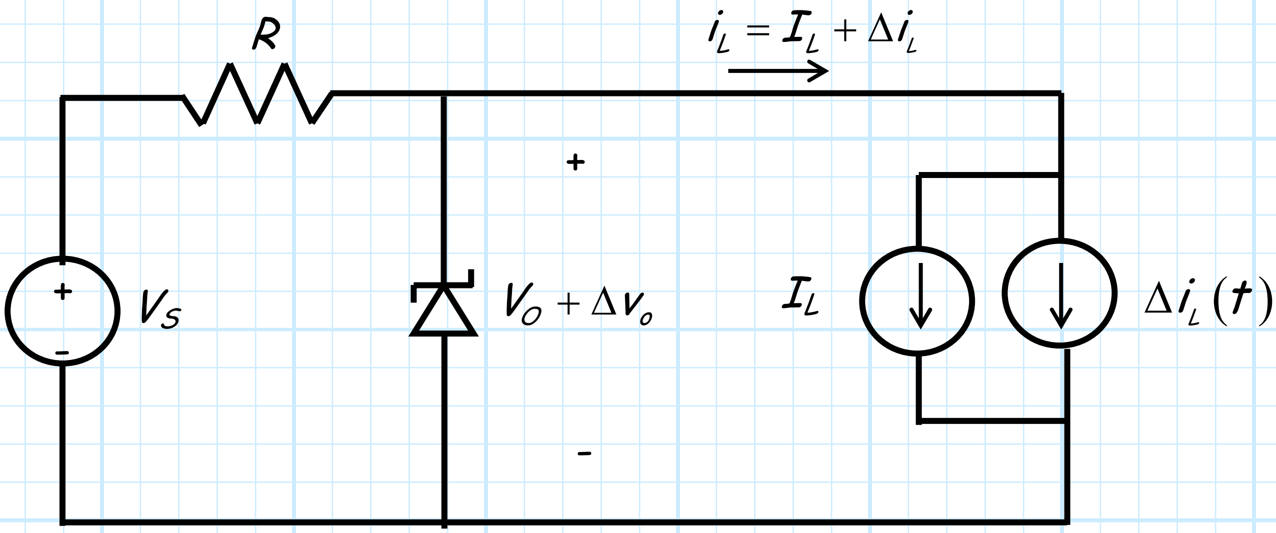
$$i_L(t) = I_L + \Delta i_l(t)$$

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.

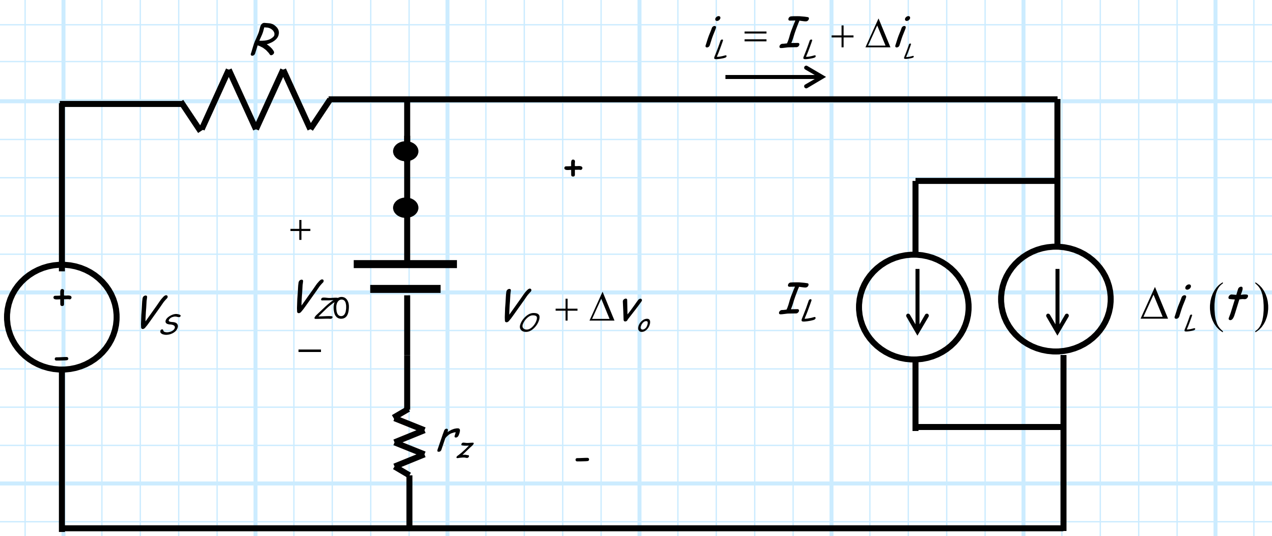
We can **replace** the load resistor with **current sources** to represent this load current:



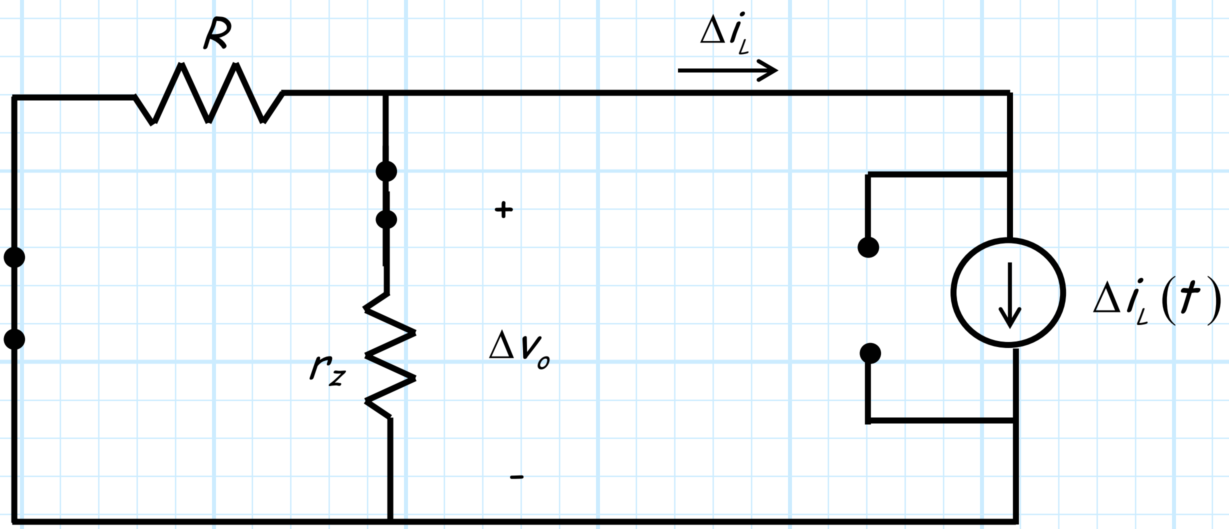
Q: *Just how are Δi_L and Δv_o **related**? I mean, if Δi_L equals, say, **50 mA**, what will value of Δv_o be?*

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:

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

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).

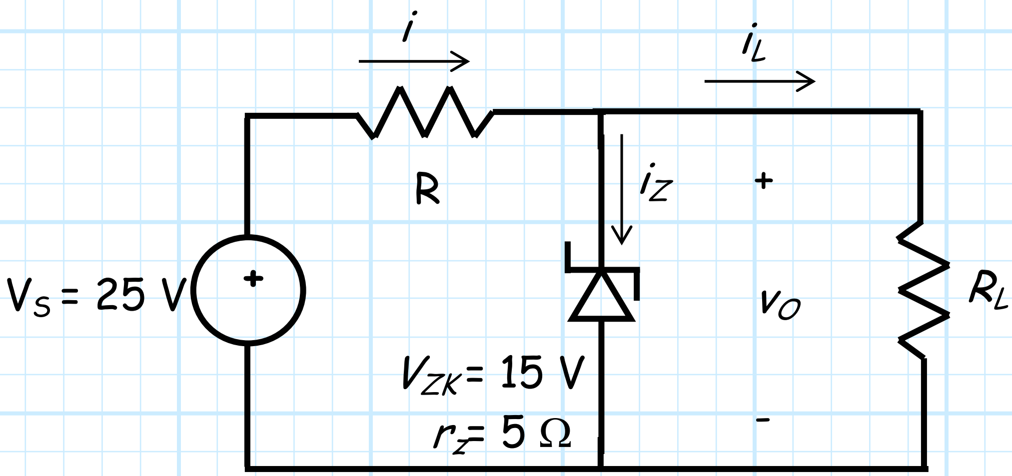
* Load regulation allows us to determine the **amount** that the load voltage changes (Δv_o) when the load current changes (Δi_L).

* 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**.

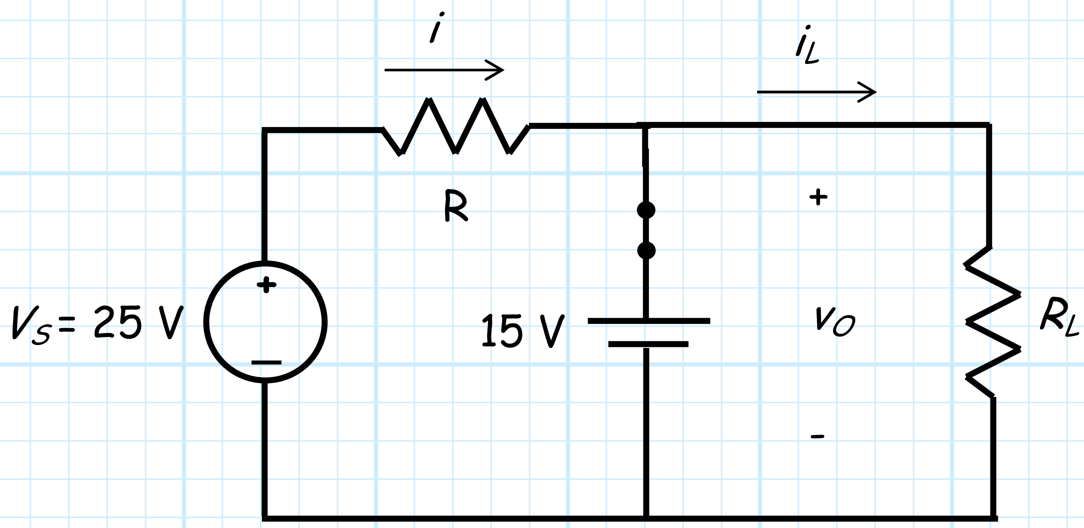
i.e., $i_Z = i - i_L > 0$

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. $\boldsymbol{i > 20mA}$

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 $i > 20\text{mA}$ **if**:

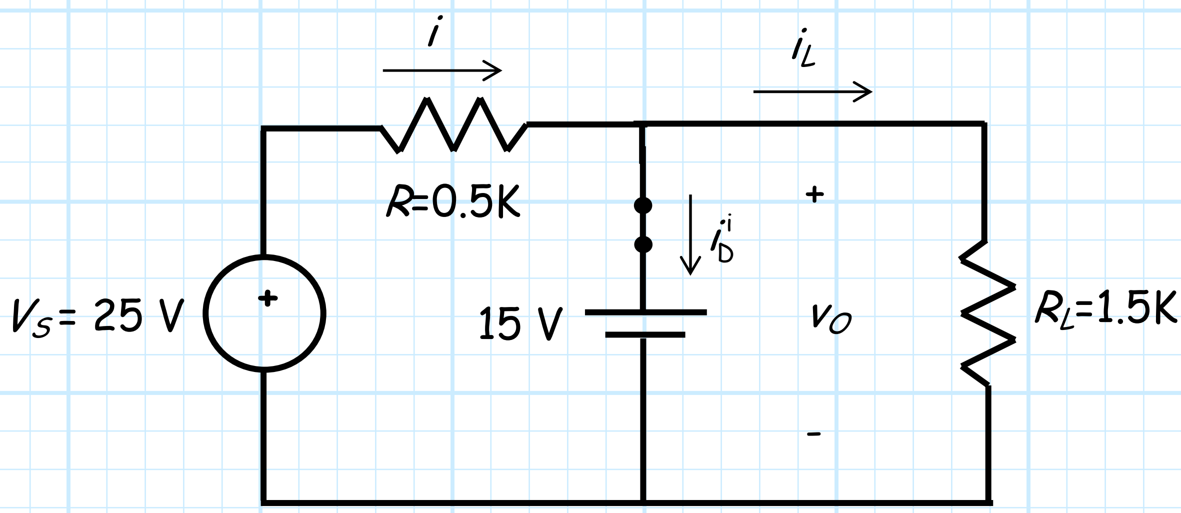
$$R < \frac{10}{20} = 0.5 \text{ K} = 500 \ \Omega$$

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 $i_D^i = i - i_L = 20 - 10 = 10.0 \ mA \ \ (\therefore i_D^i = 10 > 0$ ✔)

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:

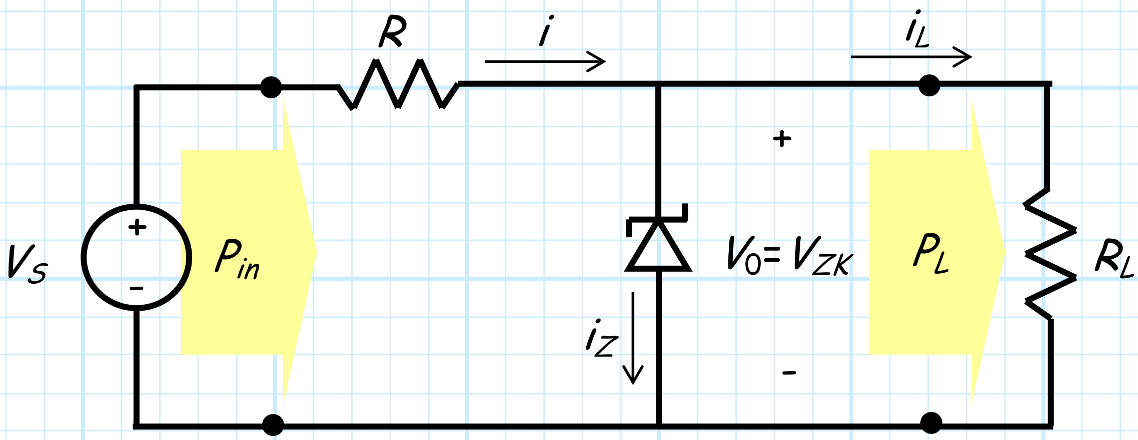
$$\text{Load Regulation} = \frac{-R \ r_z}{R + r_z} = \frac{-(500)5}{500 + 5} = -4.95 \ \Omega$$

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

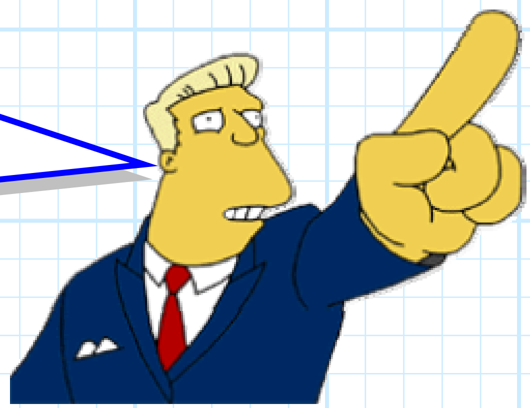
Regulator Power and Efficiency

Consider now the shunt regulator in terms of **power**.

The **source** V_s delivers power P_{in} to the regulator, and then the regulator in turn delivers power P_L to the **load**.



*Q: So, is the power delivered by the source **equal** to the power absorbed the load ?*



A: Not hardly! The power delivered by the source is distributed to three devices—the load R_L, the zener diode, and the shunt resistor R.

The power **delivered** by the **source** is:

$$\begin{aligned} P_{in} &= V_s \ i \\ &= V_s \ \frac{(V_s - V_{ZK})}{R} \end{aligned}$$

while the power **absorbed** by the **load** is:

$$\begin{aligned} P_L &= V_L \ i_L \\ &= V_{ZK} \ \frac{V_{ZK}}{R_L} \\ &= \frac{V_{ZK}^2}{R_L} \end{aligned}$$

Thus, the power absorbed by the shunt resistor and zener diode combined is the difference of the two (i.e., P_{in}-P_L).

Note that the power absorbed by the load **increases** as R_L decreases (i.e., the load current increases as R_L decreases).

Recall that the load resistance can be arbitrarily large, but there is a **lower limit** on the value of R_L, enforced by the condition:

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

Remember, if the above constraint is **not** satisfied, the zener will **not** breakdown, and the output voltage will drop **below** the desired regulated voltage V_{ZK}!

We can rewrite this constraint in terms of R_L:

$$R_L > \frac{V_{ZK}\, R}{V_s - V_{ZK}}$$

Rearranging the expression for load power (i.e., $P_L = V_{ZK}^2 / R_L$):

$$R_L = \frac{V_{ZK}^2}{P_L}$$

we can likewise determine an **upper bound** on the power delivered to the load:

$$R_L = \frac{V_{ZK}^2}{P_L} > \frac{V_{ZK}\, R}{V_s - V_{ZK}}$$

and thus:

$$P_L < \frac{V_{ZK}\left(V_s - V_{ZK}\right)}{R}$$

we can thus conclude that the **maximum** amount of power that can be delivered to the load (while keeping a regulated voltage) is:

$$P_L^{max} = \frac{V_{ZK}\left(V_s - V_{ZK}\right)}{R}$$

which occurs when the **load** is at its **minimum** allowed value:

$$R_L^{min} = \frac{V_{ZK}\, R}{V_s - V_{ZK}}$$

Note, as R_L increases (i.e., i_L decreases), the load power decreases. As R_L approaches infinity (an open circuit), the load power becomes zero. Thus, we can state:

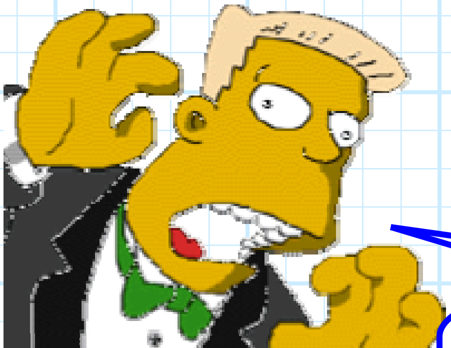
$$0 \leq P_L \leq P_L^{max}$$

Every voltage regulator (shunt or otherwise) will have a **maximum load power rating** P_L^{max}. This effectively is the output power available to the load. Try to lower R_L (increase i_L) such that you **exceed** this rating, and one of two **bad things** may happen:

1) the regulated voltage will no longer be regulated, and **drop** below its nominal value.

2) the regulator will melt!

Now, contrast load power P_L with the **input power** P_{in}:



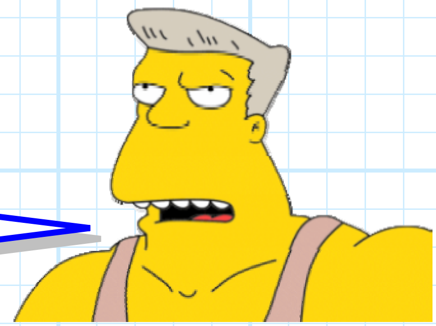
$$P_{in} = V_s \frac{(V_s - V_{ZK})}{R}$$

Q: *Wait! It appears that the input power is independent of the load resistance R_L! Doesn't that mean that P_{in} is independent of P_L?*

A: That's correct! The power flowing **into** the shunt regulator is **constant**, regardless of how much power is being delivered to the load.

In fact, **even** if P_L**=0**, the input power is **still** the same value shown above.

Q: *But **where** does this input power go, if **not** delivered to the load?*



A: Remember, the input power not delivered to the load must be absorbed by the **shunt resistor** R and the **zener diode**. More specifically, as the load power P_L decreases, the power absorbed by the **zener** must increase by an **identical** amount!

Q: *Is this **bad**?*

A: It sure is! Not only must we dissipate the **heat** that this power generates in the regulator, the energy absorbed by the shunt resistor and zener diode is essentially **wasted**.

This is particularly a concern if our source voltage V_s is from a **storage battery**.

A storage battery holds only so much energy. To maximize the time before its depleted, we need to make sure that we use the energy effectively and **efficiently**.

Heating up a zener diode is **not** an efficient use of this limited energy!

Thus, another important parameter in evaluating regulator performance is its **efficiency**. Simply stated, regulator efficiency indicates the **percentage** of input power that is delivered to the load:

$$\text{regulator efficiency} \quad e_r \doteq \frac{P_L}{P_{in}}$$

Ideally, this efficiency value is $e_r = 1$, while the **worst** possible efficiency is $e_r = 0$.

For a **shunt regulator**, this efficiency is:

$$e_r \doteq \frac{P_L}{P_{in}} = \frac{R}{R_L} \frac{V_{ZK}^2}{V_s(V_s - V_{ZK})}$$

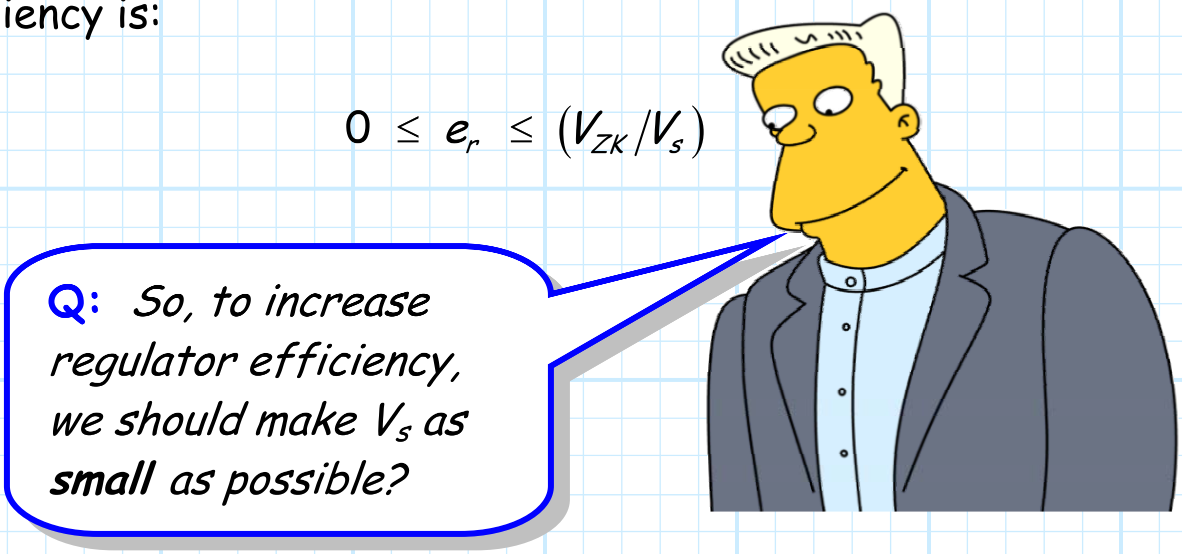
Note that this efficiency **depends on the load** value R_L. As R_L increased toward infinity, the efficiency of the shunt regulator will plummet toward e_r=0 (this is bad!).

On the other hand, the **best** possible efficiency occurs when $P_L = P_L^{max}$:

$$
\begin{aligned}
e_r^{max} &\doteq \frac{P_L^{max}}{P_{in}} \\
&= \frac{V_{ZK}\left(V_s - V_{ZK}\right)}{R} \frac{R}{V_s\left(V_s - V_{ZK}\right)} \\
&= \frac{V_{ZK}}{V_s}
\end{aligned}
$$

Thus, for the **shunt regulator design** we have studied, the efficiency is:

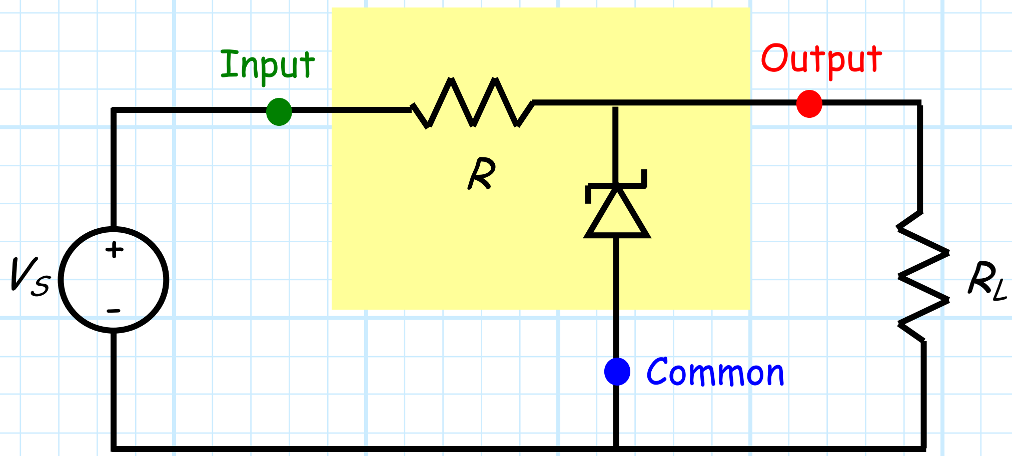
$$0 \leq e_r \leq \left(V_{ZK}/V_s\right)$$



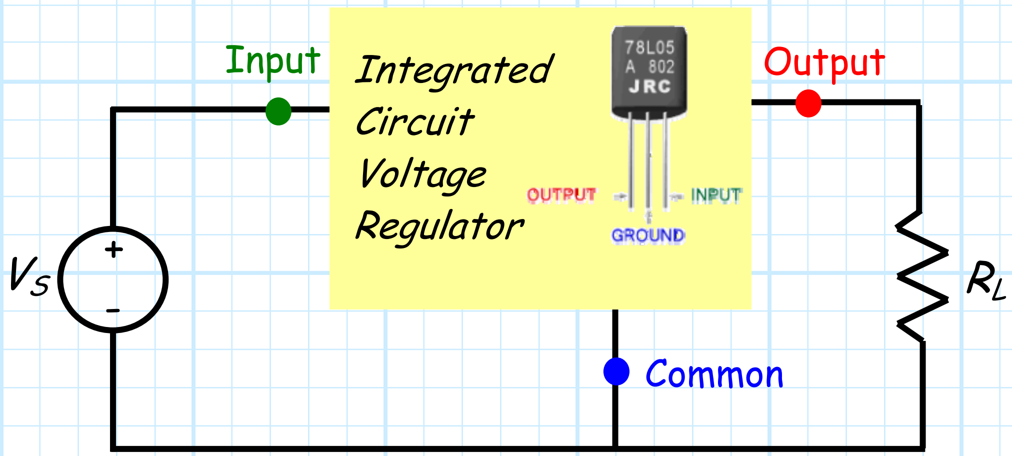
A: That **would** in fact improve regulator efficiency, but **beware**! Reducing V_s will likewise **lower** the maximum possible load power P_L^{max} .

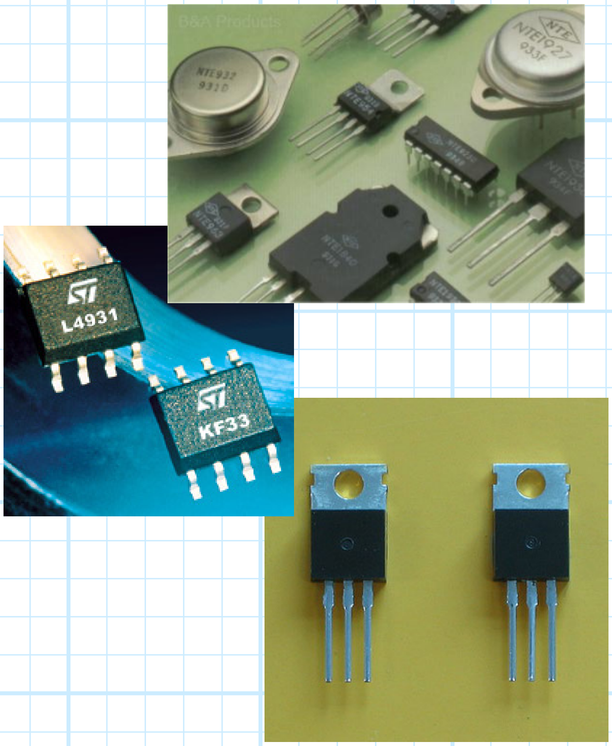
Voltage Regulators

Note that we can view a shunt regulator as a **three-terminal** device, inserted between a voltage source and a load:



Integrated circuit technology has resulted in the creation of other three terminal voltage regulator designs—regulators that do **not** necessarily use zener diodes!





These integrated circuit voltage regulators are **small** and relatively **inexpensive**.

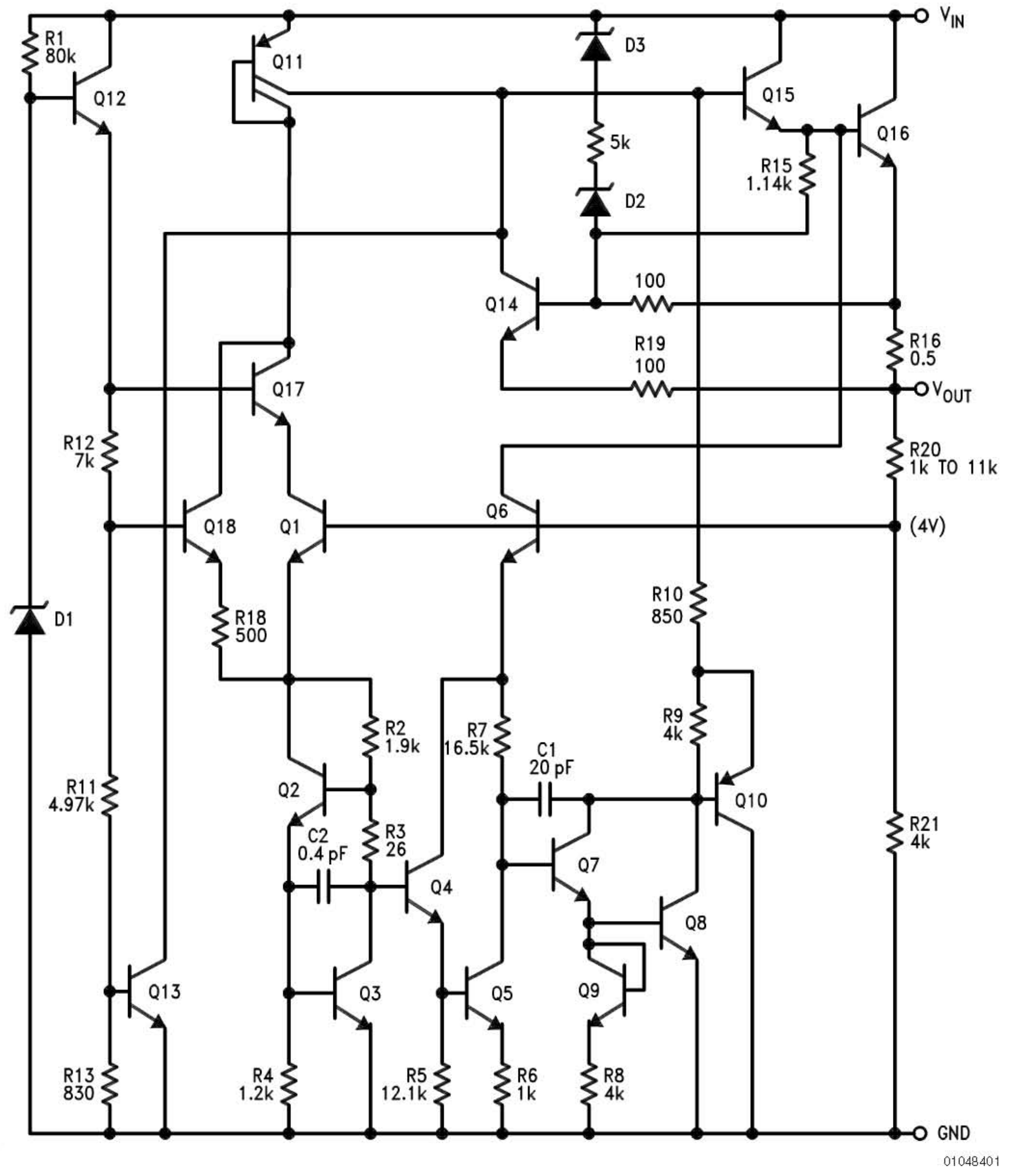
In addition, these IC regulators typically have **better** load regulation, line regulation, and/or efficiency than the zener diode shunt regulator!

Q: *Wow! The **designers** of these IC regulators obviously had a much better electronics professor than the **dope** we got stuck with! With what device did they **replace** the zener diode?*

A: The electronic design engineers did not simply "replace" a zener diode with another component. Instead, they replaced the **entire** shunt regulator design with a **complex circuit** requiring many **transistor** components.

LM341/LM78MXX Series

Schematic Diagram



Integrated circuit technology then allows this complex circuit to be manufactured in a **very small space** and at **very small cost!**