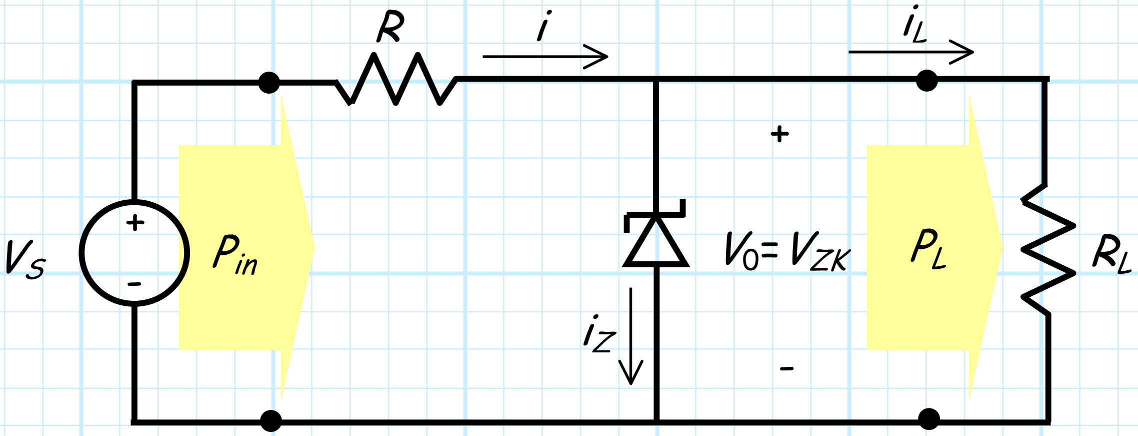
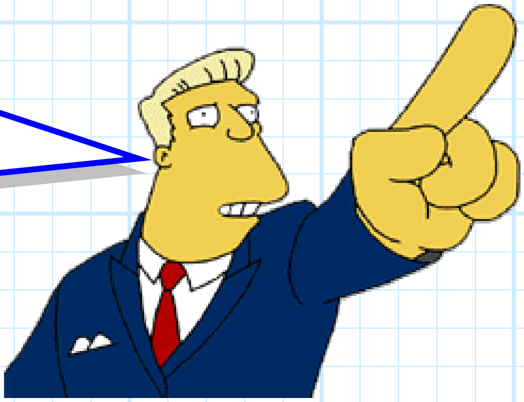
Regulator Power and Efficiency

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:

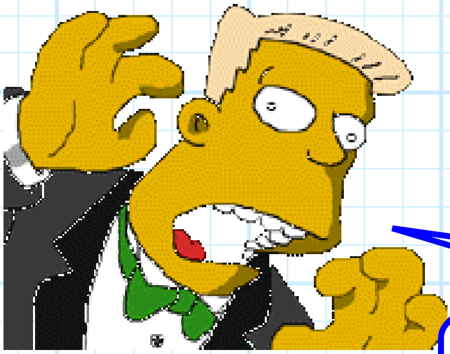
$$0 \leq P_L \leq P_L^{max}$$

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}:



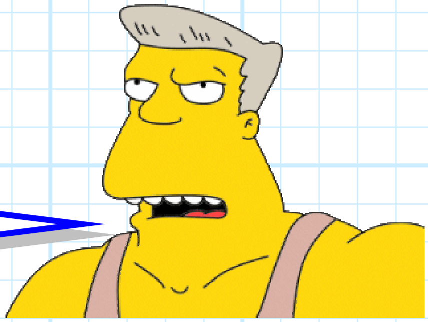
$$P_{in} = V_s \frac{(V_s - V_{ZK})}{R}$$

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.

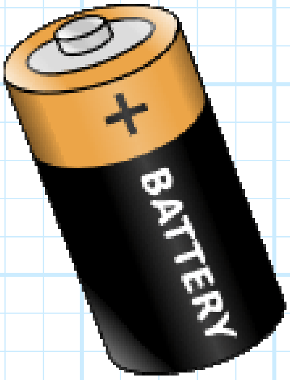
Q: *But* ***where*** *does this input power go, if* ***not*** *delivered to the load?*



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:

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

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

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

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

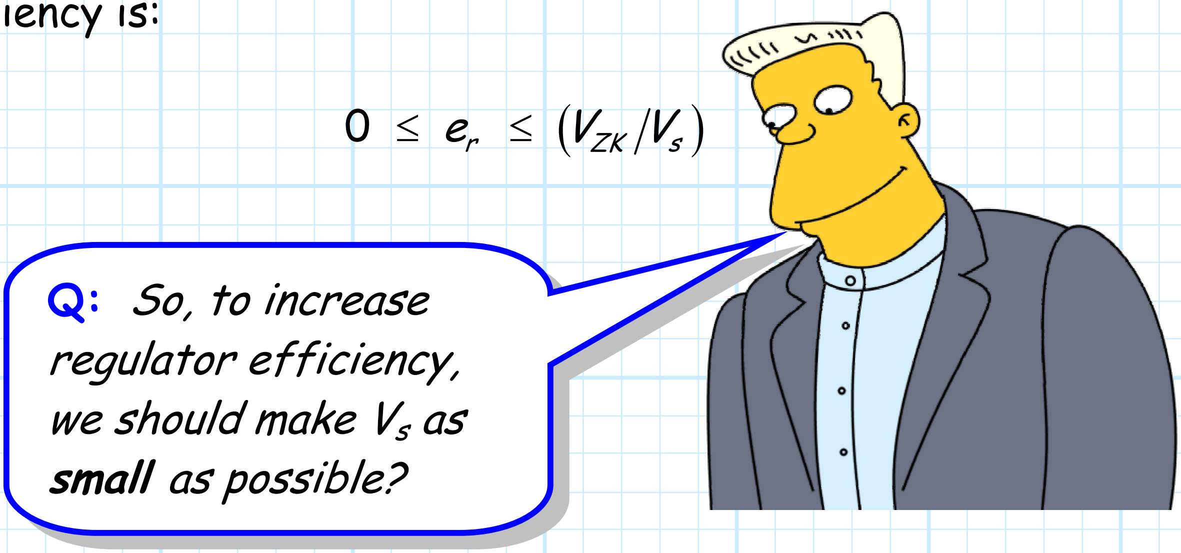
Note that this efficiency **depends on the load** value R_L. As R_L increased toward infinity, the efficiency of the shunt regulator will plummet toward e_r=0 (this is bad!).

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:

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



Q: *So, to increase regulator efficiency, we should make V_s as* ***small*** *as possible?*

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