4.4 Operation in the Reverse Breakdown Region — Zener Diodes

Reading Assignment: *pp. 190-191*

A **Zener** Diode is simply a p-n **junction diode** that is meant to be operated in breakdown.

Understanding the **differences** between a **Zener** diode and a **junction** diode is **crucial**.

HO: THE ZENER DIODE

Since a Zener diode is **usually** operating in the breakdown or reverse bias regions, we alter the current/voltage **notation** (but this does **not** alter the device) for Zener diodes.

HO: ZENER DIODE NOTATION

Our junction diode models are **not accurate** if a diode is operating in **breakdown**. Since a Zener diode is often operating in the breakdown region, we require some **new diode models**.

HO: ZENER DIODE MODELS

Let's use these new models to **analyze** a Zener diode circuit!

EXAMPLE: FUN WITH ZENER DIODES

Q: *I'm tired of all these **pointless academic exercises**!*

*What's the point of diodes and diode circuits if they don't actually **do something useful**? Can't we get to the "practical" and "**hands-on**" portion of this course?*

A: That is exactly the place at which **we have arrived** in this course (or at least, with respect to diodes)! Note that **you** now:

- understand the **operation** of junction and Zener diodes
- understand how to **approximate** these devices using ideal diode **models** (e.g., the CVD model).
- understand how to **analyze** junction and Zener diode circuits, implementing various ideal diode models.

Our **tool box** is now **full**—it's time to go **build something** useful!

The first useful application we will consider is **voltage regulation**. A Zener diode in breakdown acts somewhat like a **voltage source**—the voltage across it is **nearly independent** of the (positive) **current** through it. This makes a Zener diode in breakdown **very useful** for voltage regulation!

HO: THE SHUNT REGULATOR

Say your boss wants you to **design a shunt regulator**; be careful, engineering is not as **easy** as it looks!

EXAMPLE: THE SHUNT REGULATOR

In addition to good load and line regulation, another important parameter of voltage regulators is **efficiency**—we do not wish to **waste energy** by creating heat.

HO: REGULATOR POWER AND EFFICIENCY

Finally, we should note that the **shunt regulator** is far from the **only way** to provide voltage regulation. Not only can we use more efficient **switching** regulators, **better** linear regulator designs (i.e., better than the shunt regulator) are available in the form of **integrated circuit** linear regulators.

HO: LINEAR VOLTAGE REGULATORS

The Zener Diode

→ A **Zener** diode is simply a *p-n* junction diode that is meant to be placed in breakdown!

Q: *Yikes!*

*A **whole new** electronic device to learn about.*

*I'm sure it's **completely different** than a junction diode; go ahead and start listing **all the differences** between a junction diode and a zener diode!*

A: Um, OK.

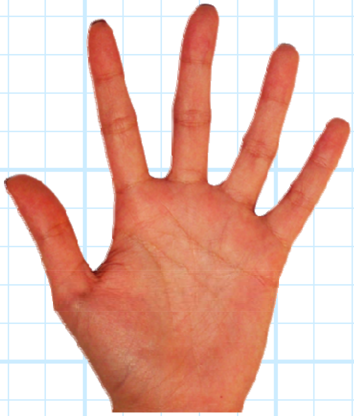
Let's **contrast** the differences between **junction** diodes and **Zener** diodes!

The first difference

On the **one** hand, a **junction** diode is:

- ***** an **asymmetric** device
- ***** **non-linear** device
- ***** a device with **two** terminals, called the **anode** and the **cathode**.

On the **other** hand, a **Zener** diode is:



- ***** an **asymmetric** device
- ***** **non-linear** device
- ***** a device with **two** terminals, called the **anode** and the **cathode**.

The second difference

Three **device parameters** characterize a **junction** diode:

- its **idealty factor**,
- its **scale current**,
- and its zener **breakdown voltage**.

However, three **device parameters** characterize a **Zener** diode:

- its **idealty factor**,
- its **scale current**,
- and its zener **breakdown voltage**.

Now the third difference

Likewise, a junction diode has **three** operating "regions", called:

- **forward** bias,
- **reverse** bias,
- and **breakdown**.

In **contrast**, a Zener diode has **three** operating "regions" ", called:

- **forward** bias,
- **reverse** bias,
- and **breakdown**.

Yet another difference— I've lost track of which one

We know that a **junction** diode operating in the **forward** bias region will exhibit:

- **significant current** will flow from **anode to cathode**,
- and the **anode** voltage will be around **700 *mV* higher** than the **cathode** voltage.

But, we find **instead** that a Zener diode operating in the **forward** bias region will exhibit:

- **significant current** will flow from **anode to cathode**,
- and the **anode** voltage will be around **700 *mV* higher** than the **cathode** voltage.

So completely different!

And, we know that a junction diode operating in the **reverse** bias region will:

- exhibit a **tiny current** flowing from **cathode to anode**,
- and a **higher** voltage at the **anode** than at the **cathode**.

Whereas, we know that a Zener diode operating in the **reverse** bias region will:

- exhibit a **tiny current** flowing from **cathode to anode**,
- and a **higher** voltage at the **anode** than at the **cathode**.

The last difference—a really big one!

Finally, a junction diode in the **breakdown** region will show:

- **significant current** flowing from **cathode** to **anode**,
- and a **cathode** voltage that is a value V_{ZK} **higher** than the **anode** voltage.

Alternatively—in a stunning **reversal**—a Zener diode in the **breakdown** region will show:

- **significant current** flowing from **cathode** to **anode**,
- and a **cathode** voltage that is a value V_{ZK} **higher** than the **anode** voltage.

Sarcasm: it's so darn effective

Q: *What?*

*This Zener diode sounds **exactly the same** as a junction diode!*

A: That's **correct**!

I'll say it **again**:

> "A **Zener** diode **is simply a *p-n* junction diode** that is **meant** to be placed in **breakdown**!"

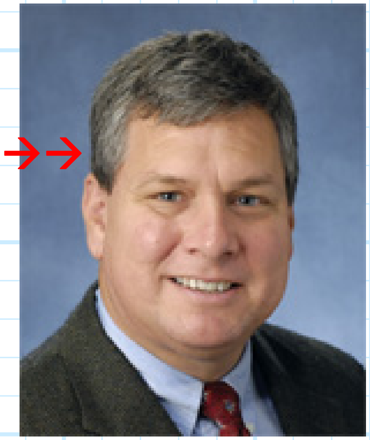
Q: *But if a Zener diode **is** a junction diode, then **why** give it a **different name**?*

A: Because a Zener diode is a junction diode that is **meant to be placed in breakdown** (I hope you're **finally** getting this)!

Speaking of annoying

Q: *You seem to be suggesting that a **junction** diode is **not** meant to be placed in breakdown?*

A: That's exactly **correct**!



For **many** diode applications, breakdown is an **annoying and useless**→→ operating mode that is not **at all** like an **IDEAL** diode.

For **these** applications, breakdown is to be **avoided**—we seek a junction diode with **a very large Zener breakdown** voltage V_{ZK}.

Thus, for these diode applications, the **ideal** value of V_{ZK} is **infinity** (i.e., making breakdown **impossible**)!

Thankfully, a badly receding hairline is no longer required for a job in engineering

Q: *Is that why our junction diode **models** did **not** consider breakdown?*

A: That's right—it is **implicitly assumed** in those models that V_{ZK} is sufficiently large, such that breakdown **cannot** happen.

The forward and reverse bias regions **only** are **modeled**.

But—and **here's the exciting part**—industrious and creative **electrical engineers** (as they are wont to do) discovered that the "useless" and "annoying" **breakdown** region actually has some especially **useful applications**!

So, there **are** some important **differences** between "normal" junction diodes, and the *p-n* junction diodes that we call **Zener diodes**.

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The first real difference

On the **one** hand, the Zener breakdown voltage V_{ZK} of a **junction** diode:

- * is **typically large** (e.g., 50 V or greater).
- * The manufacturing **tolerance** associated with the breakdown voltage is also usually **large** (e.g., 20%),
- * so that V_{ZK} is often specified as an **inequality** (e.g., $V_{ZK} > 65\ V$).

On the **other** hand, the Zener breakdown voltage V_{ZK} of a **Zener** diode:

- * varies over a **wide range** of values (e.g., 2 to 200 V), with some values quite **small**.
- * The manufacturing **tolerance** associated with the breakdown voltage is also **small** (e.g., < 5%),
- * so that V_{ZK} is **precisely** specified as an **equality** (e.g., $V_{ZK} = 12\ V$).

The second real difference

If a **junction** diode **does** happen to operate in the breakdown region, then it likely won't likely to operate at all for very long!

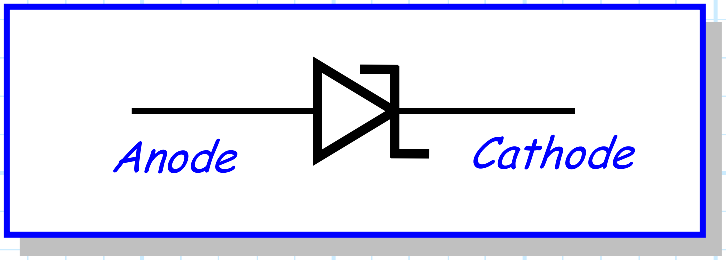
Recall that a diode in the breakdown region will **absorb** (and so must dissipate) **energy at a high rate**.

- A "normal" junction diode is **not** designed to **thermodynamically** handle this event, as its designers assumed breakdown would **not occur**.
- The junction diode in breakdown will likely be **destroyed**!

- However, **Zener** diode manufacturers assume the **opposite**—that the diode **will** operate in the breakdown region.
- As a result, Zener diodes **are designed** to efficiently **dissipate** this heat—thermal equilibrium can be achieved **before** the Zener temperature reaches its **melting** point!

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.,:

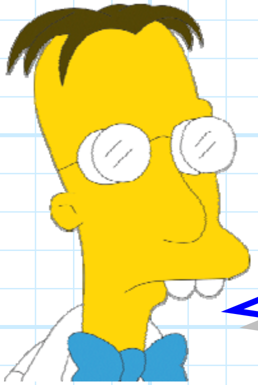
$$v_D < 0 \qquad \text{(for r.b. and bd)}$$

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

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

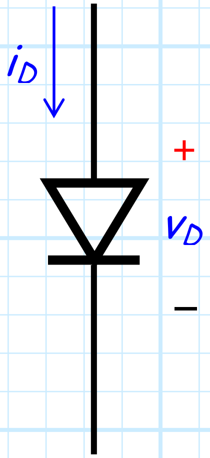
We're trying to avoid negative numbers

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).*

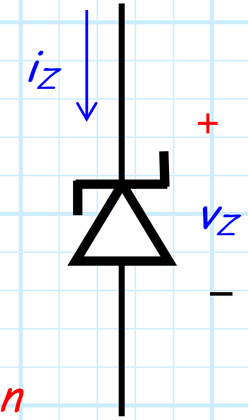


A: With the **standard** diode notation, this is true.

Thus, to **avoid** negative values in our circuit computations, we are going **to change the definitions** of diode current and voltage!



Conventional diode notation



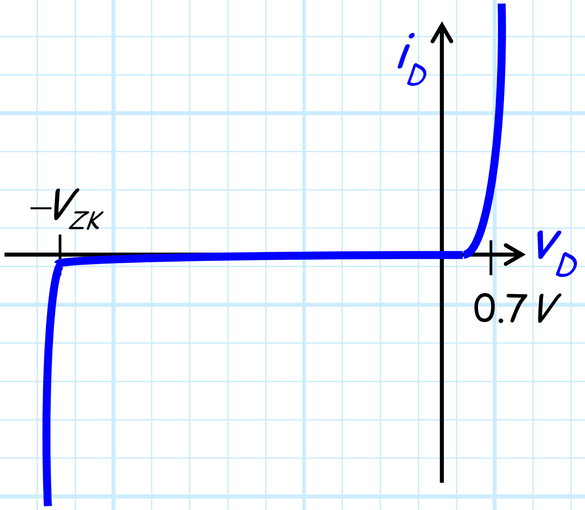
Zener diode notation

Stand on your head, and you will see that it is the same plot!

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

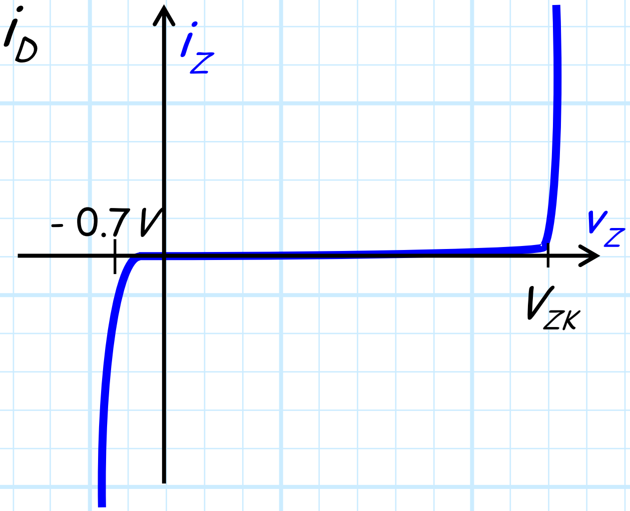
* Likewise, we denote diode voltage as the potential at the **cathode** with respect to the potential at the **anode**.

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



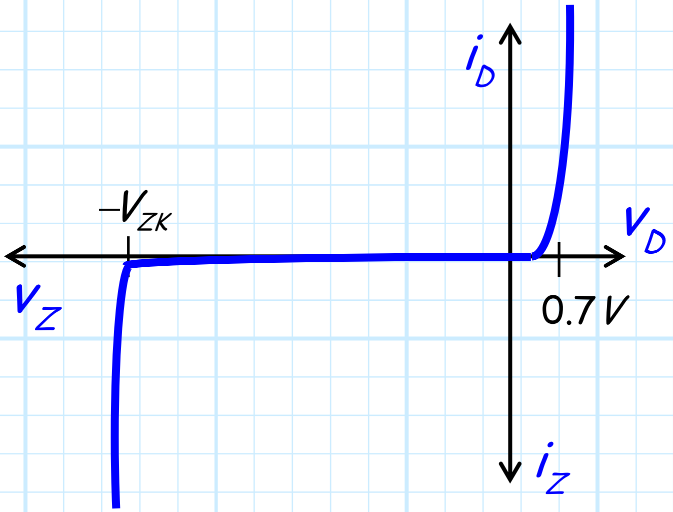
$$v_Z = -v_D \quad and \quad i_Z = -i_D$$

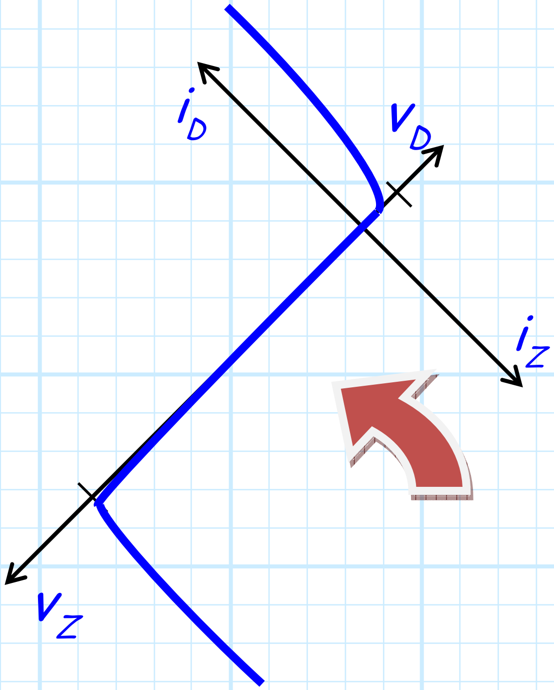
or

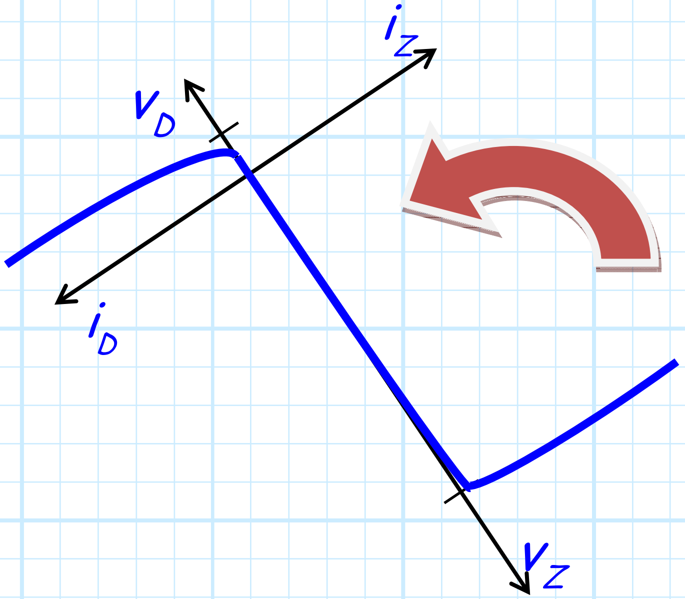


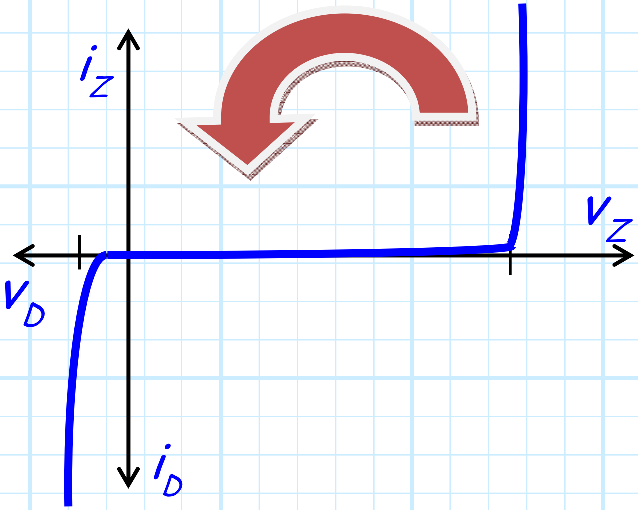
Two ways of expressing the **same** junction diode curve!

We're just rotating the plot



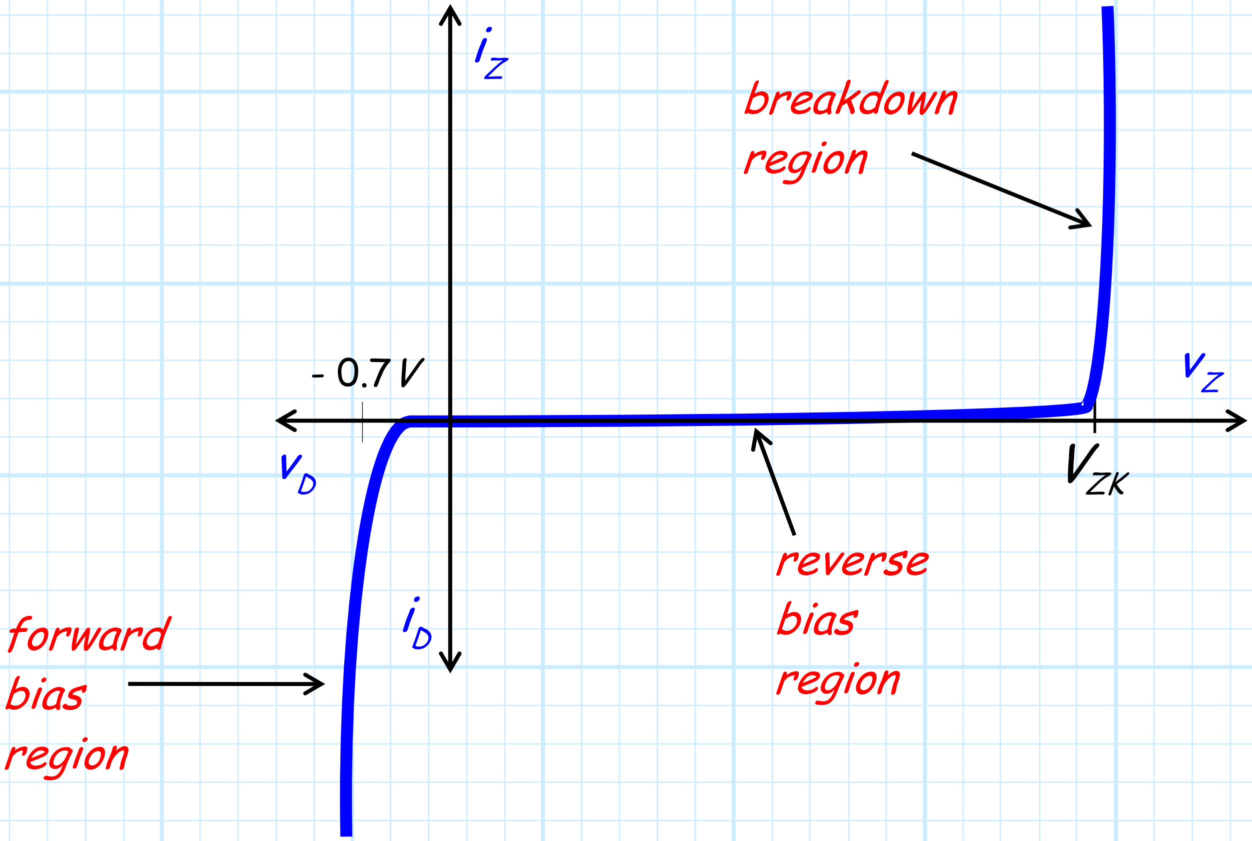






The Zener diode curve—same as the old curve (stand on head)

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



A mathematical statement of each region

Thus, in the **forward bias** region (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 region**:

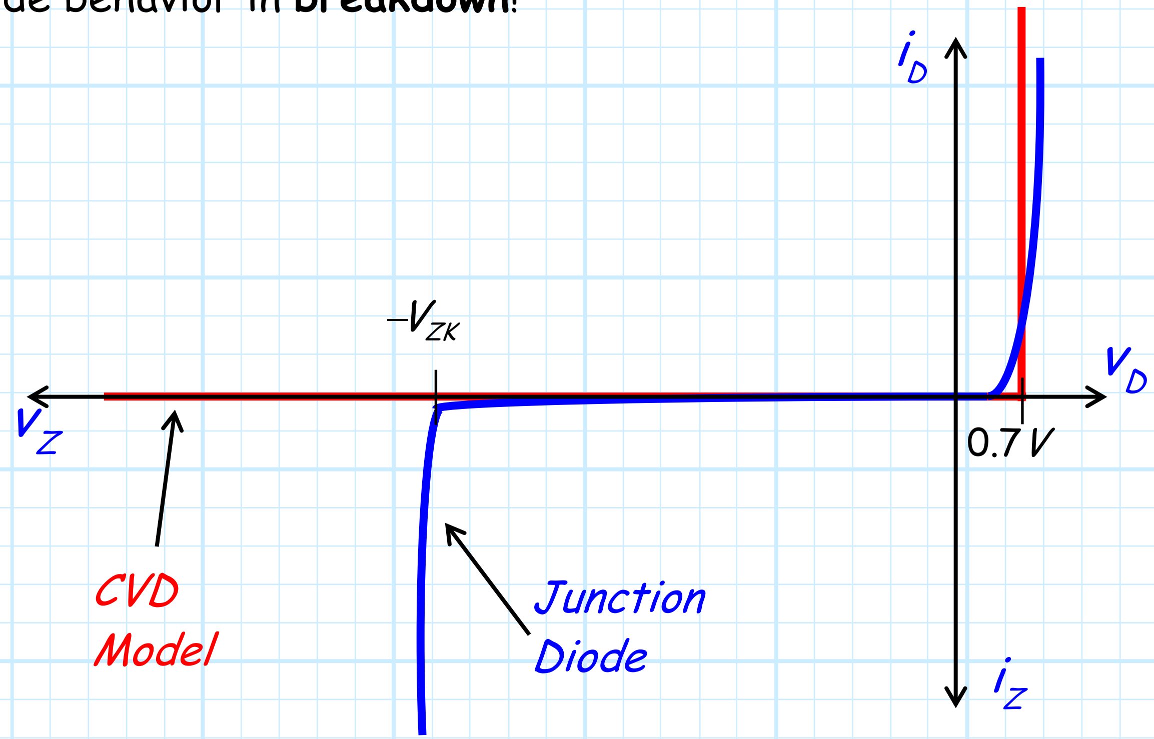
$$i_Z \approx I_s \quad \text{and} \quad 0 < v_Z < V_{ZK}$$

And finally, for **breakdown region:**

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

Zener Diode Models

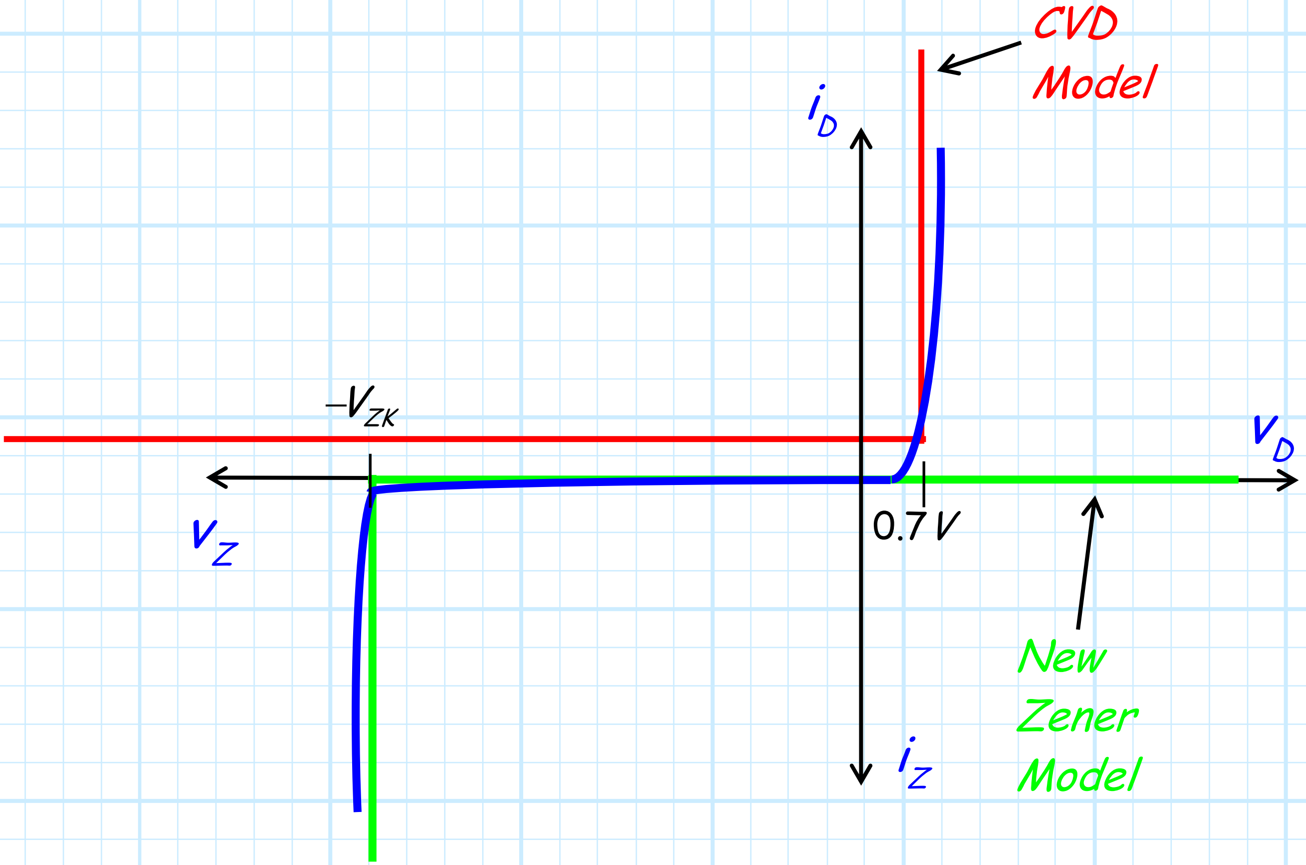
The conventional diode models we studied earlier were based on junction diode behavior in the **forward** and **reverse** bias regions—they did **not** "match" the junction diode behavior in **breakdown**!



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

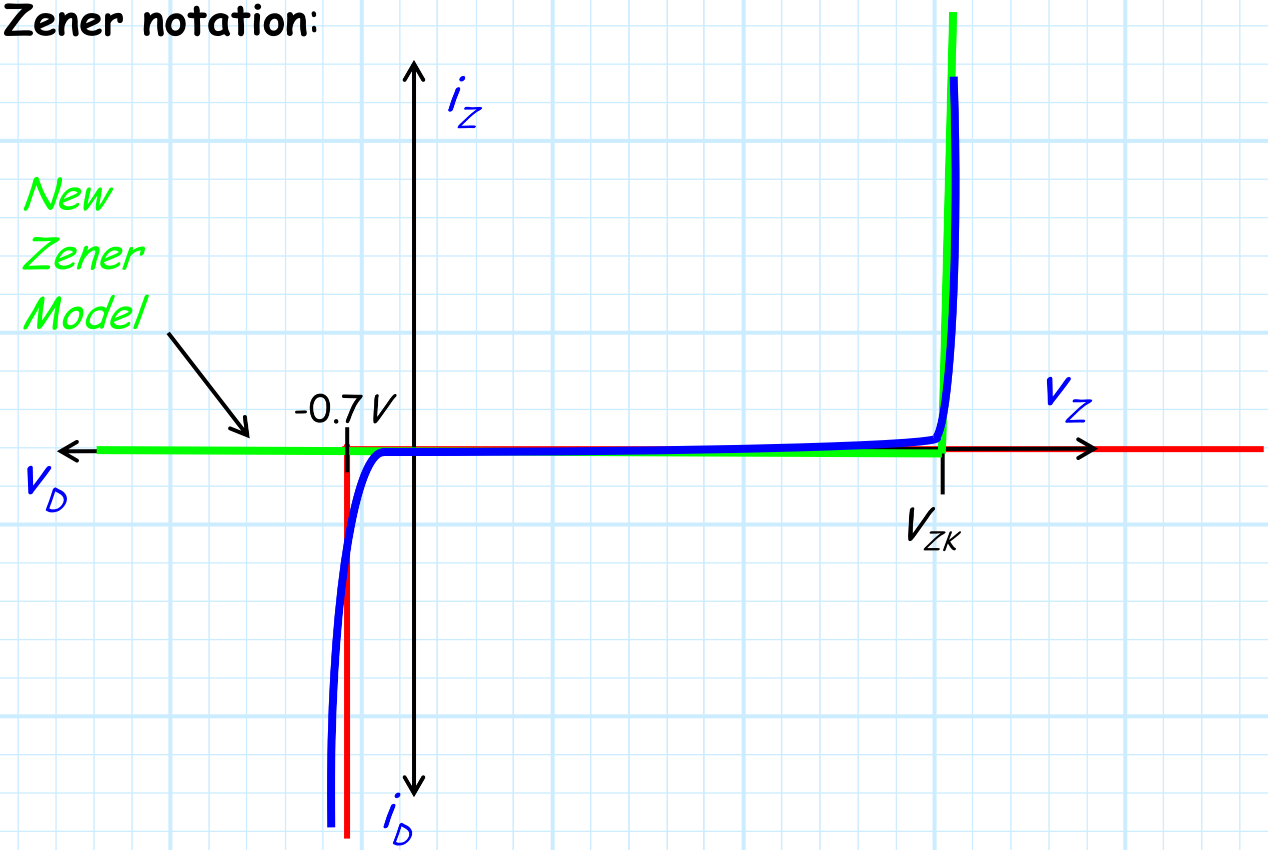
We need to match in the breakdown and reverse bias regions

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



In terms of Zener notation

Or, “rotating” into the **Zener notation**:



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

Here's an accurate model!

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

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

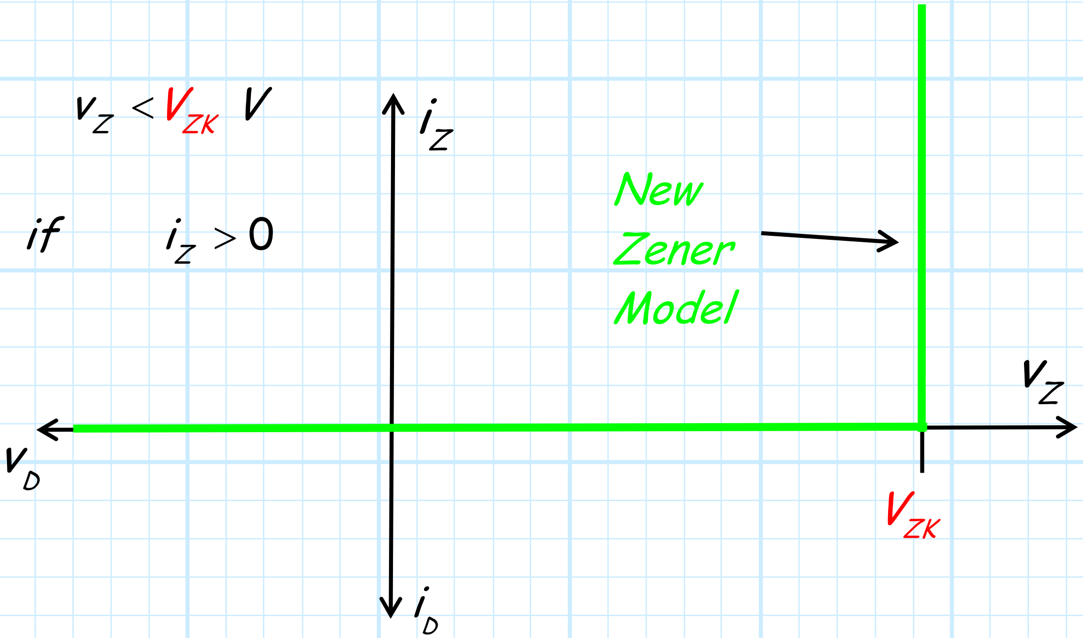
Whereas a Zener in the **breakdown** region is approximately stated as:

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

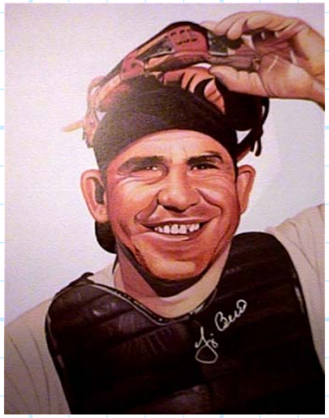
Thus, an accurate Zener model would have this "curve":

$$i_Z = 0 \qquad \text{if} \qquad v_Z < V_{ZK} \; V$$

$$v_Z = V_{ZK} \; V \qquad \text{if} \qquad i_Z > 0$$



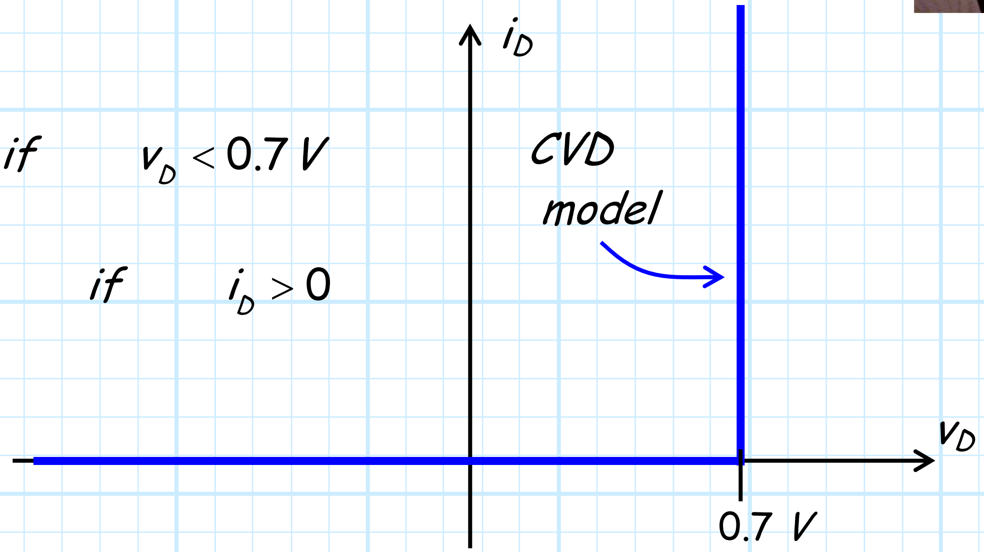
Déjà vu all over again



Q: *Hey, this is **very similar** to the **CVD** model we studied earlier:*

$$i_D = 0 \qquad if \qquad v_D < 0.7\ V$$

$$v_D = 0.7\ V \qquad if \qquad i_D > 0$$



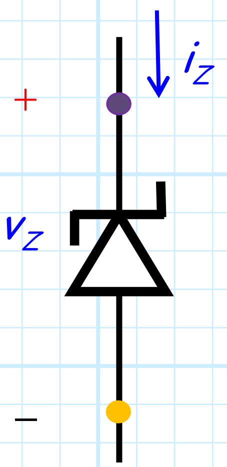
*We've just sort of **changed** 0.7 into V_{ZK}!*

*Can we just change the 0.7 V **battery** in the CVD model into a voltage source of V_{ZK}?*

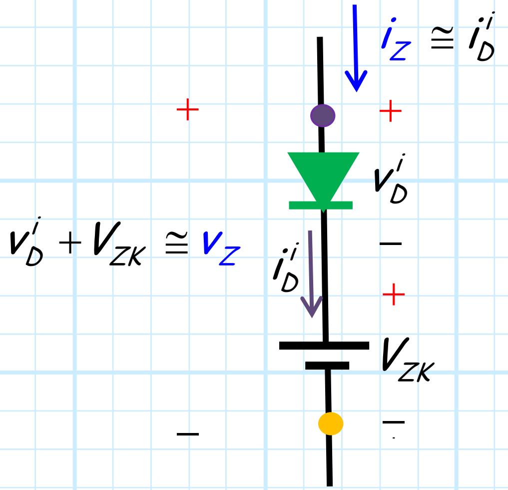
So many lost points because of this

A: That's exactly correct!

Replace:



with:



Zener
CVD
Model

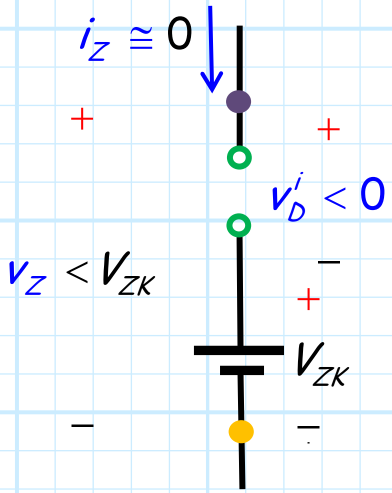
Q: *Hey wait!*

*The cathode of the Zener diode is oriented **upward** (i.e., at the purple node) while the ideal diode cathode is oriented **downward** (i.e., the anode is at the purple node).*

*Is that **correct**?*

A: Absolutely! Make sure **you** get this **right**!

Ideal is *reverse* biased, Zener is *reverse* biased, but…



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**.

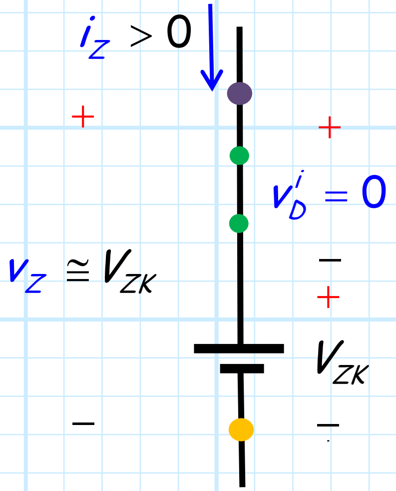
In other words:

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

Just like a **Zener** diode in operating in the **reverse bias region**!

...if Ideal is *forward* biased, Zener is in *breakdown*!

Likewise, we find that **if** the model current is positive ($i_Z > 0$), then:



- the **ideal** diode must be **forward** biased, and
- 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 operating in the **breakdown region**!

→ Carefully consider this case—if the **IDEAL** diode is **forward biased**, the model estimates the **Zener** diode voltage and current when operating in the **breakdown** region—this is **not a contradiction**!

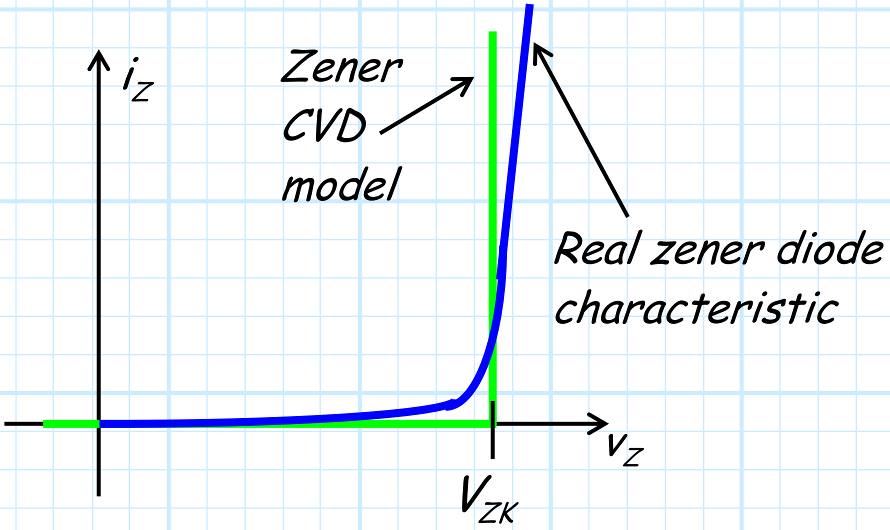
The voltage is not *quite* constant

Q: *So how **accurate** is the Zener CVD model?*

A: **Quite** accurate! But it is **not** exact.

Here's the **problem**: the voltage across a zener diode in breakdown is not **exactly** equal to V_{ZK} for all $i_z > 0$.

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

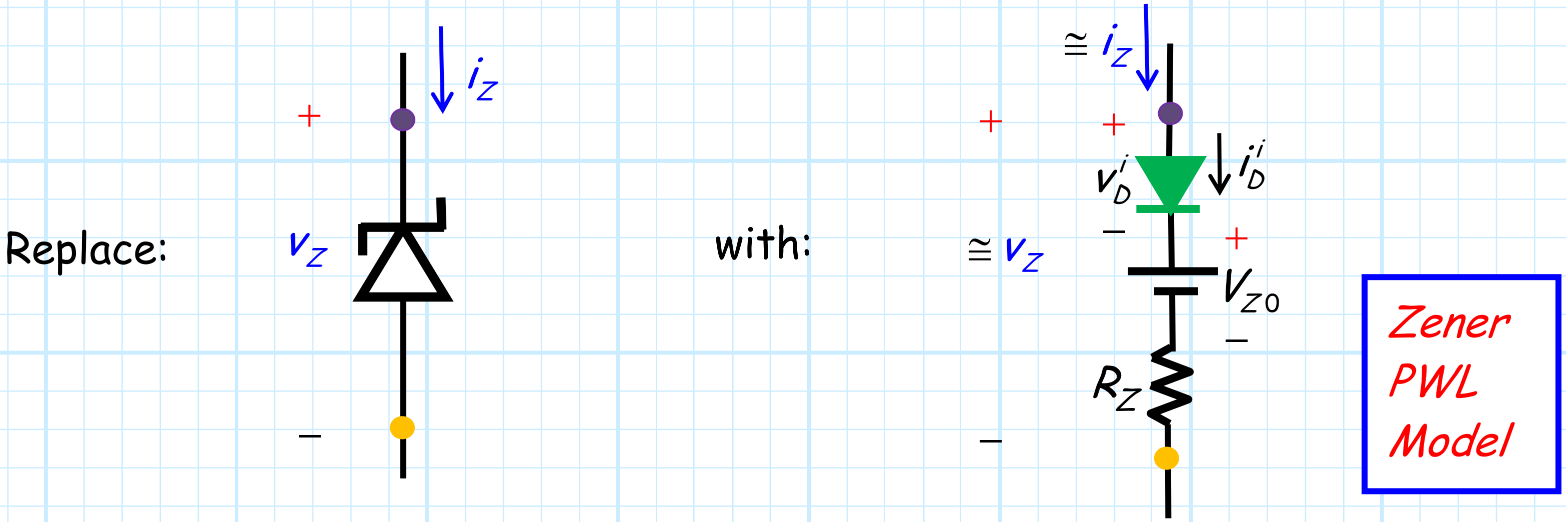


Thus, the CVD model causes a **small** error, usually acceptable—but for some cases **not**!

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

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

The Zener Piecewise Linear model



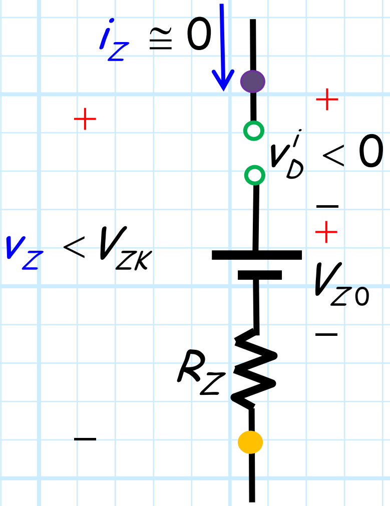
Please Note:

- * The PWL model includes a **very small** (e.g., 0.01 Ω) 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** of the Zener diode.

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

Smells like reverse bias region



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.

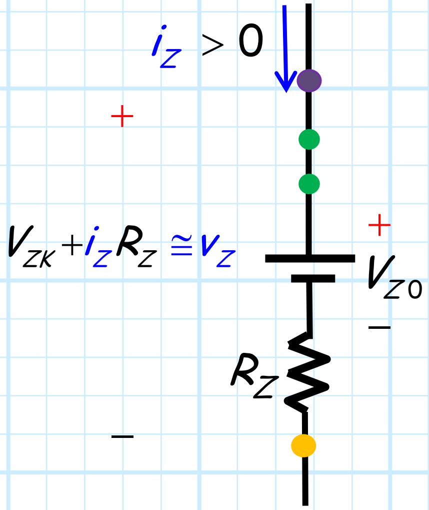
In other words:

$$i_Z = 0 \quad \text{and} \quad v_Z < V_{Z0} \cong V_{ZK}$$

Just like a **Zener** diode operating in the **reverse bias region**!

Smells like breakdown region

Likewise, we find that **if** the model current is positive ($i_Z > 0$), then:

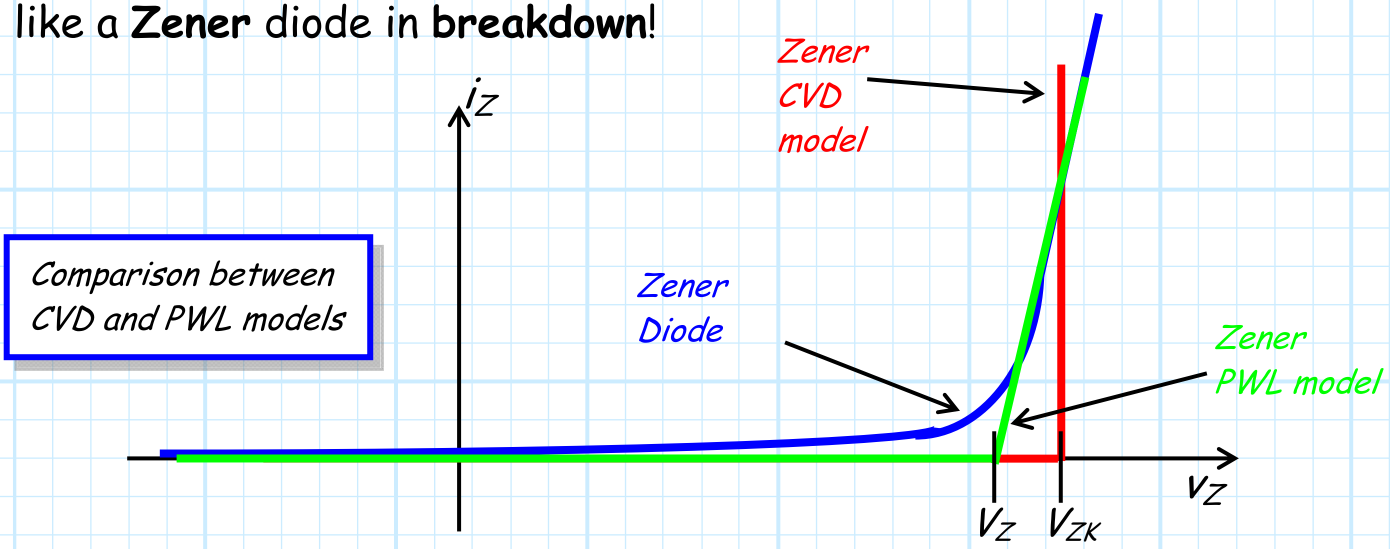


- the **ideal** diode must be **forward** biased,
- and thus the model **voltage** is:

$$v_Z = V_{Z0} + i_Z r_Z$$

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

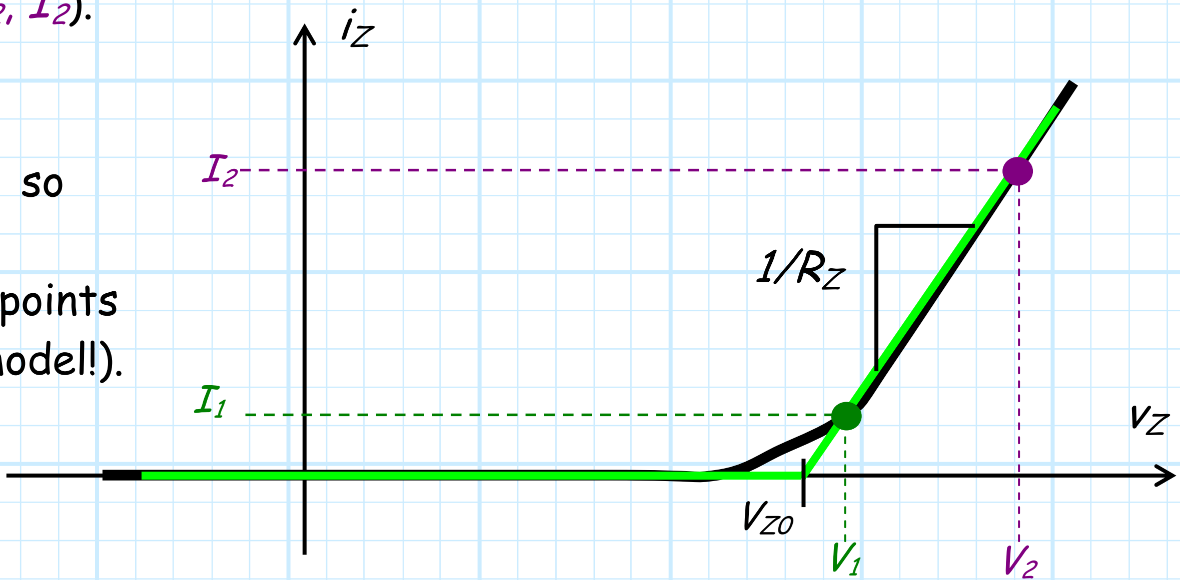
→Just like a **Zener** diode in **breakdown**!


Comparison between CVD and PWL models

Thank your middle school math teacher

Q: *But how do we **construct** this PWL model; how do we determine the values of* V_{Z0} *and* R_Z*?*

A: Typically, the manufactuer will provide **two** or more **test points** on the zener diode curve (V_1, I_1) and (V_2, I_2).



We then select R_Z and V_{Z0} so that the PWL model line **intersects** these two test points (just like the other PWL model!).

Specifically, the dynamic resistance is:

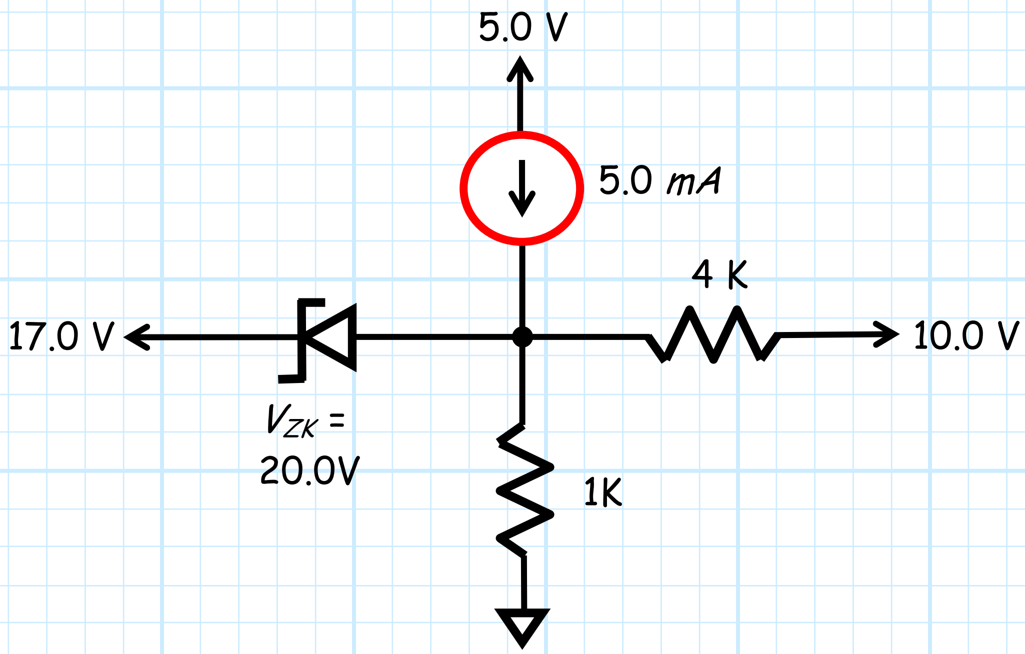
$$R_Z = \frac{V_2 - V_1}{I_2 - I_1} \quad \text{(a very small value!)}$$

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

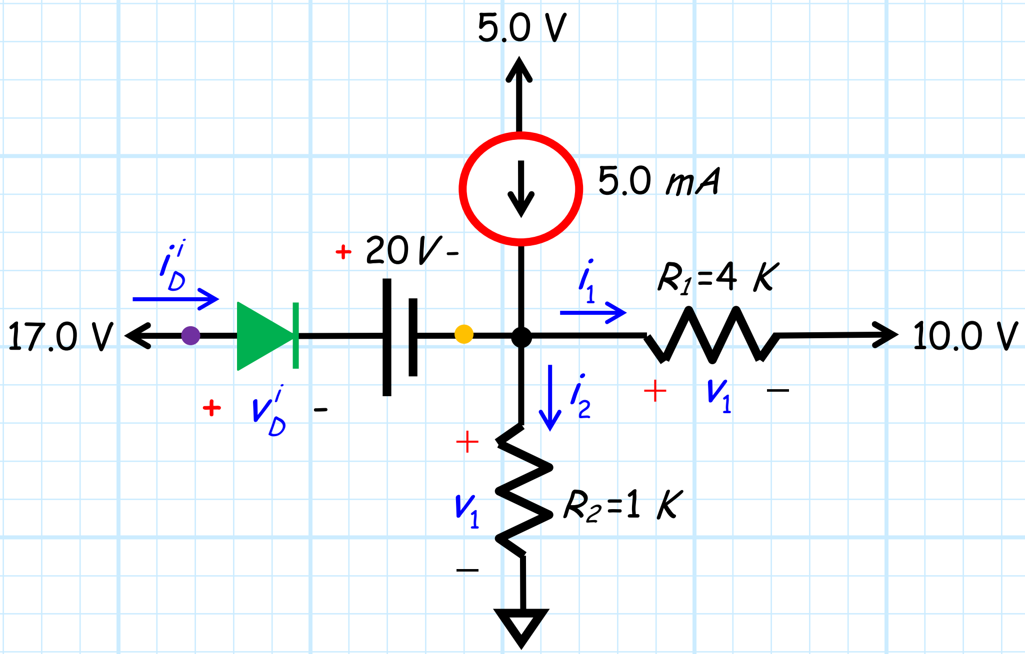
Consider **this** circuit, which includes a **Zener** diode:



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?*

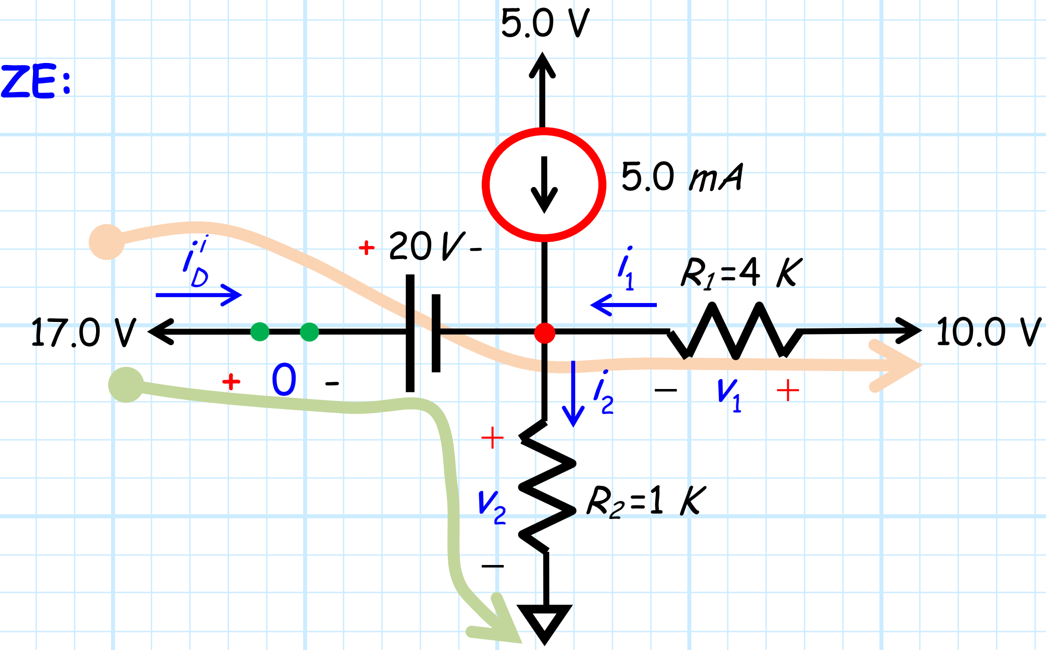
*In order to account for the **Zener** diode behavior, shouldn't we **alter** what we assume, or what we enforce, or what we check?*

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**:

$$17 - v_D^i - 20 - v_2 = 0$$

$$\therefore \quad v_2 = 17 - 0 - 20 = -3.0\,V$$

Likewise from **KVL**:

$$17 - v_D^i - 20 + v_1 = 10$$

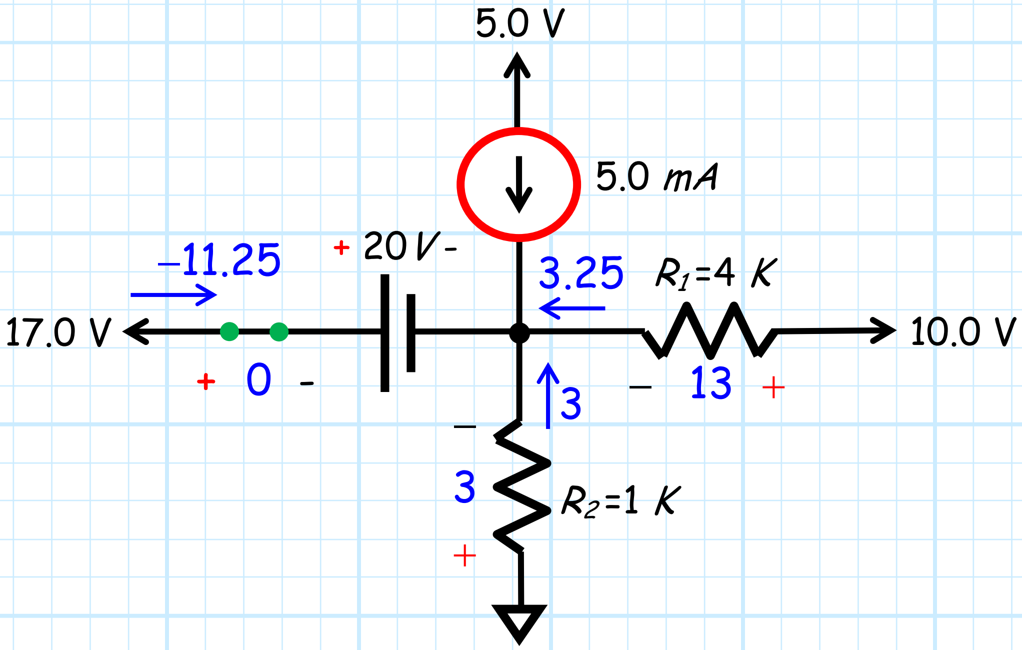
$$v_1 = 10 + 20 + 0 - 17 = 13.0\,V$$

Now from **Ohm's Law**:

$$i_1 = \frac{v_1}{R_1} = \frac{13}{4} = 3.25\,mA \qquad \text{and} \qquad i_2 = \frac{v_2}{R_2} = \frac{-3}{1} = -3.0\,mA$$

Finally, from **KCL**:

$$\begin{aligned} i_D' &= i_2 - i_1 - 5.0 \\ &= -3.0 - 3.25 - 5.0 = -11.25\ mA \end{aligned}$$



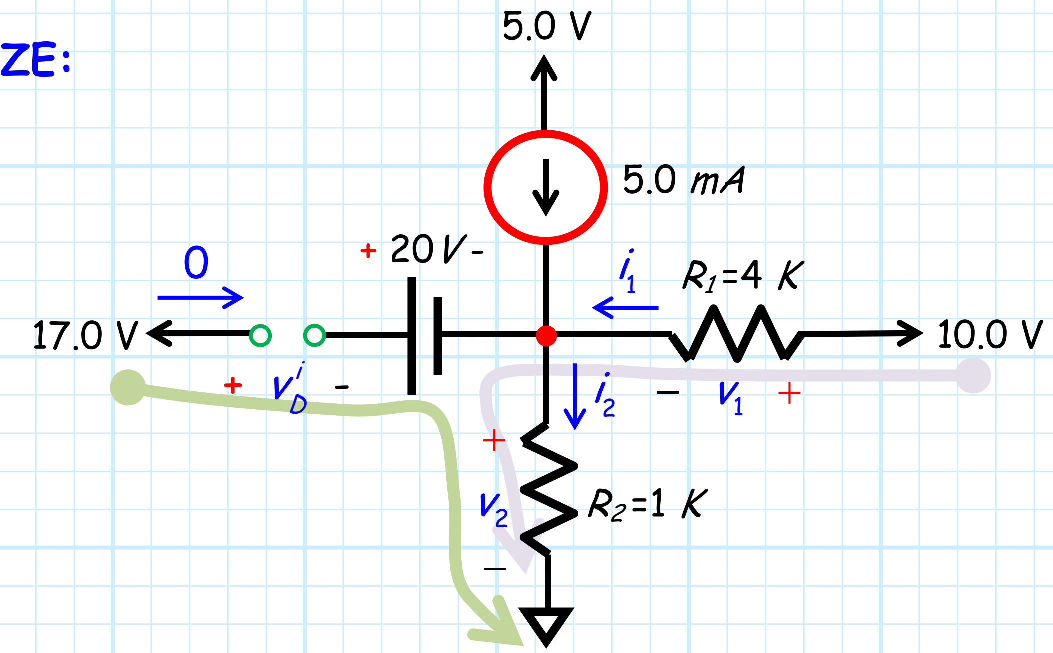
CHECK: $i_D' = -11.25\ mA \overset{?}{>} 0$ ✗

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

ASSUME: Ideal diode is **reverse** biased.

ENFORCE: $i_D' = 0$

ANALYZE:



From **KCL**:

$$i_2 = i_1 + 5 + i_D^i = i_1 + 5$$

Now from **Ohm's Law**:

$$v_1 = i_1 R_1 = 4\,i_1 \qquad \text{and} \qquad v_2 = i_2 R_2 = (i_1 + 5)(1) = i_1 + 5$$

From **KVL**:

$$10.0 - v_1 - v_2 = 0$$

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

Now solving for i_1:

$$i_1 = \frac{10 - 5}{4 + 1} = 1.0\ mA$$

Therefore:

$$i_2 = i_1 + 5 = 1 + 5 = 6.0 \; mA$$

And:

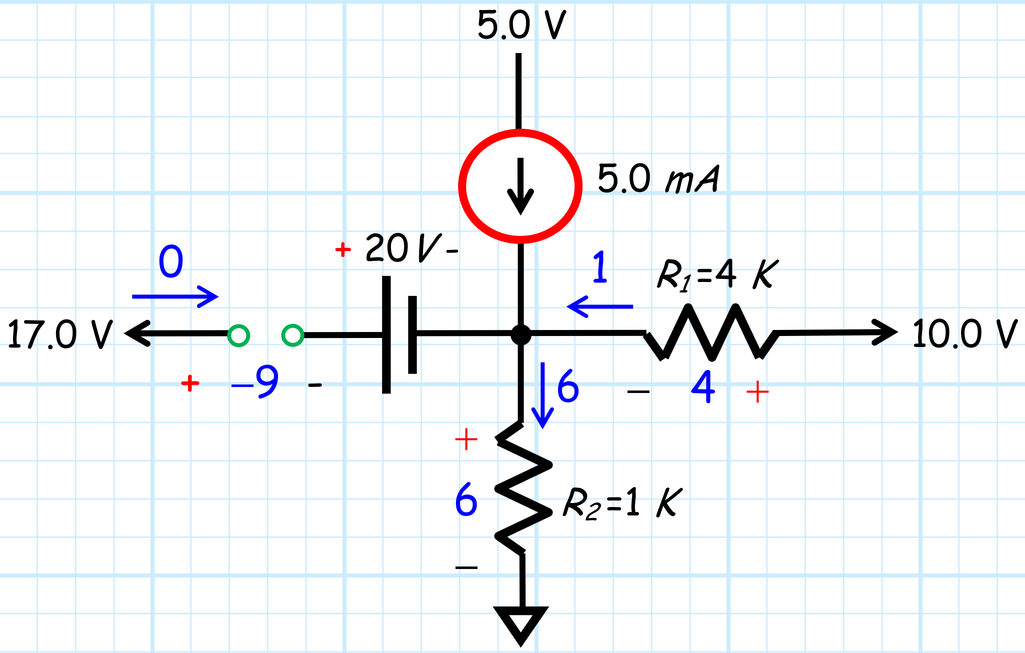
$$v_1 = 4\,i_1 = 4(1) = 4.0\;V \qquad \text{and} \qquad v_2 = i_1 + 5 = 1 + 5 = 6.0\;V$$

Now, again using **KVL**:

$$17 - v_D^i - 20 - v_2 = 0$$

Therefore

$$\begin{aligned} v_D^i &= 17 - 20 - v_2 \\ &= 17 - 20 - 6 \\ &= -9.0 \;\; V \end{aligned}$$



CHECK: $v_D^i = -11.0\ V \overset{?}{<} 0$ ✓

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,

$$\begin{aligned} v_Z &\cong v_D^i + V_{ZK} \\ &= -11 + 20 \\ &= 9.0\ V \end{aligned}$$

and

$$i_Z = i_D^i = 0$$

We're **done**!

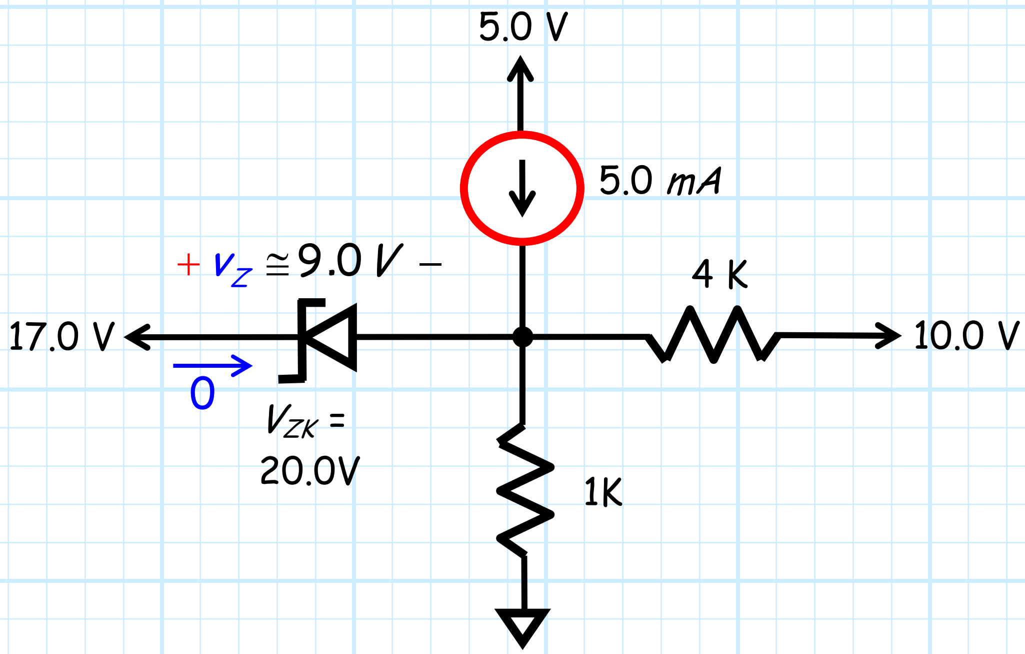
Q: *Wait! Don't we have to somehow CHECK these values?*

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.

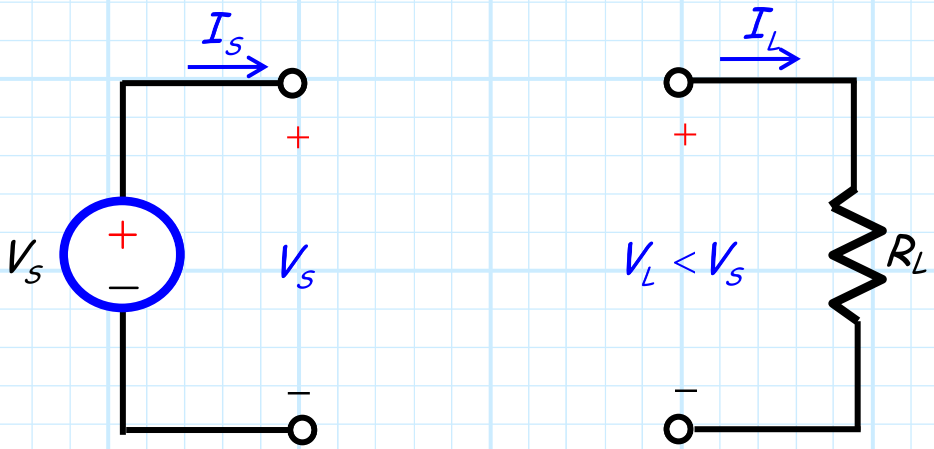
So, let **me** ask **you** the question **Q:** Does this answer make physical sense?

A:

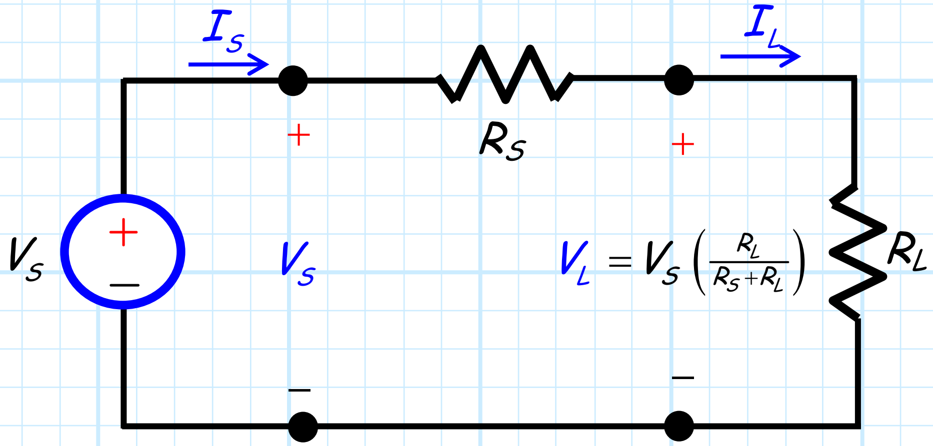


The Shunt Regulator

Say that we have some **source** voltage V_s, but our **load** requires a lower voltage V_L:



Q: *Piece of cake! We just insert the proper series resistor R_S to form a **voltage divider**, right?*



A: This in fact is a very **bad solution**—we need a **regulated voltage** across the load.

He's been like that since 1863

A **regulated voltage** is one that is **constant;** it never, **ever** changes—period.

For example, the voltage V_L across the load must be **independent** of the load itself.

If R_L increases or decreases, then the **load current** I_L will decrease or increase—but the voltage V_L should remain **unchanged**.

→This is know as a **load regulation**.

Or maybe you start watching Netflix

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**).

Thus, modeling the load as a **resistor** R_L is often not especially accurate; the load instead is **defined by the current I_L** that it "draws".

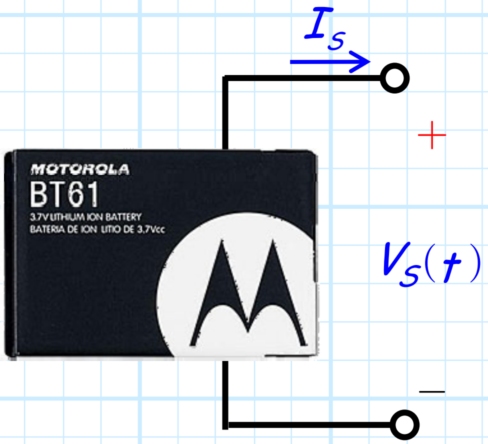
The source voltage changes

Likewise, a regulated voltage **must** remain constant, even if the source voltage V_s changes—this is known as **line regulation**.

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**.

For example, the energy for an electrical system, such as a "smart phone", often is supplied by a **chemical battery**.

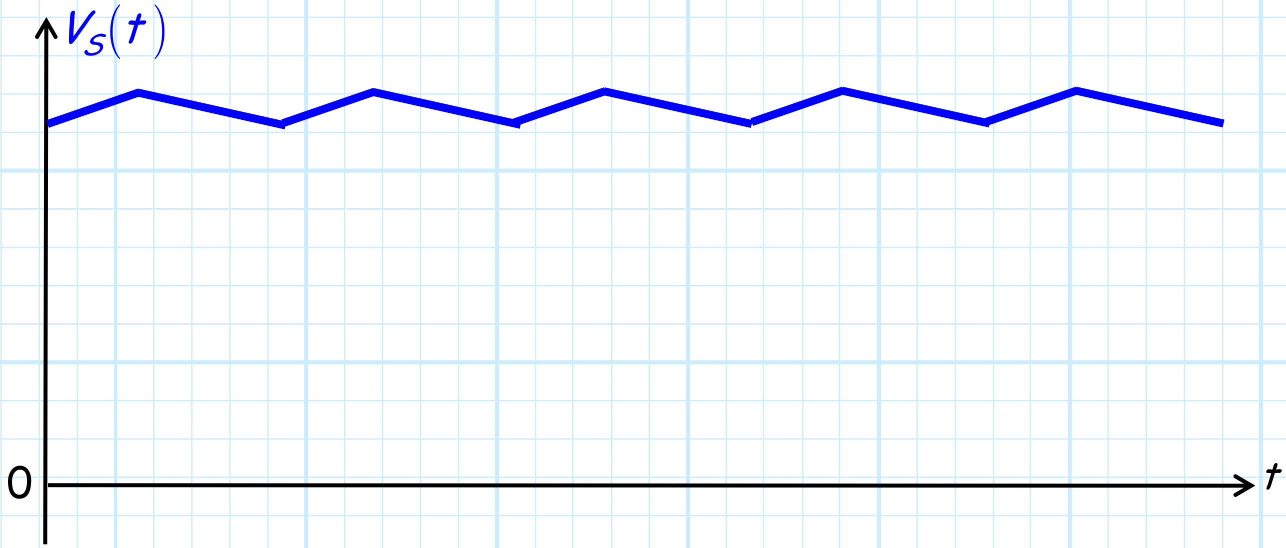


As this battery delivers energy, the voltage across it will slowly **diminish**—it **"runs down"**.

Yet, we need the **regulated** voltage to remain **constant**!

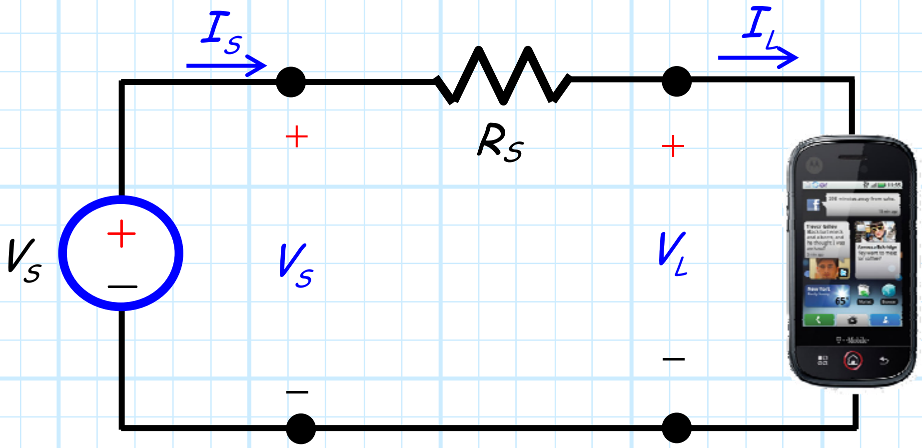
Ripple voltage

Likewise—as we shall learn later—if the source voltage V_S is the output of an **AC** to **DC** power supply, it will likely include an AC component—a time-varying (not constant!) signal that we call the **ripple voltage**.



Yikes, the load voltage is unregulated

Let's return to **original** circuit:



From **KVL**, it circuit analysis, it is apparent that the difference between the source voltage V_S and load voltage V_L is simply the voltage drop across the **series** resistor R_S

$$V_L = V_S - I_L R_S$$

Clearly, the load voltage V_L depends on **both** source voltage V_S **and** load current I_L—the load voltage V_L will **change** when V_S and/or I_L change (this is **bad**!).

Calculus: Is there anything it can't do?

To **quantify** this, we simply take the derivative of V_L with respect to V_S and I_L:

$$\frac{\partial V_L}{\partial V_S} = \frac{\partial \left(V_S - I_L R_S \right)}{\partial V_S} = 1.0$$

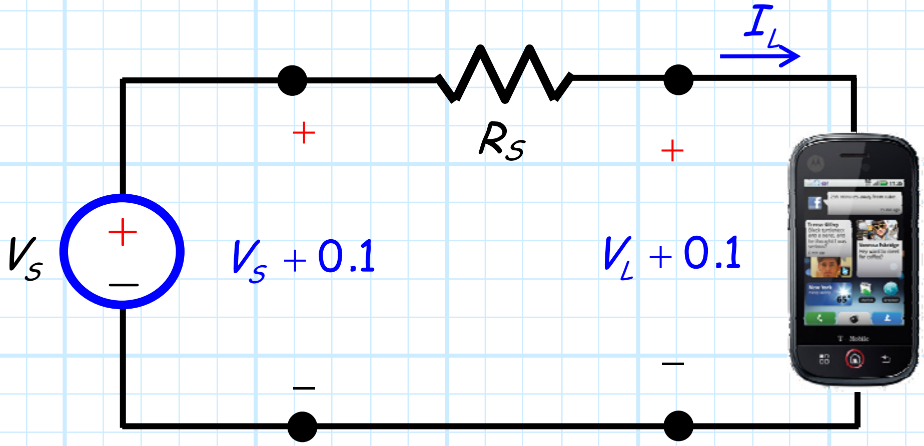
$$\frac{\partial V_L}{\partial I_L} = \frac{\partial \left(V_S - I_L R_S \right)}{\partial I_L} = -R_S$$

The first of these derivatives quantifies the **line regulation**.

Since the value is 1.0, the load voltage changes **directly** with the source voltage (provided load current I_L remains **unchanged**).

Line regulation: stinky

For **example**, if the source voltage increases by **100 mV**, the load voltage will increase by **100 mV** as well (again, if I_L remains constant).



This is **very poor** line regulation!

Contrast this with the **ideal** case, wherein the derivative is equal to zero,

This means that a source voltage increase of **100 mV** (or any value, for that matter) results in **no change** in the load voltage.

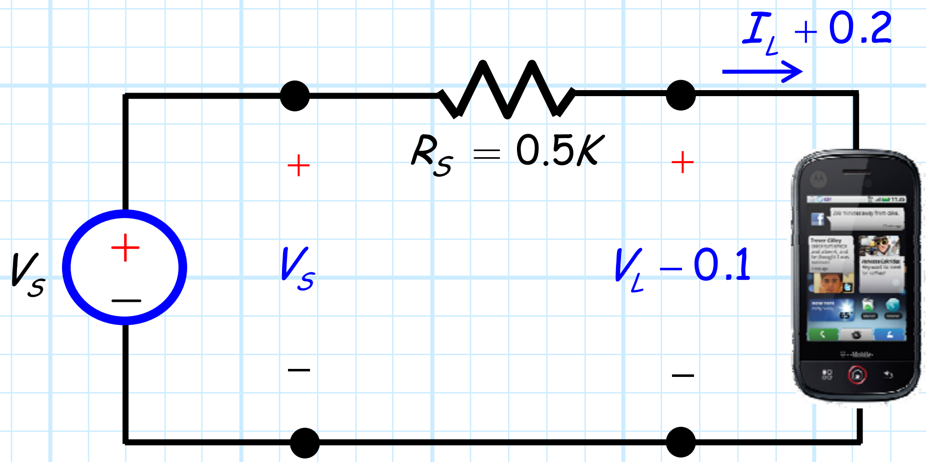
Load regulation: stinky

The second of the derivatives quantifies **load regulation**:

$$\frac{\partial V_L}{\partial I_L} = \frac{\partial \left(V_S - I_L R_S \right)}{\partial I_L} = -R_S$$

The **minus** sign in this case means that an **increasing** load current I_L will result in a **decreasing** load voltage (and vice versa).

For **example,** if the series resistor R_S has a value of 500 Ohms ($R_S = 0.5K$), an increase in the load current of **0.2 mA** will cause a **100mV** reduction in the load voltage V_L.



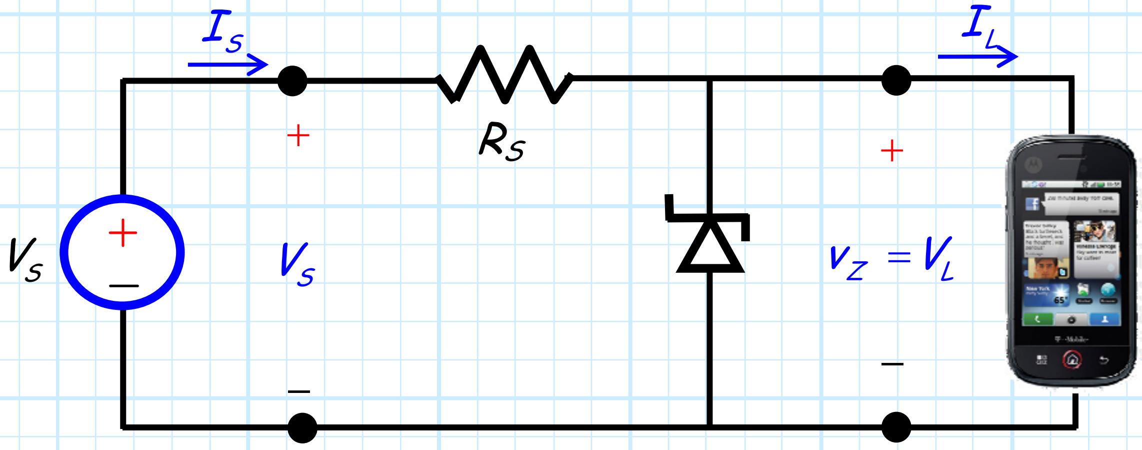
This is **very poor** load regulation!

Contrast this with the **ideal** case, wherein this derivative is equal to zero, meaning that a load current increase of **0.2 mA** (or any value, for that matter) results in **no change** in the load voltage.

Zener diodes to the rescue!

Q: *So what do we do? How do we achieve **voltage regulation**?*

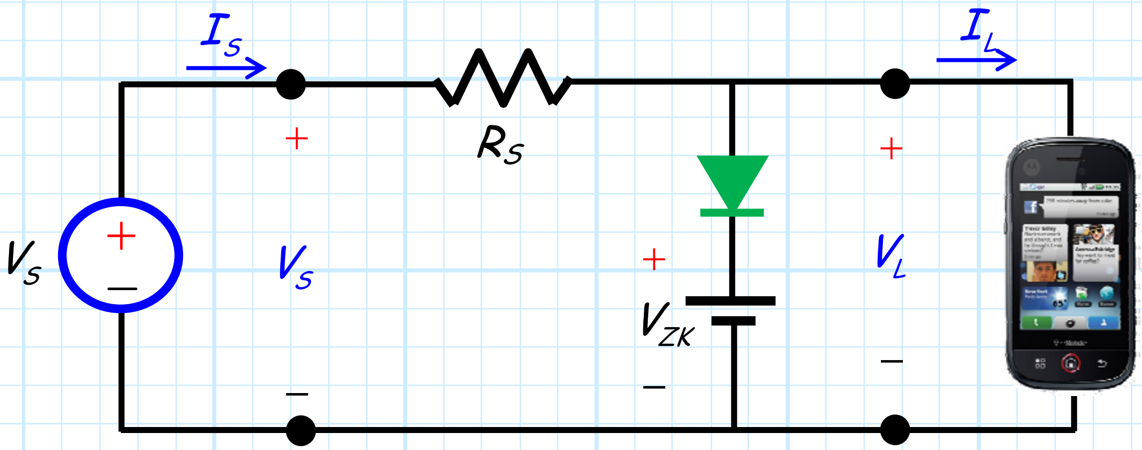
A: One solution is very **simple**—we just add a shunt **Zener diode**!



Q: *Huh? What good would **this** do?*

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

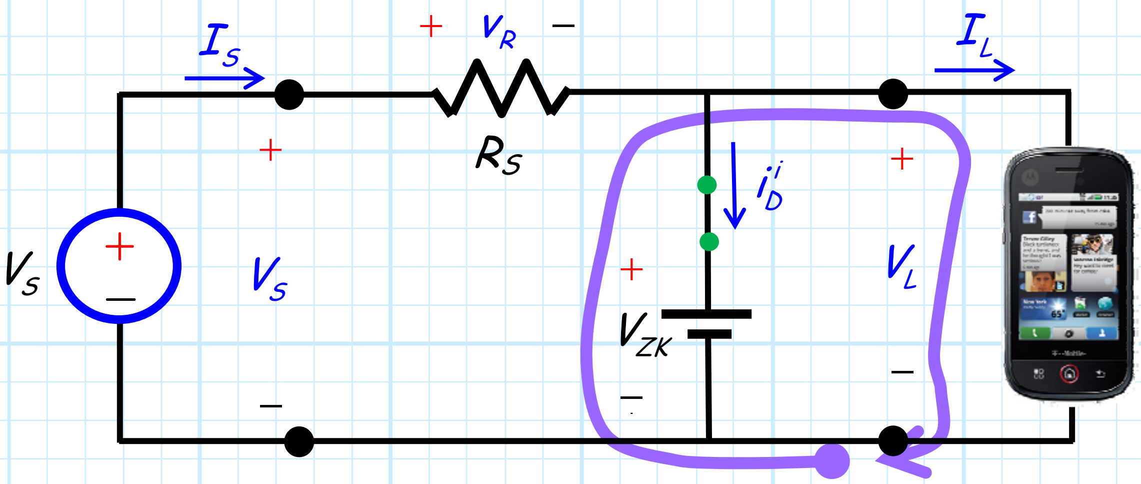
Be careful!



Now let's:

- ASSUME the **ideal** diode is forward biased,
- ENFORCE the assumption with a short,
- and then ANALYZE the resulting circuit.

$V_L = V_{ZK}$!!!!!!!!!!!!!!



From **KVL**, we arrive at an important result:

$$V_L = V_{ZK} \quad !!!!!!!$$

→The load voltage is equal to the Zener breakdown voltage!!!

Q: *Wow! Is this **always** true?*

A: It is **if** the ideal diode forward bias ASSUMPTION is correct!

We need to find the ideal diode current

Q: ***Is** the ASSUMPTION correct?*

A: Let's determine the **ideal** diode current and **find out**!

First, from **KCL**:

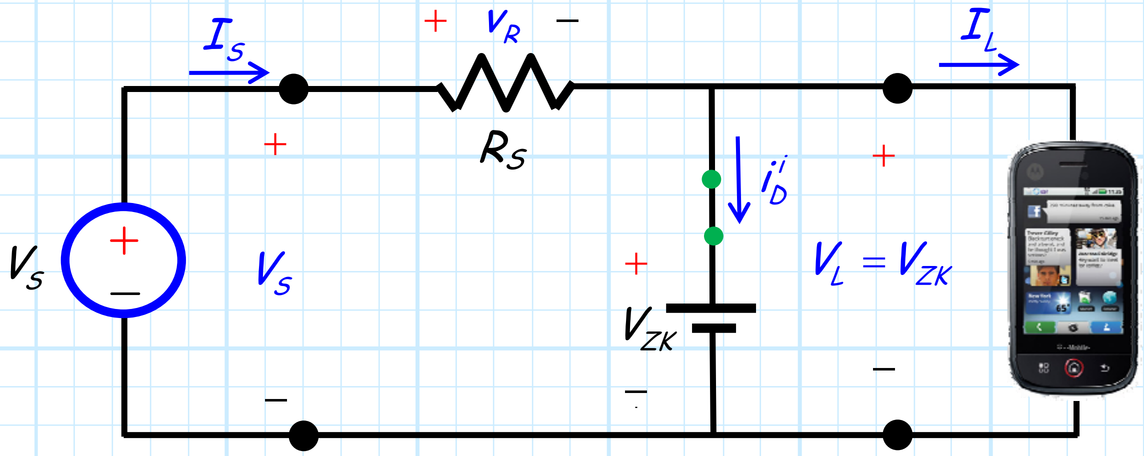
$$i_D^i = I_S - I_L$$

And from Ohm's Law:

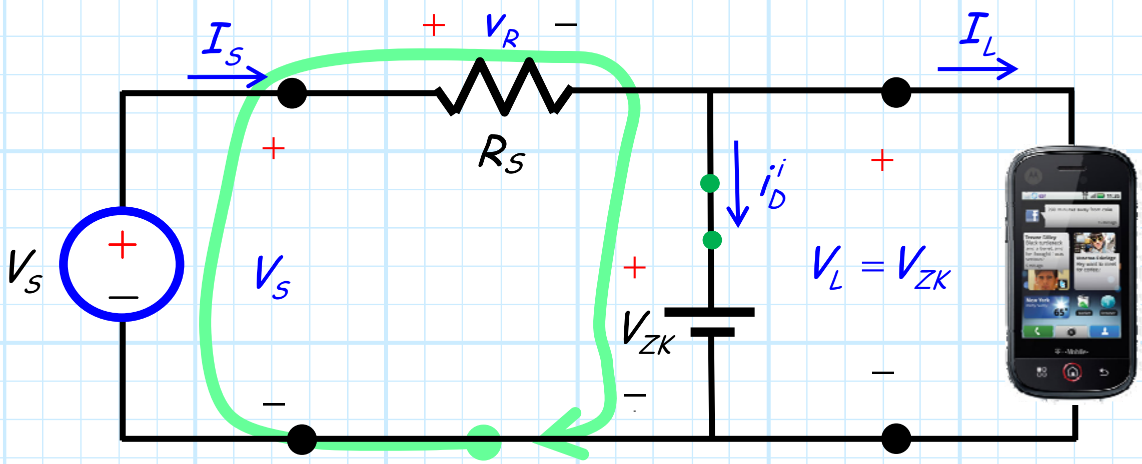
$$I_S = \frac{V_R}{R_S}$$

Therefore:

$$i_D^i = I_S - I_L = \frac{V_R}{R_S} - I_L$$



We found the ideal diode current!



Finally, from **KVL**:

$$V_S - v_R - V_{ZK} = 0 \qquad \Rightarrow \qquad v_R = V_S - V_{ZK}$$

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

$$i_D^i = \frac{v_R}{R_S} - I_L = \frac{V_S - V_{ZK}}{R_S} - I_L = \frac{V_S}{R_S} - \left(\frac{V_{ZK}}{R_S} + I_L\right)$$

Not if, but *when*!

Q: *So how do we **CHECK** to see if this is **positive**?*

A: Since there are **no numeric values** given to the variable names, we cannot in this case determine **if** the current is positive.

Rather, we can determine **when** the current is positive!

In other words, we can determine the **conditions** that will make this ideal diode current positive. I.E., if:

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

we find that:

$$\frac{V_S}{R_S} > \frac{V_{ZK}}{R_S} + I_L$$

$$\Rightarrow \quad V_S > V_{ZK} + R_S I_L$$

They better be true…

Thus, the source voltage V_S **must** be at least $R_S I_L$ **larger** than the load voltage $V_L = V_{ZK}$.

Or rearranging, we equivalently find that the **load** current I_L has a maximum value—it **must** be **less** than the **source** current I_S:

$$I_L < \frac{V_S - V_{ZK}}{R_S} = I_S$$

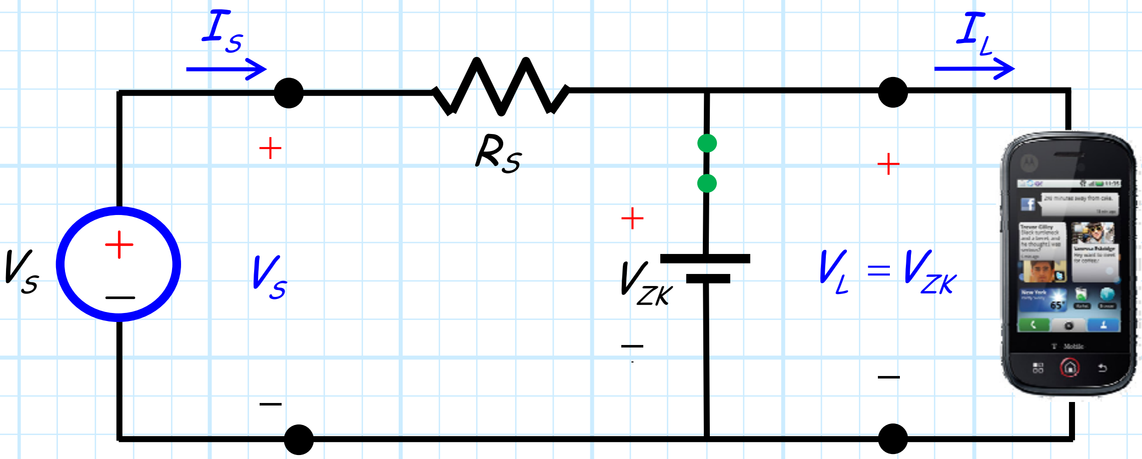
Q: *I'm confused; why* ***must*** *these things be true?*

A: They **must** be true in order for the **ideal** diode current in the Zener CVD model to be **positive** (i.e., $i_D^i > 0$)—they **must** be true in order for our ASSUMPTION to be correct.

...or else we have no regulation!

And as a result, they **must** be true in order for the **load voltage** V_L to be **equal** to the **Zener breakdown voltage**:

$$V_L = V_{ZK} \qquad if \qquad V_S > V_{ZK} + R_S I_L \quad !!!!!!$$



Since 1863

Q: ***Why*** *do you keep putting exclamation points (!!!!!) after* $V_L = V_{ZK}$*?*

Why is this result such a "big deal"?

A: Because the Zener breakdown voltage V_{ZK} is a **device parameter**—it is a **constant.**

→ It never, **ever** changes—period.

Thus, since the load voltage V_L is equal to V_{ZK}, the load voltage is a constant.

→ It never, **ever** changes—period.

That's what I call regulation!

The **line regulation** is thus:

$$\frac{\partial V_L}{\partial V_S} = \frac{\partial V_{ZK}}{\partial V_S} = 0.0$$

And the **load regulation** is:

$$\frac{\partial V_L}{\partial I_L} = \frac{\partial V_{ZK}}{\partial I_L} = 0.0$$

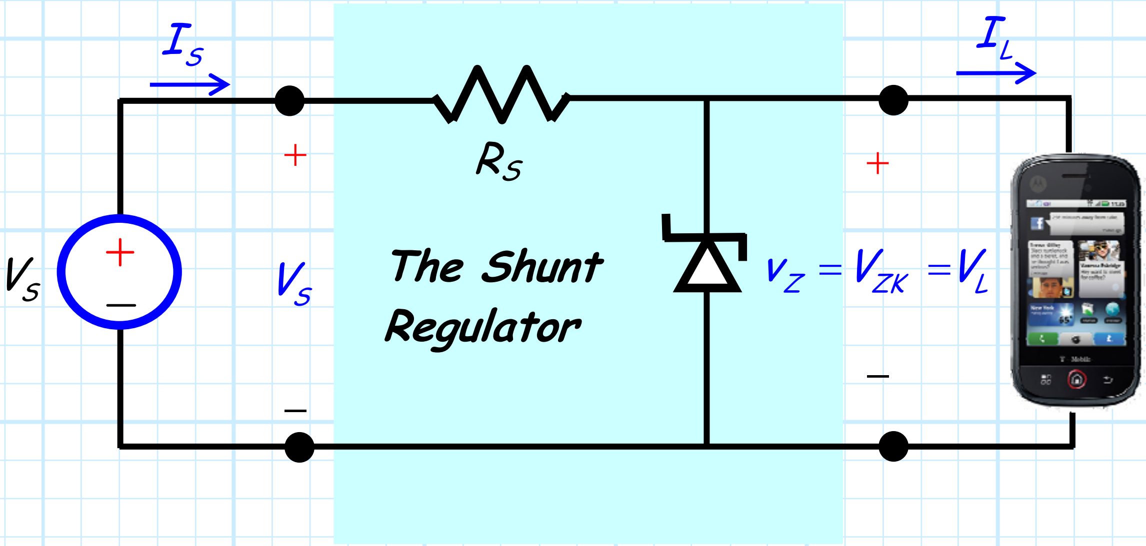
They're both **zero**!

This means that the load voltage will **not change**—it will **remain at** V_{ZK}—even if the source voltage V_S and/or load current I_L **change value** (provided that $V_S > V_{ZK} + R_S I_L$).

→ Now **that's** voltage regulation!

The shunt regulator

This **two-port** circuit is known as the **shunt regulator**.



A summary

Summarizing, we find that **if**:

$$V_S > V_{ZK} + R_S I_L$$

then:

1. The Zener diode will be operating in the **breakdown** region (i.e., $v_Z = V_{ZK}$ and $i_Z > 0$).

2. The **load voltage** is therefore equal to the Zener breakdown voltage (i.e., $V_L = v_Z = V_{ZK}$).

4. The **source current** I_S is $I_S = \left(V_S - V_{ZK}\right)/R_S$.

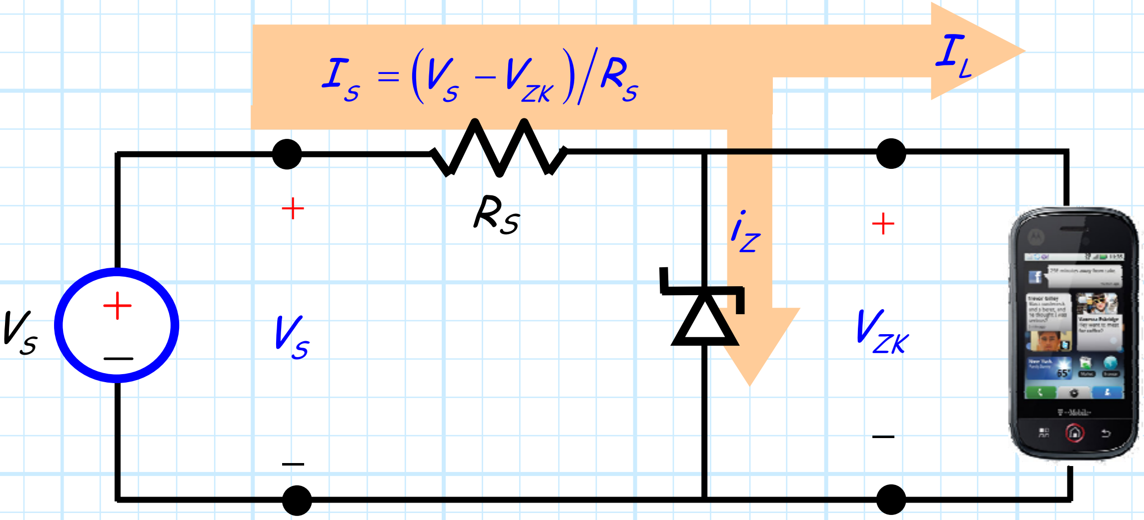
5. The the Zener diode current is less than the source current (i.e., $0 < i_Z < I_S$).

Source current must be larger than the load current

In a shunt regulator, the **source** current $I_S = (V_S - V_{ZK})/R_S$ must be **larger** than the **load** current I_L.

From KCL, we see that the **extra** source current—the current not "used" by the load—must pass through the **Zener diode**.

This causes the Zener to operate in the **breakdown** region.

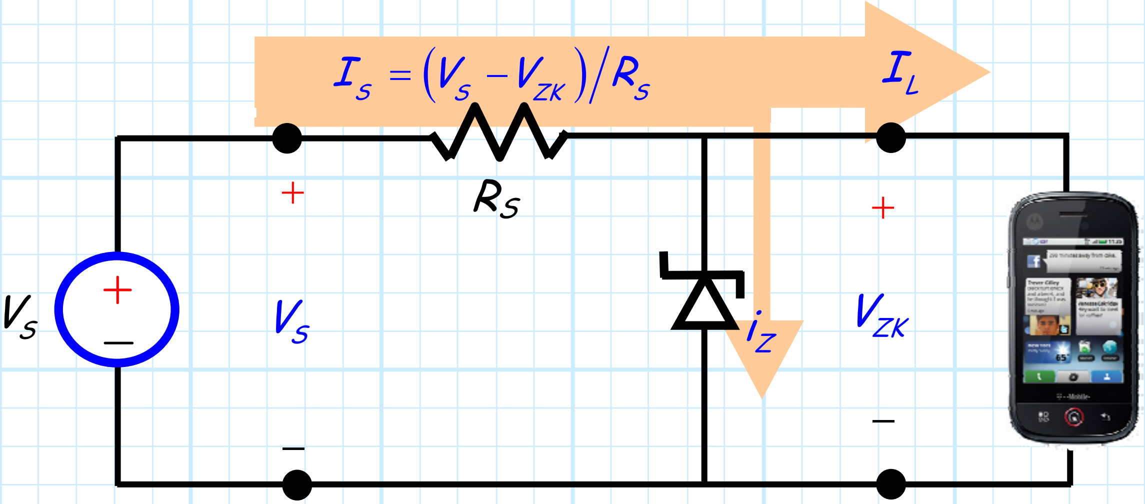


The Zener takes the extra current…

Now, say the **load changes**, such that it draws **more load current** I_L (e.g., the radio transmitter turns on).

Note though, that the source current I_S does not change—if it did, we would see a different load voltage!

Instead, some of the "extra" current from the Zener diode now goes to **load**—the load current increases, but the **source** current remains **the same ol' value** $I_S = (V_S - V_{ZK})/R_S$.



…but the Zener voltage remains unchanged!

Q: *Hey wait!*

*If there is **less current** flowing through the **Zener** diode, won't the voltage $v_Z = V_L$ **drop** as well?*

A: Not really!

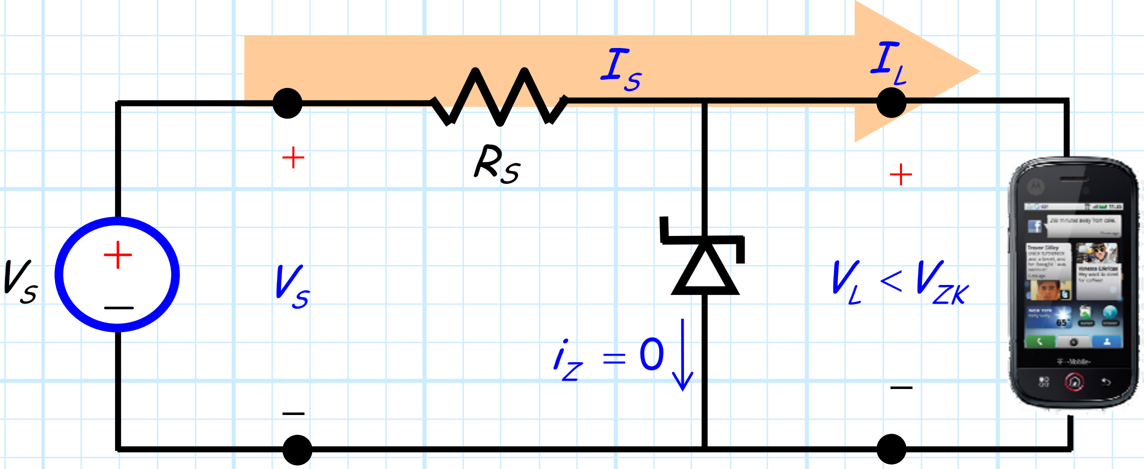
That's the great thing about the Zener in breakdown—the voltage V_{ZK} across the device is **practically independent** of the current through it.

→This is why the **load regulation** is (practically) **zero**!

The load current can only go so high

Of course, this is true **only if** the Zener diode is operating in the **breakdown** region.

Note that as load current I_L **increases** to a value **equal** to the source current, the **Zener current** will approach **zero**:

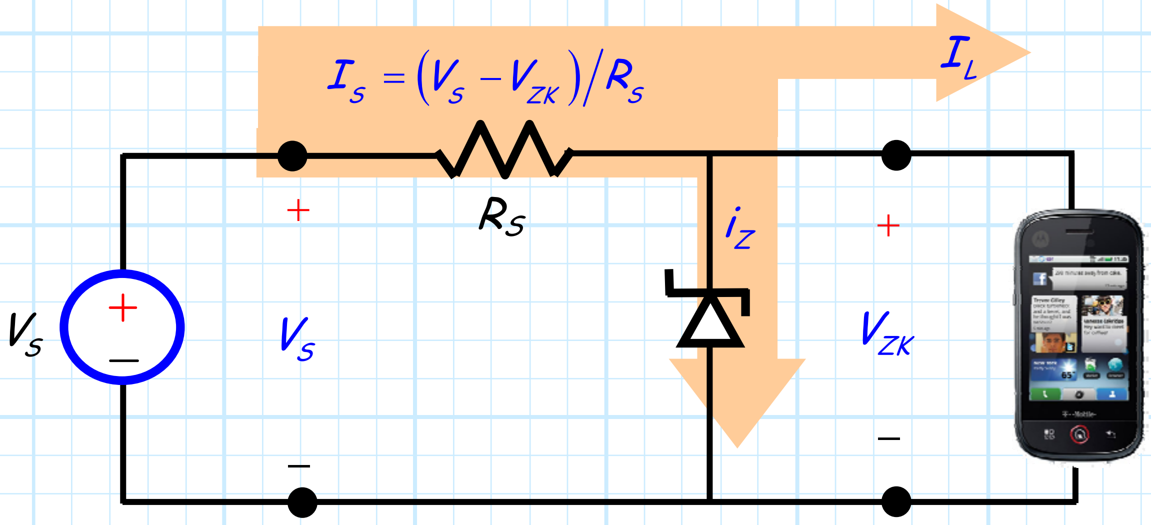


Thus, the Zener will **no longer** be in breakdown (reverse bias instead!), and so the **load voltage** will no longer be equal to V_{ZK}! I.E.,:

$$\text{If} \quad I_L \geq \frac{V_S - V_{ZK}}{R_S} \quad \text{then} \quad V_L \leq V_{ZK}$$

It also provides line regulation!

Likewise, if the source voltage **increases**, then the **source current** will increase as well.



But, the **load current** does **not** increase, as this "extra" source current simply results in **greater Zener diode current**.

Remember, greater Zener diode current will **not** increase Zener diode voltage → $v_Z = V_{ZK} = V_L$!

→This is why the **line regulation** is (practically) **zero**!

Example: The Shunt Regulator

Your **boss** rushes in and excitedly asks/demands that you design a **voltage regulator** for a new **gizmo** the company is about to manufacture.

The gizmo requires a voltage of precisely **6.0 Volts**, and at a **maximum** will require power of **1.2 Watts**.

The gizmo will require a **standard battery(s)** as a source (the kind you buy at **Quick Trip**), with as high a voltage as possible.

However, **at least 60%** of this battery power must be delivered to the gizmo.

The regulator must likewise be **simple** and **cheap**.

➔ You decide to design a **shunt** regulator to **meet these criteria**!

This of course means that you must select the **Zener diode**, the series **resistor**, and the **source** (i.e., **battery**) voltage.

The Zener diode is pretty simple, its **breakdown** voltage must be equal to the widget voltage of **6.0 volts**:

$$V_{ZK} = 6.0\,V$$

Likewise, the **efficiency** of this regulator must be greater than 60%, therefore:

$$\eta = \frac{V_{ZK}}{V_s} > 0.6 \qquad \Rightarrow \qquad V_s < \frac{V_{ZK}}{0.6}$$

Since the **battery voltage** should also be as **high as possible**, you decide to make it the largest value that **still satisfies** the **efficiency** requirement:

$$V_s = \frac{V_{ZK}}{\eta} = \frac{6.0}{0.6} = 10.0\,V$$

Now, the **maximum power** that the gizmo will draw is **1.2 Watts**, which corresponds to a **maximum current** of:

$$I_L^{\max} = \frac{P_L^{\max}}{V_{ZK}} = \frac{1.2}{6.0} = 200\,mA$$

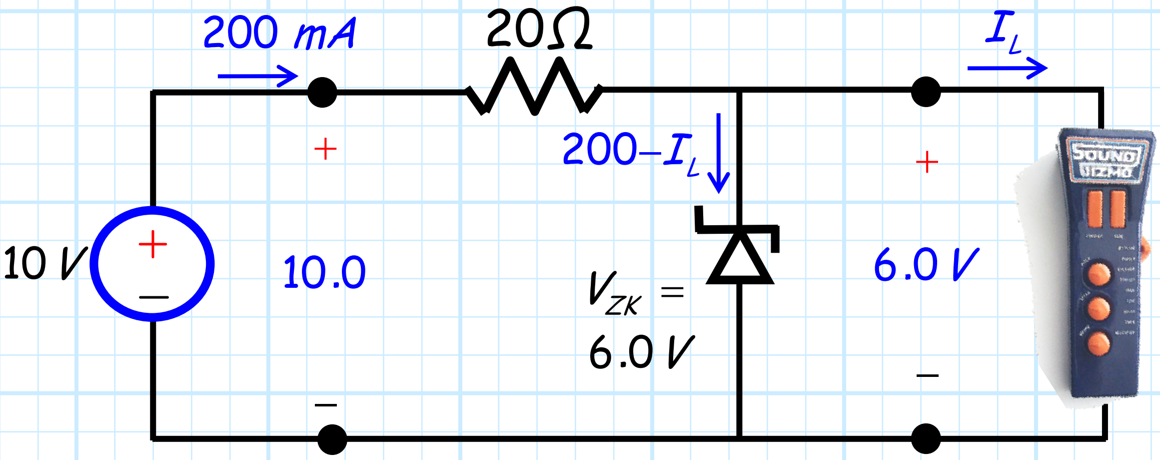
The **source current** should be made **equal** to this maximum **load current** value:

$$I_s = \frac{V_s - V_{ZK}}{R_s} = I_L^{\max}$$

so that the **series resistance** should be:

$$R_s = \frac{V_s - V_{ZK}}{I_L^{\max}} = \frac{10-6}{200} = 0.02\,K = 20\Omega$$

Thus, your **design is complete**!



You **eagerly** present this design to your **boss.** Your heart thumps as you anticipate both **praise and reward**. Will you get a raise? a bonus? a promotion? **stock options**?

Instead, your boss looks at you with **derision** and **disgust**.

You palms begin to **sweat** as you consider what might have **gone wrong**. You checked all the math; **KCL** and **KVL** are verified.

Most of all:

*You are **sure** that you used **the "right equations"** !*

Finally, your boss breaks the **awkward silence** with this question:

*"Where are **we**—or our **customers for that matter**—supposed to get a **10 volt** battery?"*

Yikes! Batteries—at least the kind you can by at **Quick Trip**—are typically **1.5 Volts**. The standard AAA, AA, B, C, and D-cell batteries are **all 1.5 volts**.

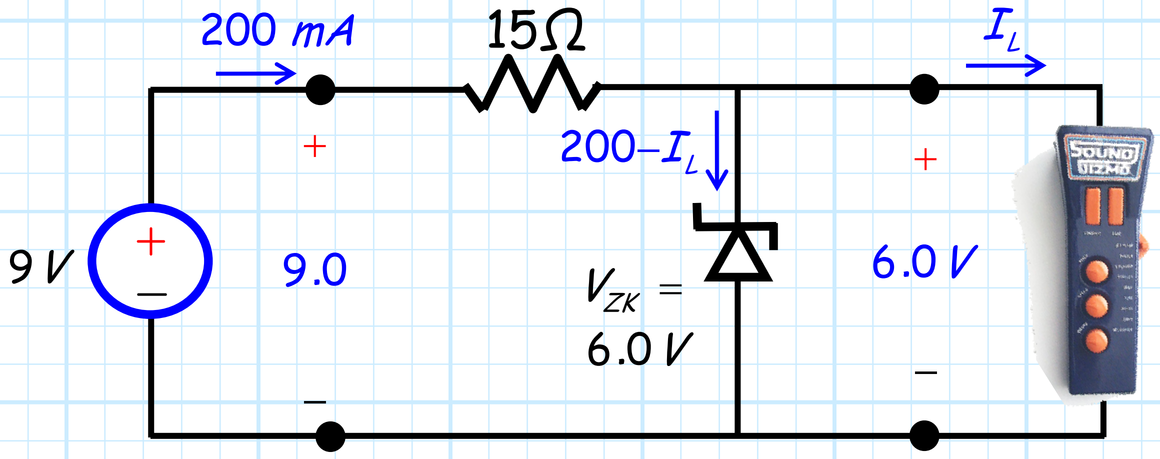
Of course we can create a **higher** voltage by **"stacking"** them in **series**, but the result would be an **integer multiple** of 1.5 V.

Of course **10 Volts** (*i.e.*, **your** embarrassing solution) is **not** an integer multiple of 1.5 Volts!

The closest multiples to 10 Volts are **10.5 Volts** and **9.0 Volts**.

The problem with the 10.5 Volt solution is that the regulator efficiency would be **less than 60%**. Thus, the **9.0 Volt** solution appears to be the best—**6 batteries connected in series**.

Therefore, modifying your design for this **9.0 Volt** source:



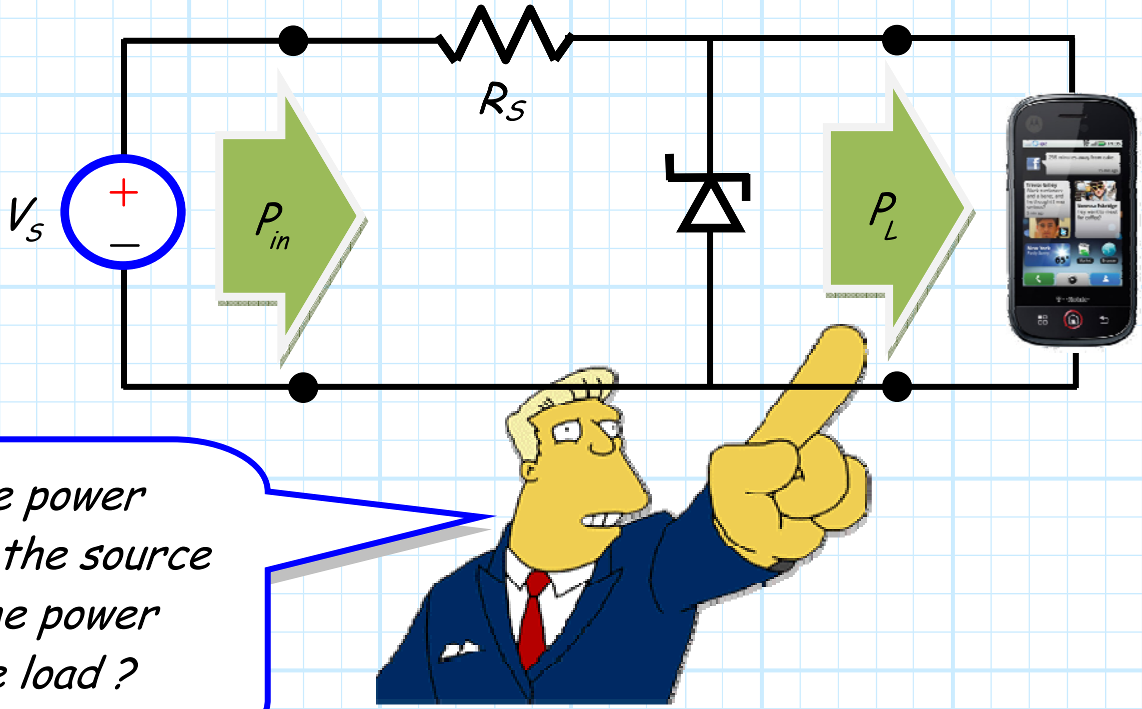
Your job is **safe** (at least for **one more** day!).

Be **aware**: circuit design is **not** a academic exercise; you must provide a design that is **producible** and **maintainable**—you must create a design with components and parts that **actually exist**!

Regulator Power and Efficiency

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

The **source** V_s **delivers** energy at a rate P_{in} (J/sec) to the regulator, and then the regulator in turn delivers energy at a rate P_L (J/sec) to the **load**.

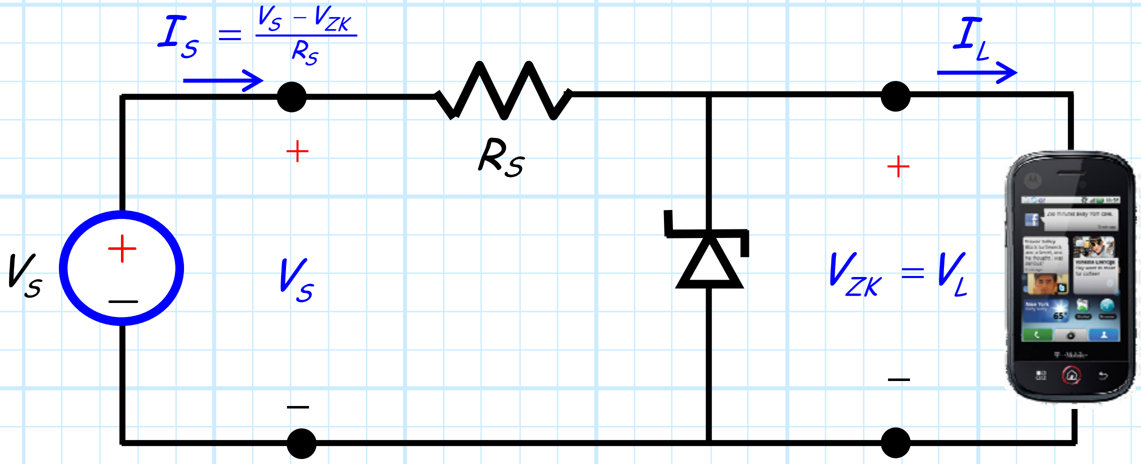


Q: *So, is the power delivered by the source is **equal** to the power absorbed the load ?*

Power goes to the resistor and diode also

A: Not hardly!

The power delivered by the **source** is distributed to **three** devices—the **load**, the Zener **diode**, and the **series** resistor R_S.



We can determine the rate at which **power** is delivered and absorbed, in terms of the **device parameters** of this regulator circuit—we have **four** devices, we have **four device parameters**.

There are four circuit parameters

Specifically, those devices/parameters are:

1. **Source** voltage V_S

2. Series **resistance** R_S

3. **Zener** breakdown voltage V_{ZK}

4. **Load** current I_L

First we determine the rate at which energy is **absorbed** by the **load**:

$$P_L = V_L I_L = V_{ZK} I_L$$

Note, as load **current** I_L decreases, the load **power** likewise **decreases**.

As I_L approaches **zero** (the load is an open circuit), the load power also becomes **zero**.

The source delivers energy— whether the load uses it or not

Now, energy is **delivered** by the **source** at a rate:

$$P_{in} = V_S \; I_S = V_S \left(\frac{V_S - V_{ZK}}{R_S} \right)$$

Q: *Wait! It appears that the input power is **independent** of the load current I_L!*

Doesn't that mean that P_{in} is independent of P_L?

A: That's correct!

The energy flowing **into** the shunt regulator is **independent** of the rate at which energy is being delivered to the load.

Some goes to resistor, some to the diode

In fact, **even** if the load is drawing no current (i.e., P_L=0), the input power is **still** the same value shown above.

A: The **Zener diode** also absorbs energy, at a rate:

$$\begin{aligned} P_Z &= v_Z\, i_Z \\ &= V_{ZK}\left(I_S - I_L\right) \\ &= V_{ZK} I_S - V_{ZK} I_L \\ &= V_{ZK}\left(\frac{V_S - V_{ZK}}{R_S}\right) - V_{ZK} I_L \\ &= \frac{V_{ZK}}{R_S}\left(V_S - V_{ZK}\right) - V_{ZK} I_L \end{aligned}$$

And, the **series resistor** absorbs energy at a rate:

$$\begin{aligned} P_R &= I_S^2\, R_S \\ &= \left(\frac{V_S - V_{ZK}}{R_S}\right)^2 R_S \\ &= \frac{\left(V_S - V_{ZK}\right)^2}{R_S} \end{aligned}$$

Energy comes from the source, but then is absorbed by the load, resistor and diode

Remember, the source V_S is an **active** device—it is a **source** of energy.

In contrast, the series resistor, Zener diode, and load are **passive** devices—they can only **absorb** the energy that the source provides.

Energy is conserved…

By conservation of energy, we conclude then that the power **delivered** by source must be **equal** to all **absorbed** power:

$$P_{in} = P_R + P_Z + P_L$$

Now, using the results above, this **absorbed power** can be specified in terms of regulator **circuit parameters**:

$$\begin{aligned}
P_R + P_Z + P_L &= \frac{\left(V_S - V_{ZK}\right)^2}{R_S} + \left(\frac{V_{ZK}}{R_S}\left(V_S - V_{ZK}\right) - V_{ZK} I_L\right) + V_{ZK} I_L \\
&= \frac{\left(V_S - V_{ZK}\right)^2}{R_S} + \frac{V_{ZK}}{R_S}\left(V_S - V_{ZK}\right) \\
&= \frac{\left(V_S - V_{ZK}\right)}{R_S}\left(V_S - V_{ZK} + V_{ZK}\right) \\
&= \left(\frac{V_S - V_{ZK}}{R_S}\right) V_S
\end{aligned}$$

...and it better be!

But of course, we found earlier that:

$$P_{in} = V_S \left(\frac{V_S - V_{ZK}}{R_S} \right) = P_R + P_Z + P_L$$

And so, we have verified that **conservation of energy is indeed correct** (I can't **begin** to tell you what trouble we'd be in if we had determined **otherwise**!).

Q: *So **who cares**? Why are you telling us this?*

A: This analysis shows the relative **inefficiency** of the shunt regulator.

Let's say the source is powering your phone

Ideally, **all** the power **delivered** by the source would be **absorbed** by the load:

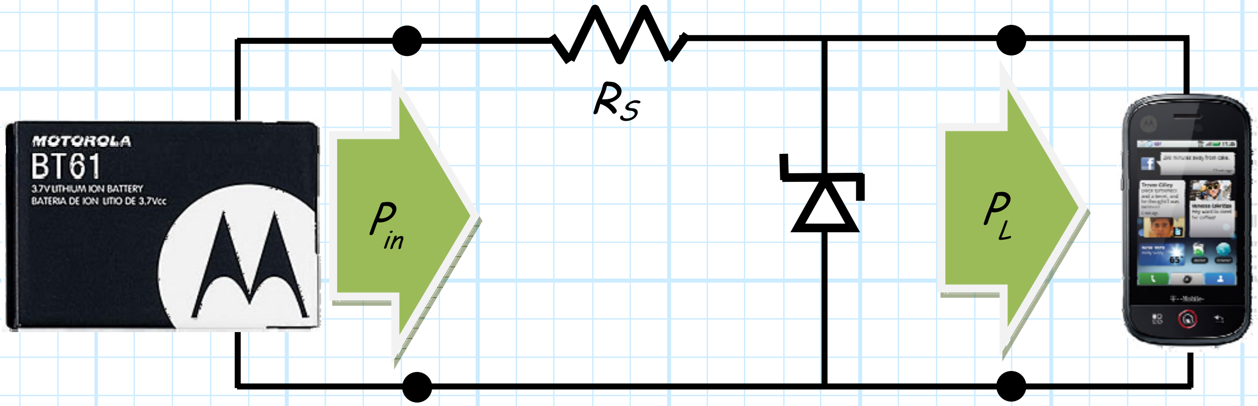
$$P_L = P_{in} \qquad \therefore P_{in} - P_L = 0$$

But alas, we find for the **shunt regulator**:

$$P_{in} - P_L = P_R + P_Z \qquad \therefore P_L < P_{in}$$

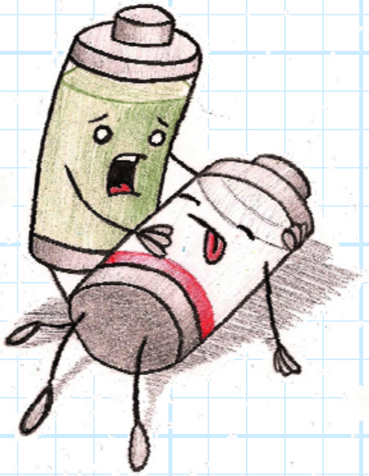
Q: *You've not answered my question—again, **who cares**?*

A: Let's say the source is in fact the battery to **your** phone—I bet then **you** would be the one who **cares**!



Sarcasm alert!

The energy **not** delivered to the load (your phone) is **wasted**—it simply **heats** up the series **resistor** and the Zener **diode**.



This **wasted** energy causes your **battery** to “run down” jiffy quick, and your phone soon **stops operating**!

GrimStarable, Matt Grimmer

As a result, you might **miss** one of those lucid, erudite, fascinating, and otherwise **life-altering** text/twitter messages that you apparently receive with **astonishing frequency**.

→ And wouldn’t **that** be a horrible tragedy!

Got milk? No! We wasted it all!

Thus, voltage regulators need to be **efficient**; the **difference** between P_{in} and P_L should be as **small as possible**.

Note that the ratio P_L/P_{in} provides the **percentage** of the source power that is delivered to the load.

For **example**, if $P_L/P_{in} = 0.6$, then **60%** of the source power is delivered to the load—the other **40% is wasted** as heat in the regulator circuit.

For the **shunt regulator**, we find this ratio to be:

$$\frac{P_L}{P_{in}} = \frac{R_S}{V_S}\left(\frac{1}{V_S - V_{ZK}}\right)V_{ZK}I_L = \frac{V_{ZK}}{V_S}\left(\frac{R_S I_L}{V_S - V_{ZK}}\right)$$

Remember, there is a maximum I_L

Q: *Huh? According to this equation, if the load current is **really big**, then then 100%—or even more—of the source power is delivered the load!?*

$$\frac{P_L}{P_{in}} = \frac{V_{ZK}}{V_S}\left(\frac{R_S I_L}{V_S - V_{ZK}}\right)$$

A: But remember, the load current has a **maximum possible** value:

$$I_L < I_S = \frac{V_S - V_{ZK}}{R_S}$$

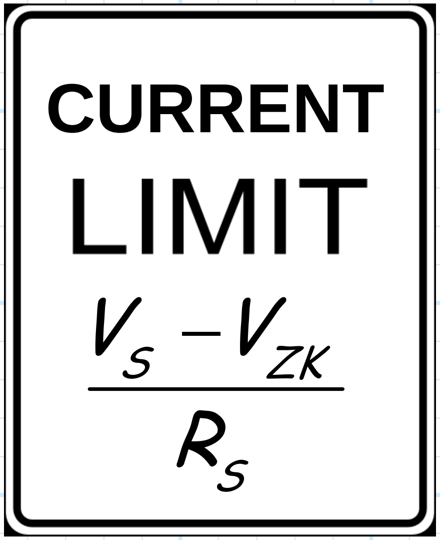
Thus, we can define a **maximum load current** for a shunt regulator—a **upper limit** on the **load current**:

$$I_L^{\max} = \frac{V_S - V_{ZK}}{R_S}$$

And thus likewise an **upper limit** on **load power**:

$$P_L^{\max} = V_{ZK} I_L^{\max}$$

And bad things happen when unregulated



$$\frac{V_S - V_{ZK}}{R_S}$$

Q: ***Why*** *is this a limit?*

Why ***can't*** *the* ***load*** *current exceed this values?*

A: Remember, **if** the load draws more current than this maximum value, the Zener diode will **leave** the breakdown region and instead will be **reverse biased**!

Q: *???*

A: As a result, the voltage $v_Z = V_L$ will be some value less than breakdown voltage V_{ZK}—the load voltage will be **completely unregulated**!

Definition: Regulator efficiency

The ratio of this **maximum load power** to the **source power** is a specific **numerical** value know as regulator efficiency η:

$$\eta = \frac{P_L^{max}}{P_{in}}$$

Obviously(?), regulator efficiency can theoretically be any value between **zero** (the worst) and **one** (the best):

$$0 \leq \eta \leq 1$$

Specifically for the **shunt** regulator, where:

$$I_L^{max} = \frac{V_S - V_{ZK}}{R_S}$$

we find that **regulator efficiency** is:

$$\begin{aligned}\eta &= \frac{P_L^{max}}{P_{in}} \\ &= \frac{V_{ZK}}{V_S}\left(\frac{R_S I_L^{max}}{V_S - V_{ZK}}\right) \\ &= \frac{V_{ZK}}{V_S}\left(\frac{R_S}{V_S - V_{ZK}}\right)\left(\frac{R_S}{V_S - V_{ZK}}\right)^{-1} \\ &= \frac{V_{ZK}}{V_S}\end{aligned}$$

Efficiency is a problem if V_S is way bigger than V_L

Recall that $V_S > V_{ZK} > 0$, so that as we would **expect** for efficiency:

$$0 \leq \frac{V_{ZK}}{V_S} \leq 1$$

Thus, is apparent that the **closer** the source voltage is to the load voltage ($V_L = V_{ZK}$), the **higher** the efficiency will be.

But be careful, this likewise will **reduce** the maximum load current:

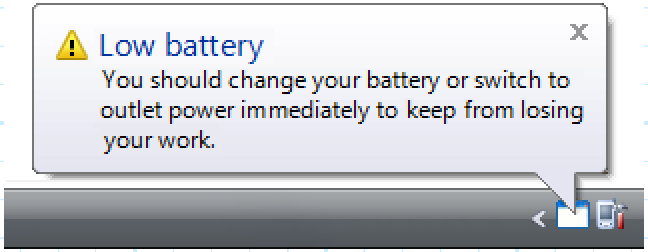
$$I_L^{max} = \frac{V_S - V_{ZK}}{R_S}$$

Regulators are either linear or switching

For **example**, say the source voltage is $V_S = 10V$, and the load voltage is $V_L = V_{ZK} = 6.0\ V$.

The efficiency of **this** shunt regulator is:

$$\eta = \frac{V_{ZK}}{V_S} = \frac{6.0}{10.0} = 0.6$$



⚠ Low battery

You should change your battery or switch to outlet power immediately to keep from losing your work.

This shunt regulator is **60% efficient**!

7.

@kanyewest

Kanye West

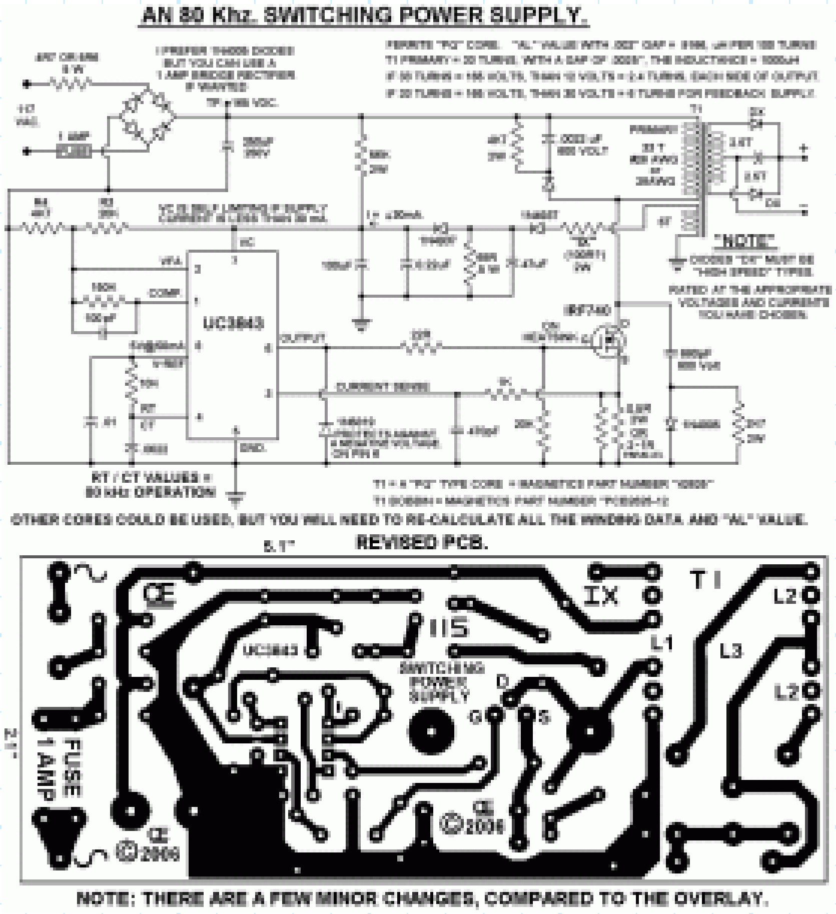
I hate when I'm on a flight and I wake up with a water bottle next to me like oh great now I gotta be responsible for this water bottle

Q: *Doh! That means **40%** of the source energy is **wasted;** isn't there some way to do **better** than that—I might miss an important **tweet**!*

A: Voltage regulators essentially come in **two** types—the **linear** regulator and the **switching** regulator.

→ The **shunt** regulator is an example of a **linear regulator**.

Switching regulators: complex but efficient



http://electronic-circuit.net/acdc-switching-power-supply/

Both the linear and switching regulator exhibit excellent line **and** load regulation.

But, the **linear** regulator is typically much **less efficient** than the **switching** regulator.

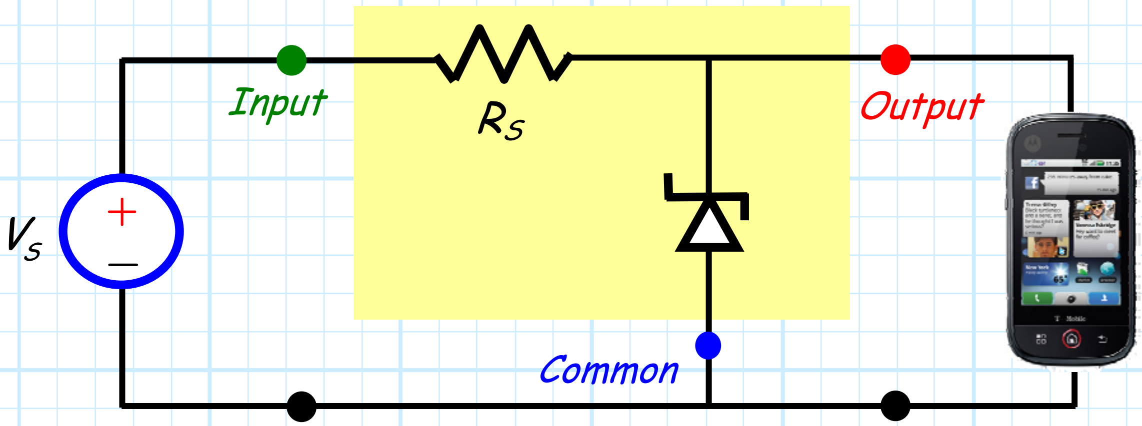
Q: *So why don't we just **always** use the **switching** regulator?*

A: Switching regulators are typically more **complex and costly** than linear regulators, and they likewise generate **Electromagnetic Interference (EMI).**

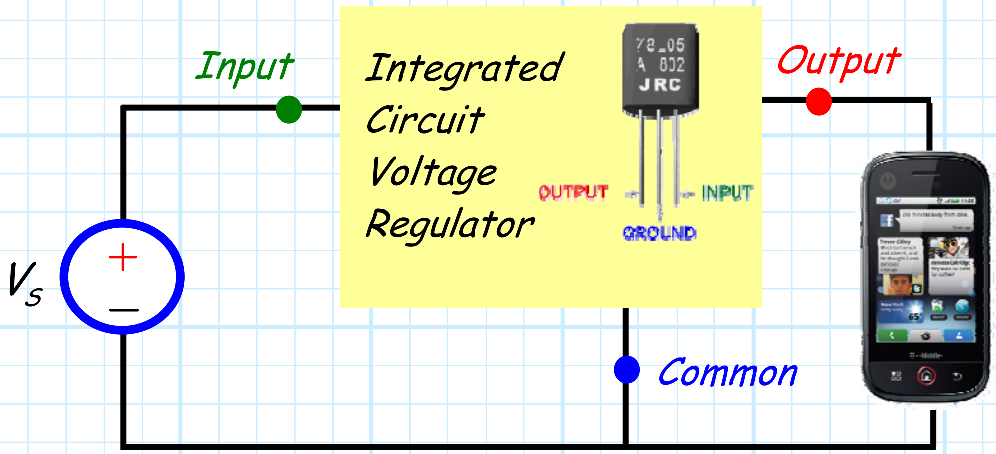
Linear regulators are typically used **if** an engineer can stand the relative inefficiency—but **often** the engineer **cannot**!

Linear Voltage Regulators

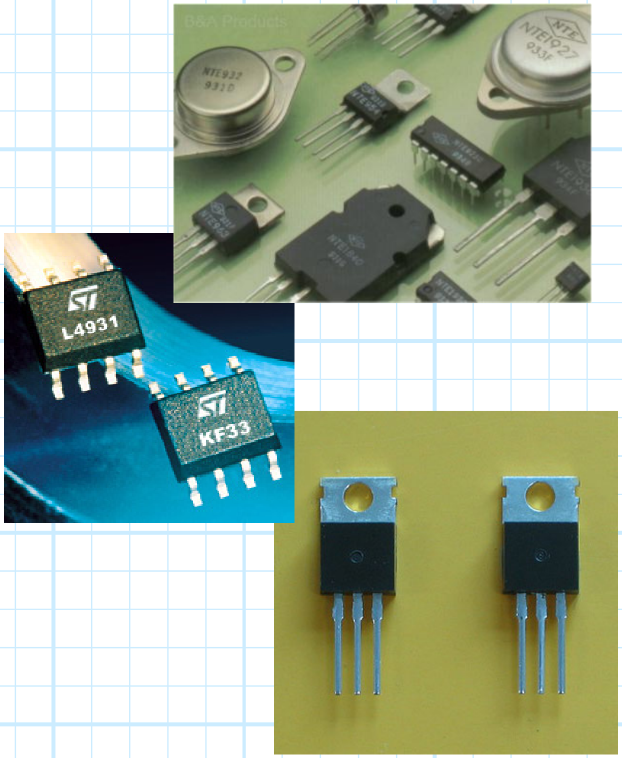
Note that we can view a shunt regulator as a **three-terminal** device, inserted **between** a voltage **source** and a **load**:



Integrated circuit technology has resulted in the creation of **other** three terminal linear voltage regulator **designs**:



Sometimes you're just unlucky



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

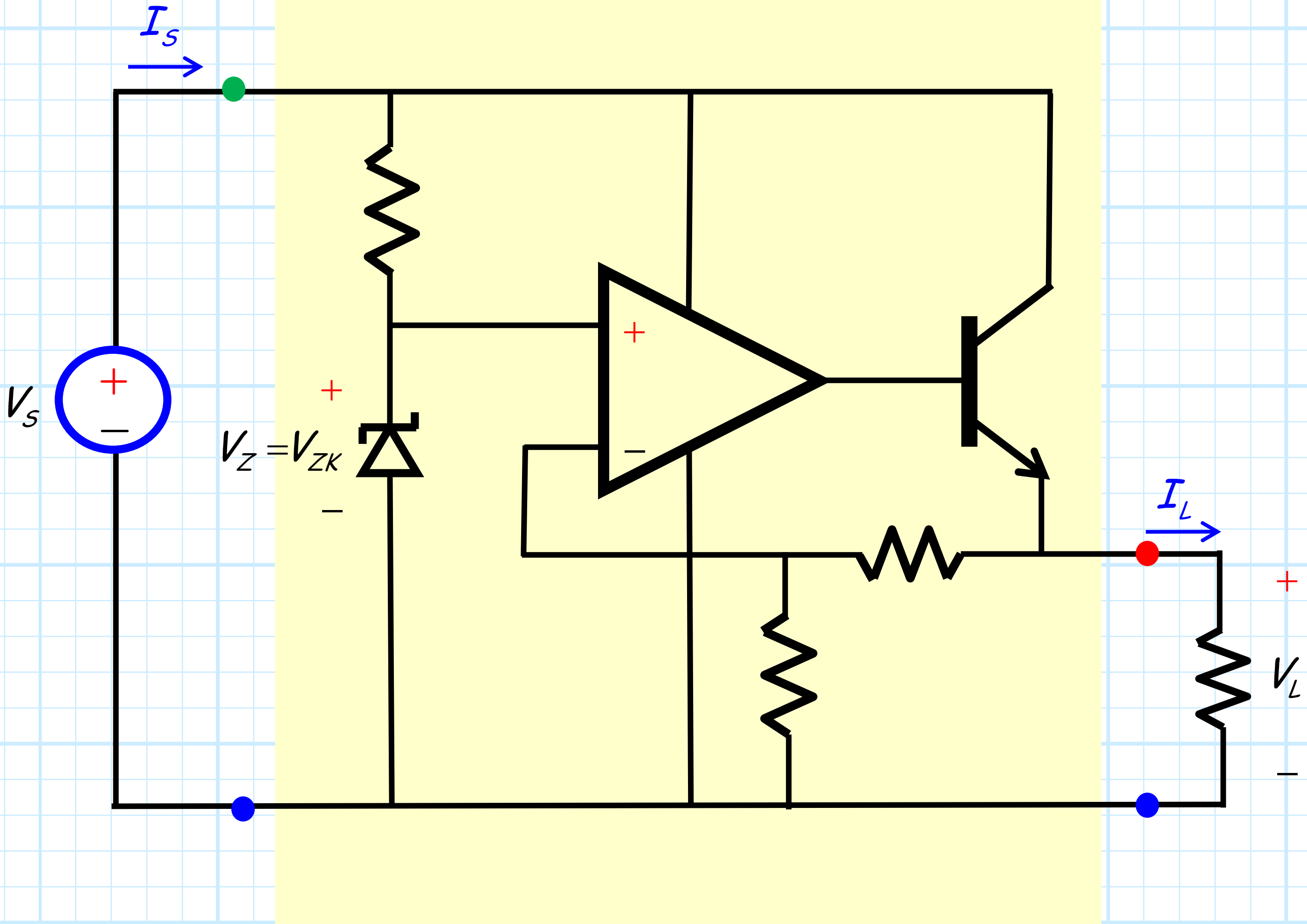
In addition, these IC regulators typically have **better** load regulation, line regulation, and/or efficiency than the zener diode **shunt** regulator!

Q: *Wow! The **designers** of these IC regulators obviously had a **much** better electronics professor than the **dope** we got stuck with!*

A: Undoubtedly so!

An improved voltage regulator

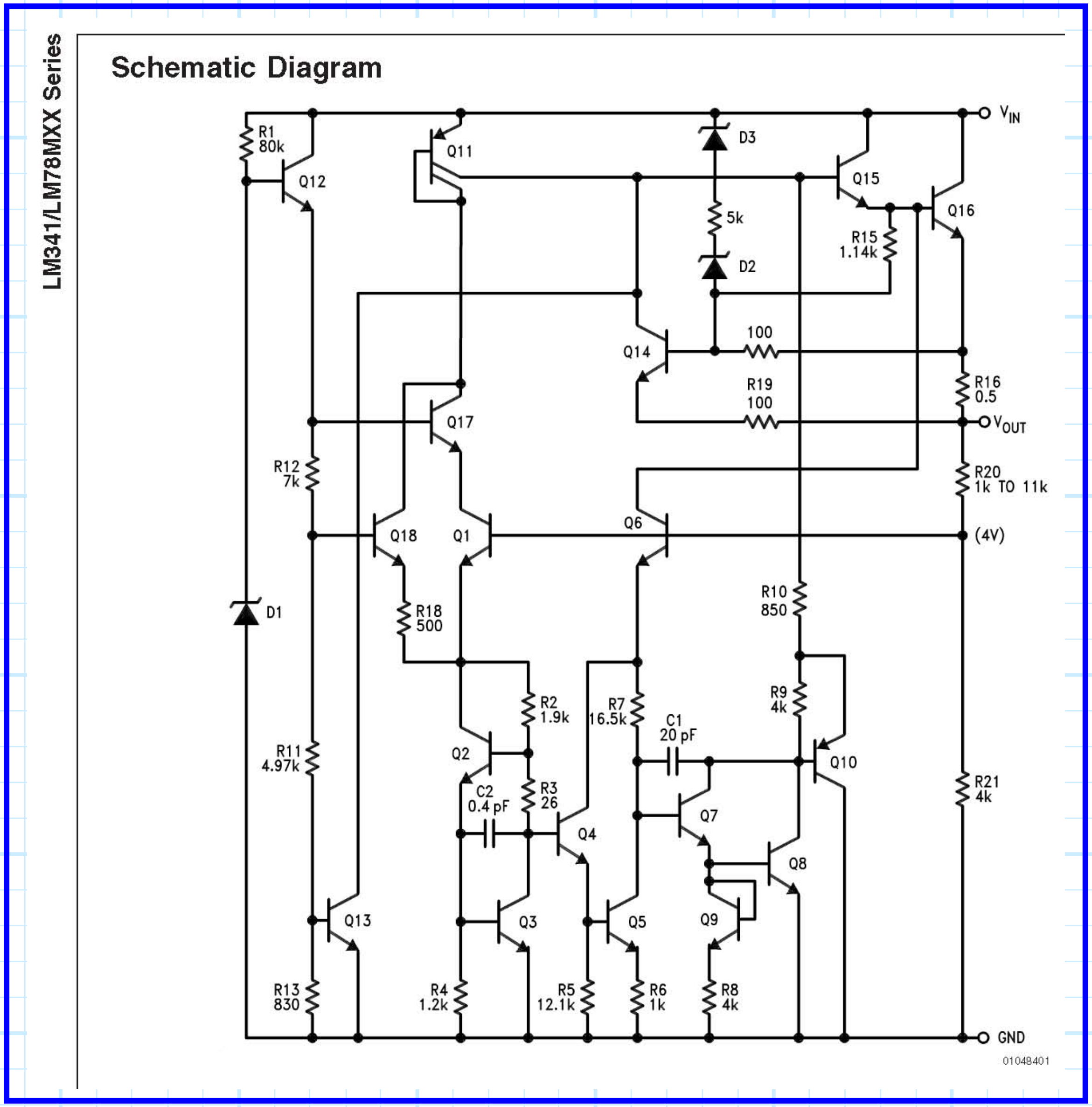
However, these integrated circuit design engineers did **not** simply create a **better shunt regulator**.



Instead, they **replaced** the entire shunt regulator design with a **complex circuit** requiring many **transistor** components.

That op-amp requires many transistors

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



The LM341 **linear voltage regulator** schematic.