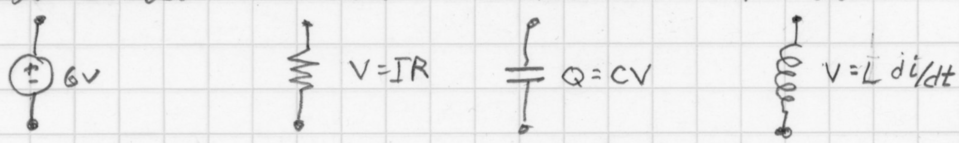
EE 251 Electronics I Introduction, Diodes

So, what's the difference between "electric" and "electronic"?

In "electric" circuits we have our usual well known components:

Voltage Sources   Resistors   Capacitors   Inductors



And many others: Motors, Transformers, Current Sources .....

These components are connected to nodes with wiring to build a circuit which performs some function, such as propelling a vehicle, lighting a room of house, etc.

These circuits are governed by fundamentals from Physics – Kirchoff's Current law, Kirchoff's Voltage law, Thevenin & Norton's Theorems, many others.

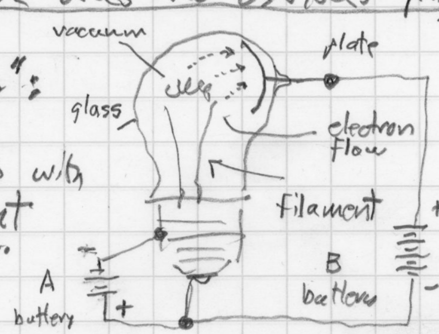
(Usually, or at least often, we have "linear" circuits in which the principle of Superposition holds and we can "solve" circuits with Linear System Theory.)

An "electronic" circuit, originally defined, was an electric circuit that had, in addition to the usual electric components, also "electronic" components.

So, what is an "electronic" component, and what's different?

Original electronic components had current flowing entirely by the movement of electrons in gas/vacuum – where there was no obvious physical connection

The original "diode": light bulb with extra element "plate"

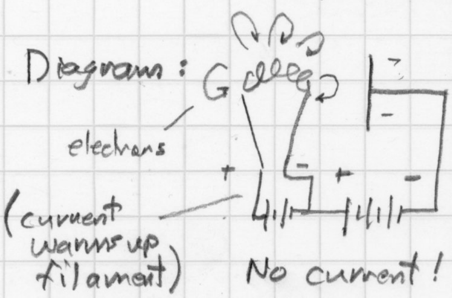


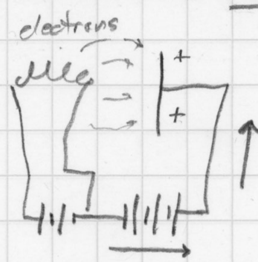
Notice: These are "free electrons" not bound to atoms. The world changed!

Observation: If the "B Battery" is positive toward the plate, and negative toward the filament, current flows! If the "B Battery is negative toward the plate and positive toward the filament – no current!

That's because: Hot filament throws off electrons, but the plate only attracts them if it is more positive than the filament.
So, electrons must be <u>negative charge carriers</u>!

Diagram:





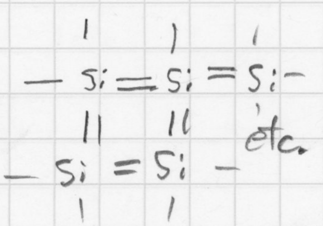
"current" as defined flows in the <u>opposite</u> direction from the electron flow.

The electron device is called a "diode". It conducts electricity in only one direction.

In <u>todays</u> world, diodes are built from semiconductors.

Silicon (and Germanium, various others) form bonds with adjacent atoms in a crystiline structure. For Si, Ge, <u>4</u> bonds (Both are in column <u>4</u> / IV of periodic table)

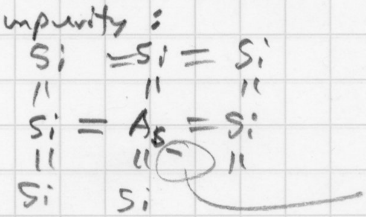
Silicon:



It's possible for electrons to get knocked loose, but not easy, <u>unless</u> there are impurities – say Al (III) or As (V)

Silicon with Arsenic impurity:

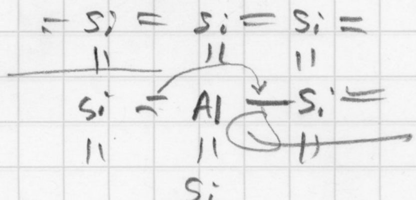
"N doped Si"



With a lone As in the Si matrix, there's a loose electron that's not tightly bound. In an electric field, it will move – <u>conduct</u>

Silicon with Al:

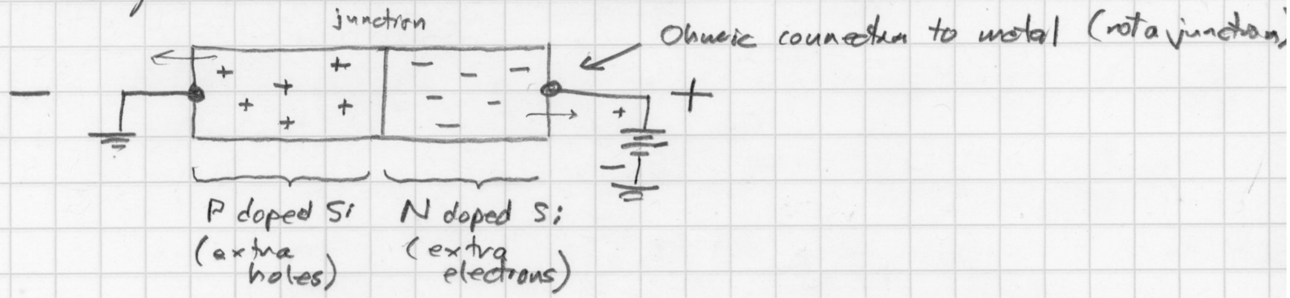
electrons can move to fill holes.



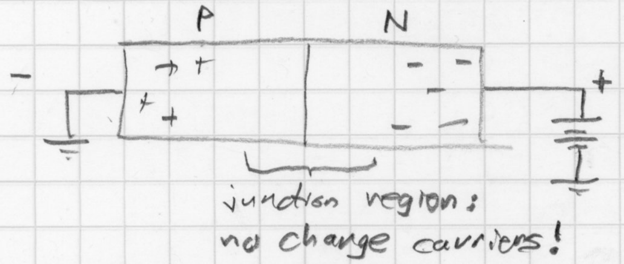
"P doped Si"

With Al in Si matrix, there is a "hole" in the matrix that wants to be filled. In an electric field, the hole <u>moves</u> – conducts.

With two pieces of "doped" silicon brought together at a "junction" we get a semiconductor diode :

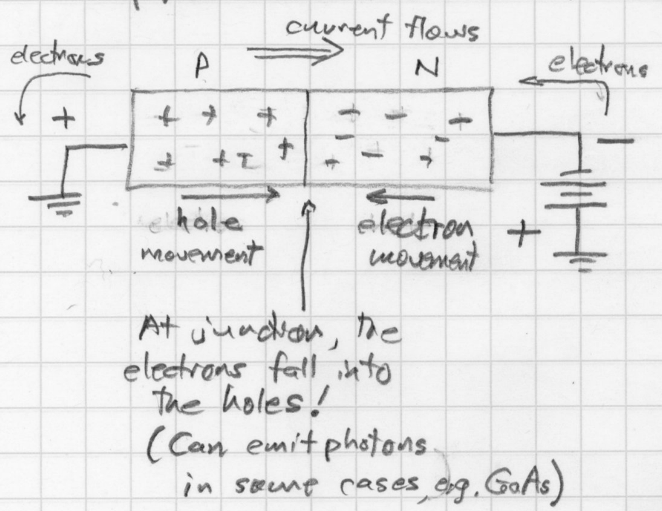


If we put a positive field from P to N − No current flows!
the holes head away from junction, and electrons too



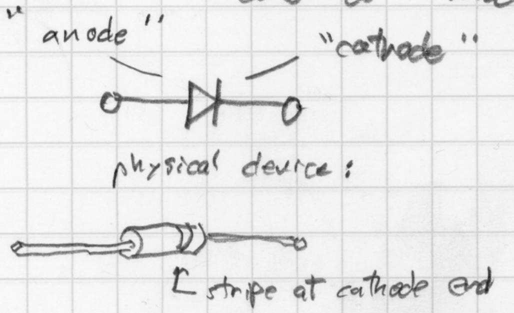
With no charge carriers in the junction region, current can't flow!
(Bulk material away from junction has to be electrically neutral, so still some there.)

(Note: Looks like small capacitor)

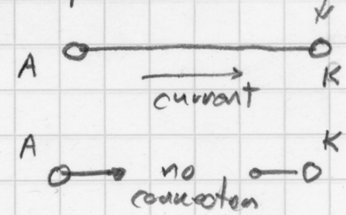


As holes + electrons mutually annihilate each other at the junction, additional electrons get injected into the N material and pulled out of the P materials to continually keep charge carriers moving. Current flows!

We abstract all this into a symbol for the part and a "model" for its behavior :



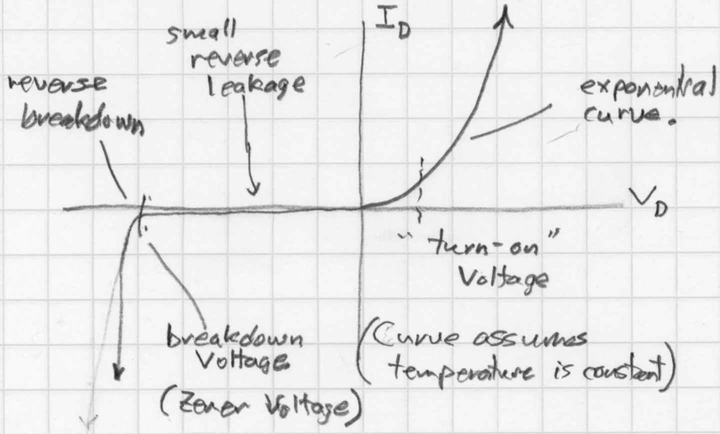
Simplest model : (symbol "K" often used for cathode)



"ON" if current flows from anode to cathode

"OFF" if $V_K > V_A$
no current
"open"

Actual diode devices behavior can be graphed with an I vs V curve:



Real semiconductor diodes have approximately exponential forward behavior — Current increases very rapidly beyond some nominal "turn on" Voltage.

At some reverse Voltage the diode "breaks down" and starts conducting in the reverse direction

In most circuits, reverse breakdown is undesirable. It will usually cause high dissipation which the diode is not designed to handle.

Because Electrical Engineering is an analytic discipline, we need mathematical models to represent diodes in circuits, so that we can use circuit principles to solve for circuit behavior, or to put into circuit simulations.

"Diode equation" (book Eq 1.18 p28.)

$$i_D = I_S \left[e^{\frac{v_D}{nV_T}} - 1 \right]$$

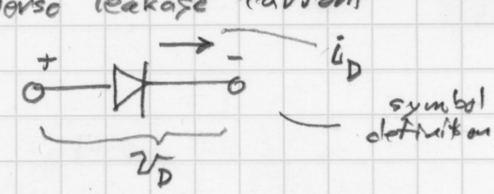
v_D ← variable (the other parameters are constants)

i_D ← Variable

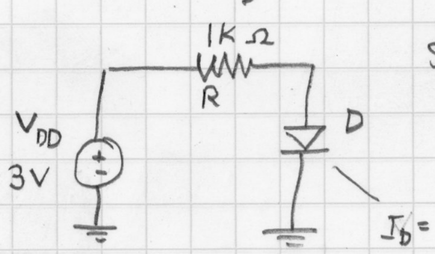
At negative v_D approaches 0
At zero v_D = 1
At positive v_D gets big exponentially

I_S ← Reverse leakage current

Note: Does NOT model the reverse breakdown behavior, but IS good for both positive and negative values of v_D.



Note also: v_D — lower case, upper case represents instantaneous to total Voltage (AC+DC)



Simple diode circuit (strictly a DC circuit)

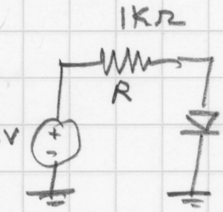
We plug this model into circuit equations to solve:

$$V_{DD} = V_R + V_D \Rightarrow 3V = 1k\Omega \cdot i_D + nV_T \cdot \ln\left(\frac{i_D}{I_S} + 1\right)$$ ← (can you solve this?)

loop equation

one equation, solve for i_D

Using the diode equation to solve a circuit:



$I_S = 10^{-14}A$
$n = 1$
$V_T = .026V$
(Si)
(small signal diode)

$3V = 1K\Omega \cdot i_D + n \cdot V_T \cdot \ln\left(\frac{i_D}{I_S} + 1\right)$ How?!?

I'm going to use "successive approximation"

Step

1. I'll assume that, since Si, $v_D = .7V$, solve for i_D:

   $3V = 1K\Omega \cdot i_D + .7V \Rightarrow$ $\boxed{i_D = 2.3mA}$ ← equal?

2. Now calculate v_D for $i_D = 2.3mA$: $i_D = 10^{-14}A \cdot e^{.7V/.026V} - 1 =$ $\boxed{1.8mA}$

   pretty close, but actual v_D must be larger.

3. I'll assume actual v_D is higher by .01V: .71V rather than .7V

   $3V = 1K\Omega \cdot i_D + .71V \Rightarrow i_D =$ $\boxed{2.29mA}$ ← equal?

4. Now calculate v_D for $i_D = 2.29mA$: $i_D = 10^{-14}A \cdot e^{.71V/.026V} - 1 =$ $\boxed{2.66mA}$

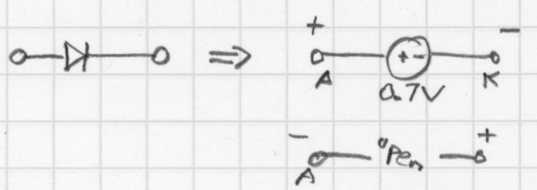
   closer, but went too far. That

   .01V change caused a +.86mA change in i_D! (only needed +.5mA)

5. I'll take just $(.5/.86) \times .01V$ so now assume $v_D = .706V$:

   $i_D = 10^{-14}A \cdot e^{.706V/.026V} - 1 = 2.28mA$ <u>close enough</u>!

In fact, our original guess of .7V for v_D wasn't bad at all! So, this suggests a simpler model for this diode:



Whenever $v_A \geq v_K + .7V$ "ON" condition

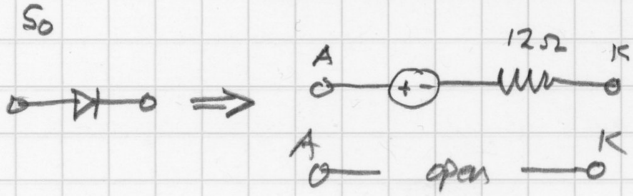
Whenever $v_A < v_K + .7V$ "OFF" condition

This will be pretty close as long as i_D is in the range of about 1mA up to several mA.

A refinement of that model would represent the <u>AC resistance</u> of the diode – how much is $\Delta v_D / \Delta i_D$

From calculations above, $.01V / .86mA = 11.6\Omega$

So



$v_A \geq v_K + .7V$

$v_A < v_K + .7V$

So, now that we have diode devices, what can we do with them?

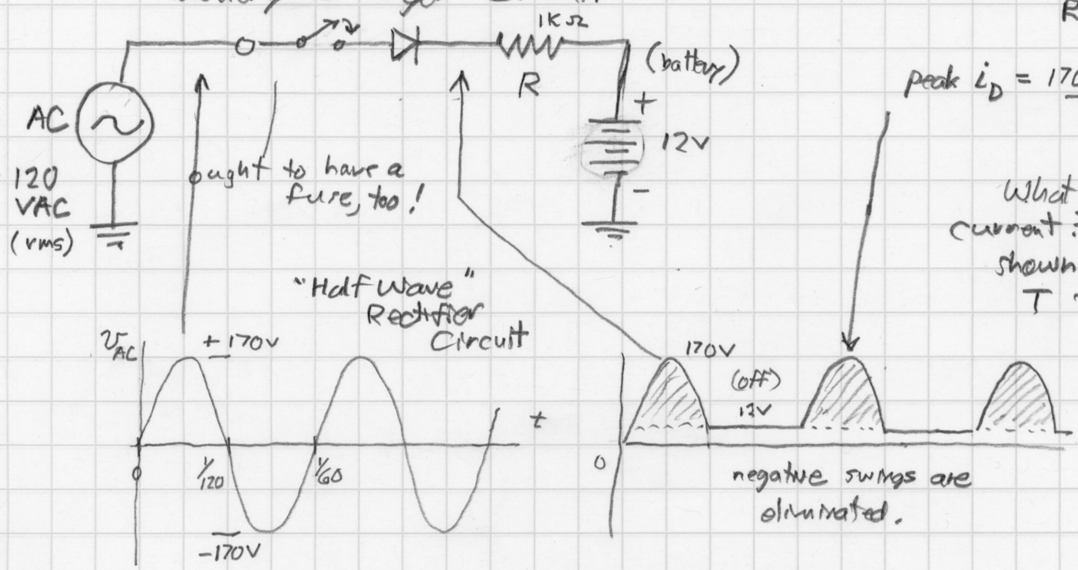
#1 <u>Power</u> application – Change AC to DC to charge batteries:

(AC is used by modern electric utilities so that they can use <u>Transformers</u> to allow high Voltages for transmission, thus reducing conductor sizes needed, for greater efficiency. That's fine for incandescent light bulbs, but need DC for battery charging or to run DC motors, DC for electronics!)

Battery Charger Circuit:

Assume $V_{D_{on}} = .7V$ (silicon)
$R = 1K\Omega$

peak $i_D = \frac{170V - .7V - 12V}{1K\Omega} = 157.3\,mA$

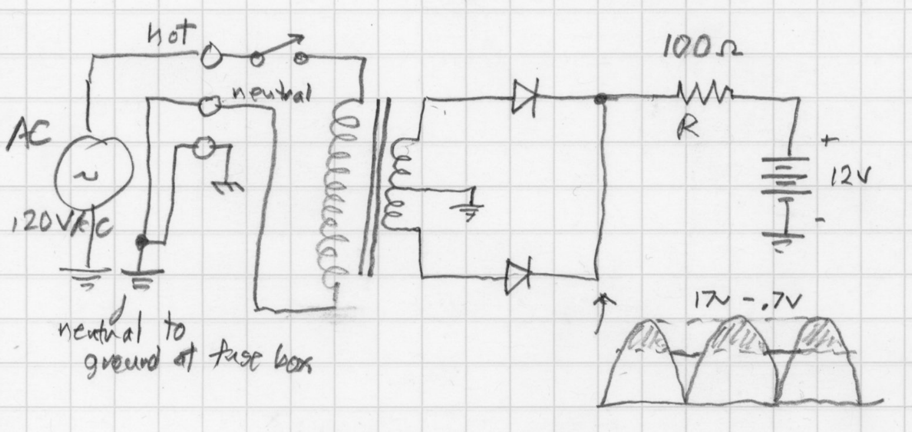


What is average charging current? Integrate areas shown and divide by T to find it.

(Approx. $\frac{157.3\,mA}{2\sqrt{2}} \approx 55\,mA$)

This is called a "Rectifier" circuit
(Diodes designed for this are called "Rectifier Diodes" or just "Rectifiers")

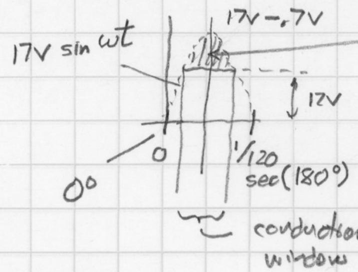
A <u>Better</u> circuit (more efficient) uses a transformer (to reduce lost power in the resistor, and to allow <u>full wave</u> rectifier



The transformer converts the negative swing to positive with lower half of secondary – <u>doubles</u> the current to the "load"

(Trickier to integrate now)

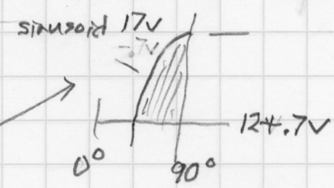
Full wave rectifier battery charger – We'd like to find average current



voltage across R x time

What is θ turn-on?

(representative x 4 per AC cycle.)



$\sin\theta = 12.7V / 17V = .747$

$\theta = 48.3°$

$$\overline{V}_R = \int_{48°}^{90°} (\underbrace{\sin\theta \cdot 17V - 12.7V}_{\text{always }+})\, d\theta \times 1/90°$$

$$= \frac{-\cos\theta \cdot 17V \Big|_{48°}^{90°}}{90°} - \frac{12.7V\,\theta \Big|_{48°}^{90°}}{90°}$$

$\times \frac{360°}{2\pi}$

$$= \frac{0 + .669 \cdot 17V}{90°} - 12.7V\left(\frac{42°}{90°}\right)$$

$$= \left(\frac{38.3°}{90°}\right) \cdot 17V -$$

$(.426)(17V) - 5.927V$
$= 7.24$

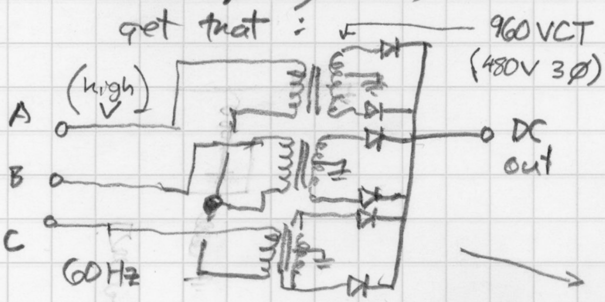
$= 1.315V$ average across 100Ω:

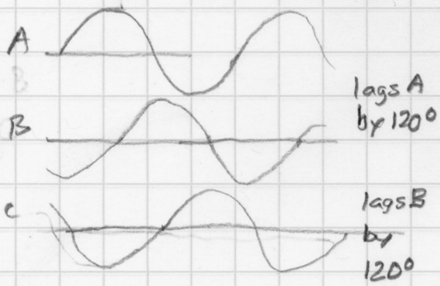
so $I_{AVERAGE} = 1.315V / 100\Omega = \boxed{13.15mA}$

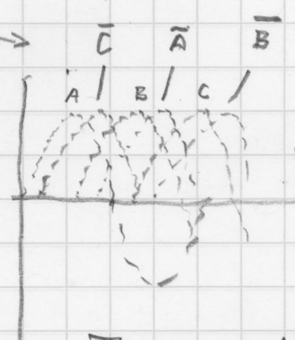
Batteries really don't care about variations in current – it's the total charge accumulated that matters. (Mostly – don't go to extremes though.)

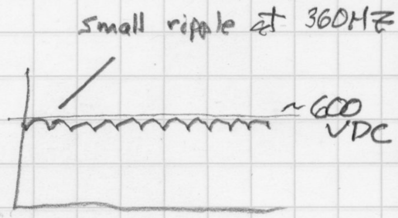
BUT We'd like, for many applications, to have smoother DC

With 3Ø systems, we can get that:



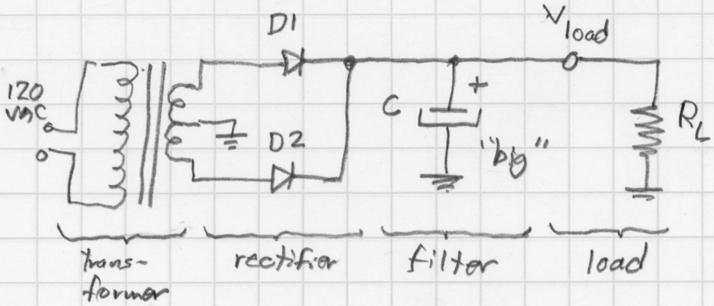






This is what is needed to run an electric trolley car. You also see this in other power applications where variable speed drive is wanted.

Getting smooth DC from a Rectifier Circuit — Capacitor Filter!

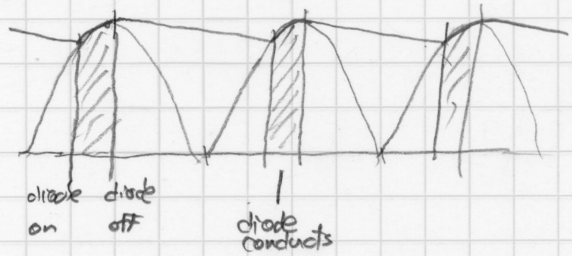


Assuming: 1) Lossless transformer (real ones have resistance)

2) $V_{D on} = .7V$

3) C is "big" (shorts out AC to ground)

Then $V_{Load} = V_{peak}(\text{transf} \times \tfrac{1}{2}) - .7V$



When diode is **on**, it supplies current to the load **AND** recharges the capacitor to its maximum Voltage

When diode is **off**, the capacitor supplies all of the current to the load. (Sort of like a battery)

[Theoretically, a battery could do this job, but batteries wear out from cycling up and down. This circuit cycles at 120Hz! Batteries aren't going to like that!]

So, with 120VAC, Transformer is 24VCT (center tapped) so each side gives 12VAC (17Vpeak). After the diode, that is reduced to 16.3V peak (Assuming $V_{D on} = .7V$)

Suppose $R_L = 1000\Omega$, $C = 1000\mu F$. How much "ripple" do we get?

Let's make this easy. C values are typically only accurate to +/- 20%. So, we will assume the C discharge time goes the full 1/120 sec between charging spikes, and the output Voltage is 16VDC (we know it can't be more than 16.3V)

$$I_C = I_L = 16V/1000\Omega = 16mA \qquad Q = CV \text{ so } I = \frac{dQ}{dt} = C\frac{dV}{dt}$$

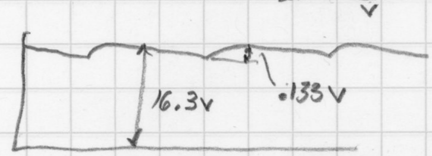
(A) (V/sec)

Because ΔT is short compared to exponential time constant RC = 1 second,

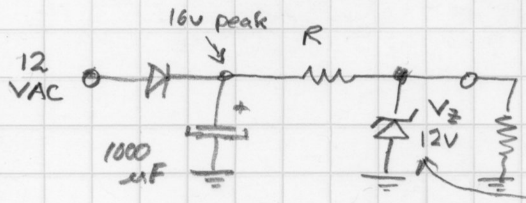
$$I = C\,\Delta V/\Delta T \quad \text{where } \Delta T = 1/120 \text{ sec}$$

$$\Delta V = 1/120 \text{ sec}\ \frac{16mA}{1000\mu F \leftarrow \frac{A\cdot s}{V}} = \boxed{.133V}$$

So Voltage will "droop" about .13V between peaks. Pretty good (about 1%)



Sometimes we want very precisely controlled DC Voltages — achieved with a "Regulator" circuit. There are 2 basic kinds — "Series" regulators and "Shunt" regulators:



Basic Shunt Regulator

(We won't cover series regulators because they need transistors. Series regulators typically require a shunt regulator internally.)

notice the modified symbol

This circuit uses the "breakdown" region of a diode.

A "Zener diode" is a diode designed to work in this manner, and is sold to operate and give a fairly precise Voltage, typically about 5V or higher, and also large enough to handle the good bit of heat from the power dissipated

V_Z is the reverse breakdown "Zener" voltage of the diode
So, match the diode to the desired output Voltage.

Choose the regulator resistance R so that at the <u>minimum</u> Voltage from the filter, you get enough current to supply the maximum load (minimum R_L).

We'll assume minimum $R_L = 500\Omega$, so at 12V, 24mA
with 24mA, that 16V peak will droop to about 15.8V

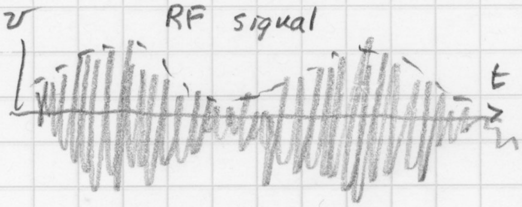
So $(15.8V - 12V)/24mA = 158\Omega$ (we'll use 150Ω)
(How much power does it have to handle? 100 mW or so.)

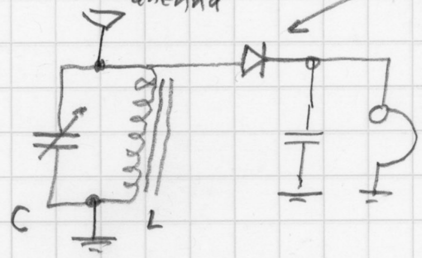
The rectifier will deliver about 25 mA to the regulator. Any of that which doesn't go to the (variable) load gets dumped into the Zener diode — as much as
$12V \cdot 25mA = 300\,mW$. (Most Zeners are good for $\approx \frac{1}{2}W$)
(If load is open, that's <u>all</u> of the power supplied.)

(A better model for a zener includes a small bit of resistance, too.)

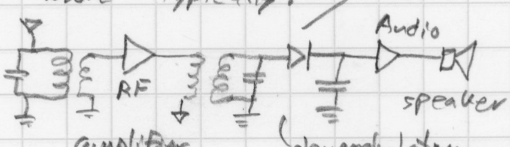
Other diode applications:

AM Radio demodulator:

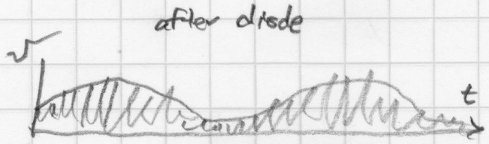




"Crystal Radio"
(no power supply!)

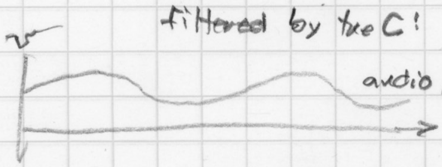


after diode

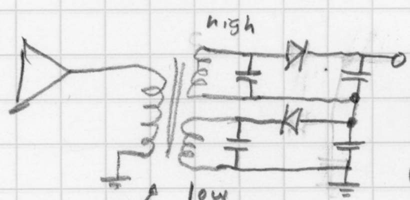


(only + side)

filtered by the C!

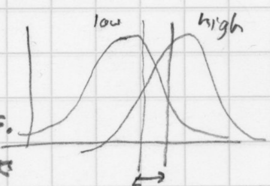


For FM

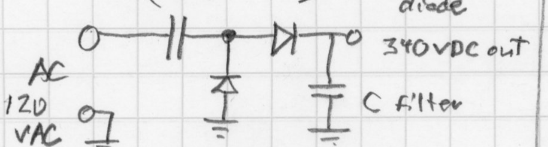


greatly (simplified)

Two AM detectors but resonant at different frequencies. Take the difference in amplitude as the audio signal out.

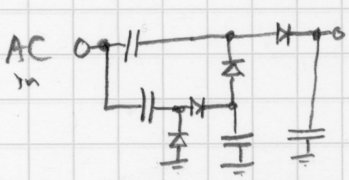


Voltage Doubla Rectifier:



clamp diode — shifts mean voltage up ≈ 170V

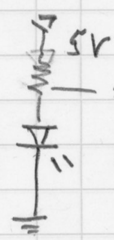
(This was used in 1960's TV sets)



quadrupler (and so forth, as many stages as you can manage)

better use good capacitors!

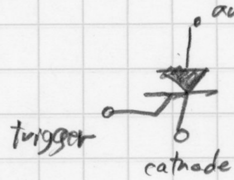
Led's:

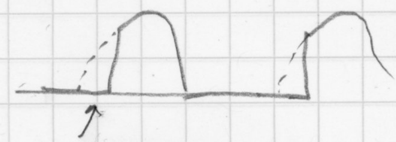


— series R to limit current

LED (~1.6V for red ~1.2V for IR ~2.2V for blue

Silicon Controlled Rectifiers:





delayed turn-on as triggered to give desired output

Opto isolators: