EECS 245 ELECTRONICS

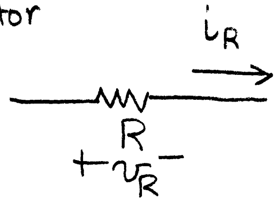
Textbook Electronics, 2/e
Prentice-Hall

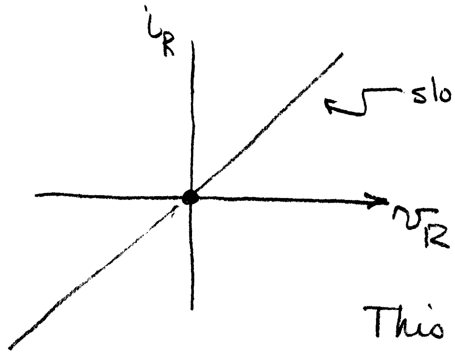
diode two terminal device

i-v characteristic curve

for electronic devices we can plot current versus voltage to characterize the device:

Resistor



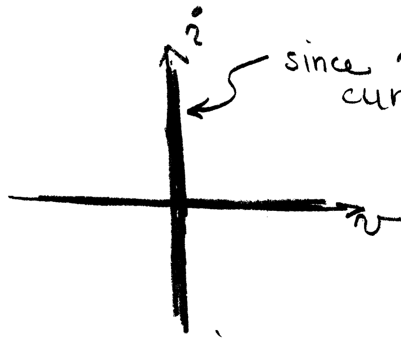


$$\text{slope} = \frac{i_R - 0}{v_R - 0} = \frac{i_R}{v_R} = \frac{1}{R}$$

This is a linear device.

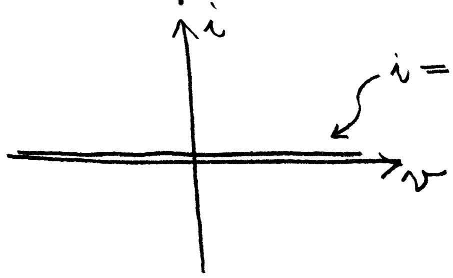
what does a wire look like?

a short



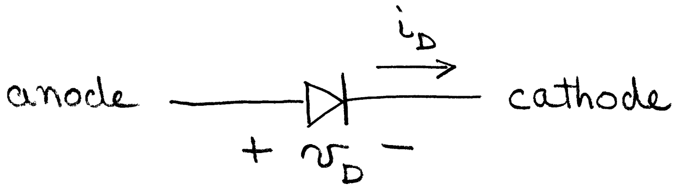
since $v=0$ for a short characteristic curve is a vertical line

an open

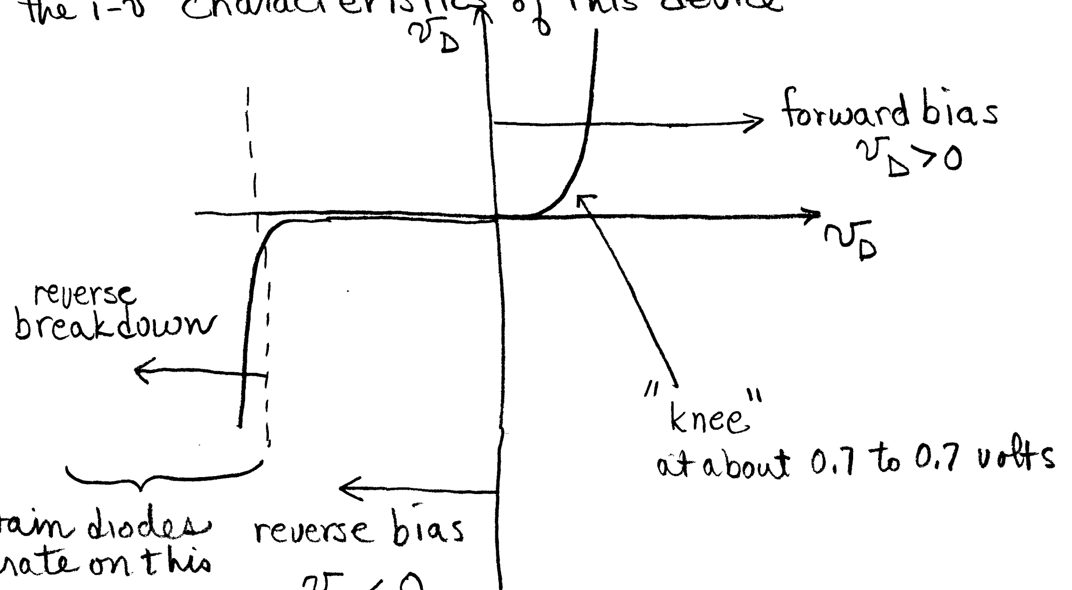


$i=0$ for all values of v

basic diode characteristics



If we hook up a variable power supply we can measure the i-v characteristics of this device



A diode is a non-linear device.

Certain diodes operate on this line in the reverse breakdown region. They are called "zener" diodes.

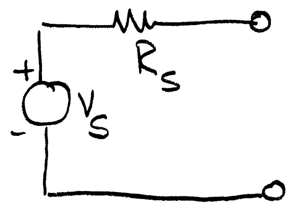
.available as diodes with specified breakdown voltages.

Examples of diodes we will use in lab:

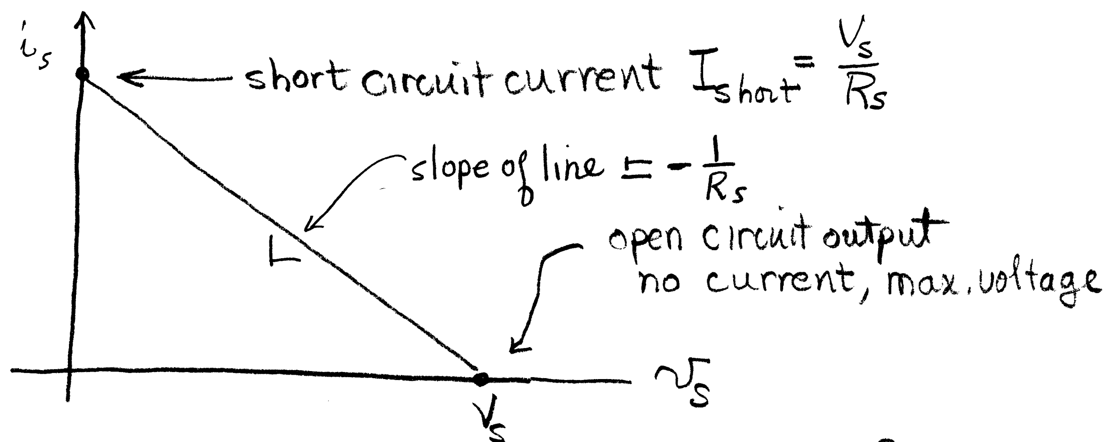
- IN914, IN4148 } low power switching
- IN400x] modest power

What is a load line? Essentially a power source. It can be a power supply, amplifier, transistor output, etc.

How do we model a power source? It looks like a Thevenin Equivalent Circuit

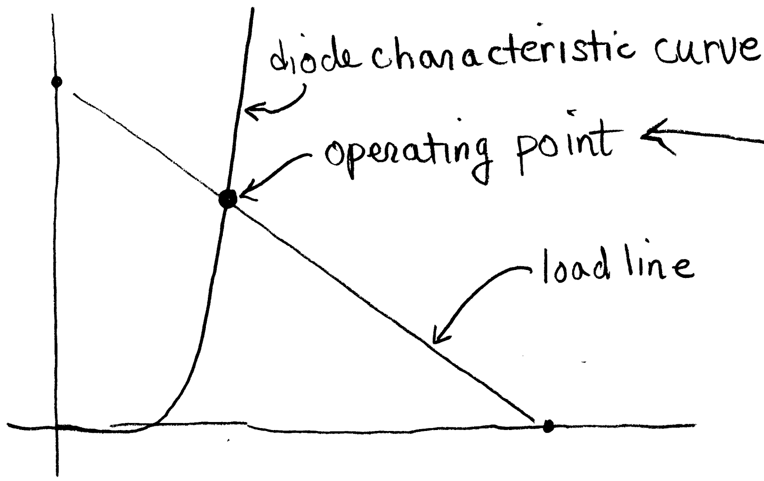


What is its i-v characteristic? a load line

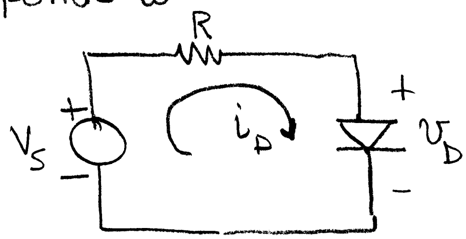


Basically a load line is a equation of the possible outputs for a source. The i-v characteristic is a plot of the possible operating points for a device.

Suppose we want to drive a non-linear device like a diode by a source. We can find the operating point by plotting the device's I-v characteristics on the same graph as the source's load line.



this corresponds to



what is i_D?

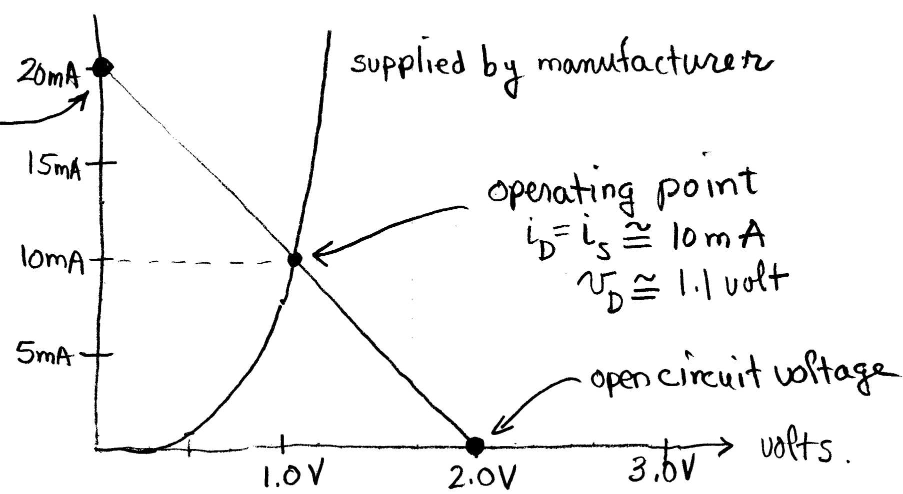
Since $i_D = i_D$ read from graph

Example: real diode (provided by manufacturer)

power source $V_{SS} = 2V$ $R = 100\,\Omega$

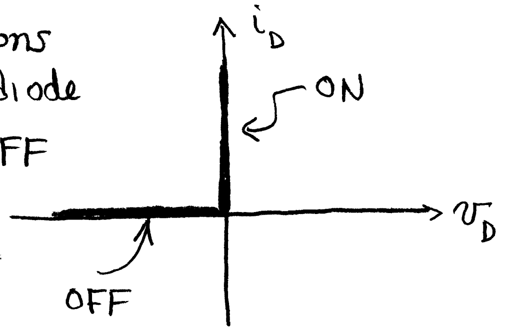
$i_{short} = \frac{\mathcal{E}}{R} = \frac{2V}{100}$

$= 20mA$



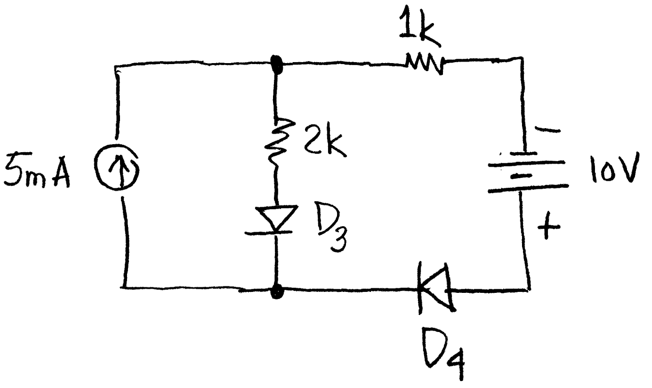
3.3 Ideal diode

for many applications we can simplify diode model to ON/OFF

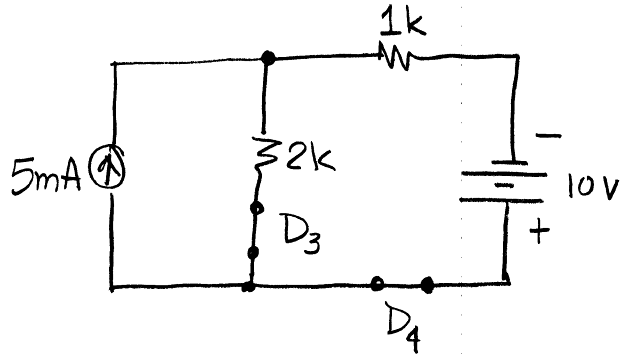


We can use this model in many circuits problems.

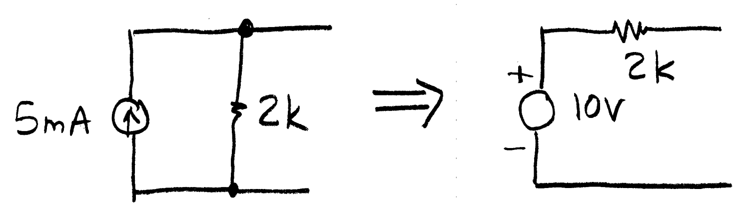
How about a multi-diode circuit like this? Which diodes are ON? which are off?



Assume both are ON. Circuit looks like

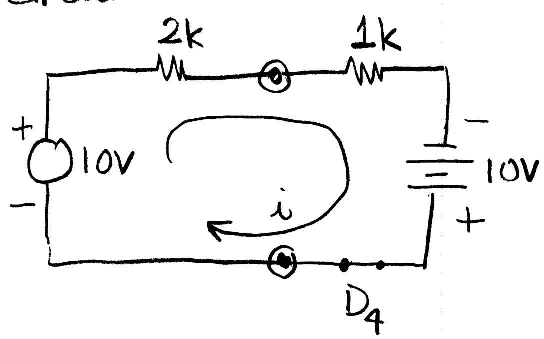


How would you solve this circuit?
I would use source transformation or superposition



$V = IR = (5mA)(2k) = 10V.$

Let's look at circuit



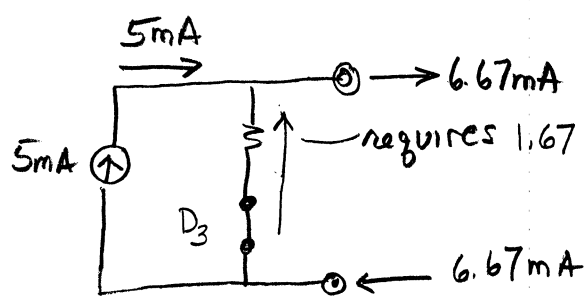
this gives a current

$$i = \frac{10+10}{2k+1k} = \frac{20}{3} mA$$

$= 6.67 mA$

∴ D_4 is ON. so this is OK.

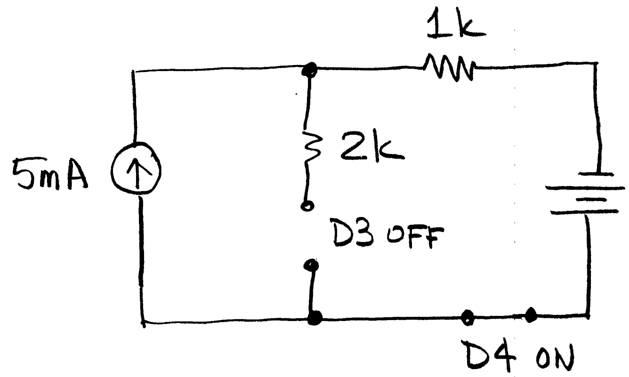
How about



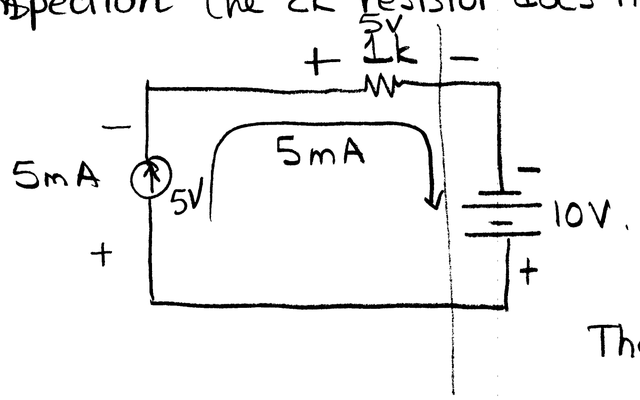
requires 1.67 in up direction

This is in violation of assumption. Current indicates reversed diode. Assume D_4 ON and D_3 off and try again.

If D3 OFF, D4 ON circuit looks like this:



by simple inspection the 2k resistor does not contribute anything



Does this circuit work ok?
Let's see.
5mA current thru everything

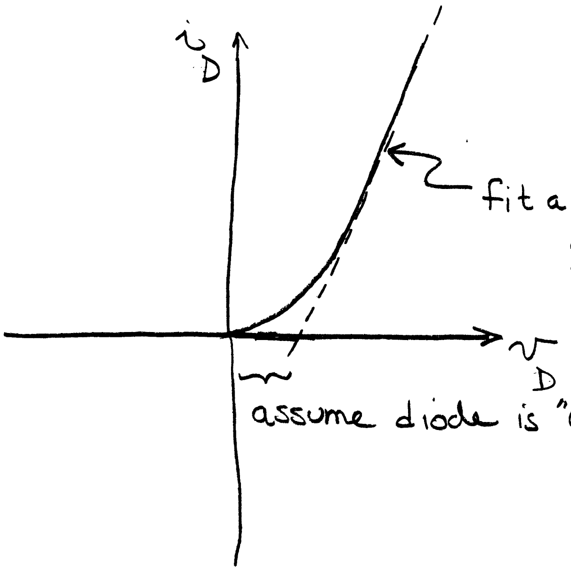
That puts 5V across 1k resistor.

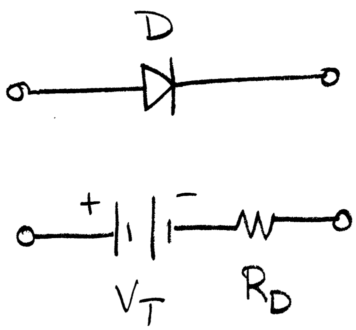
The resistor's voltage is as shown.

This puts 5V across current source as shown which is ok.

so that $\sum_{loop} v = 0$.

Better diode model:



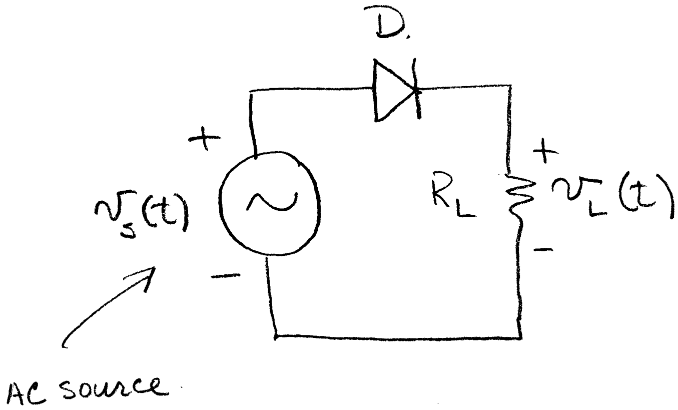


The maximum voltage a diode will withstand is called the

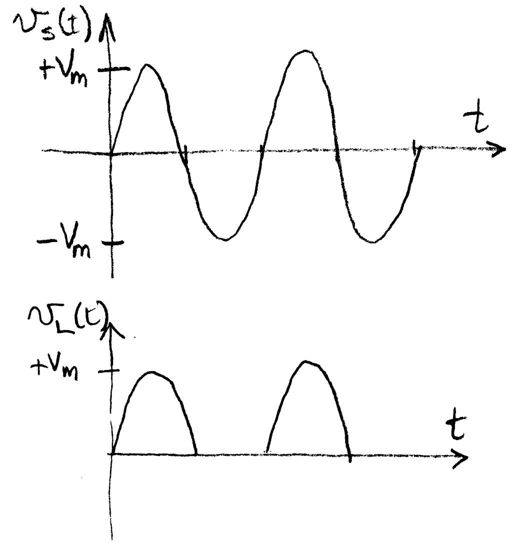
PIV – peak inverse voltage

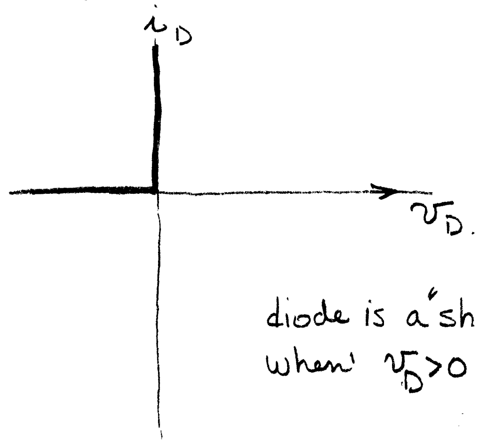
PRV – peak reverse voltage

3.4 Rectifier circuits



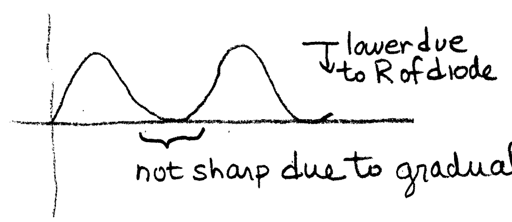
Best analyzed using "ideal" diode model.





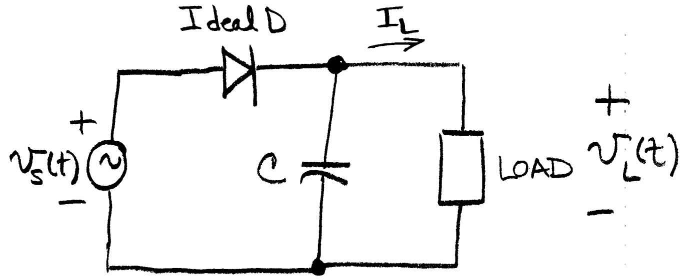
diode is a "short" when $v_D > 0$

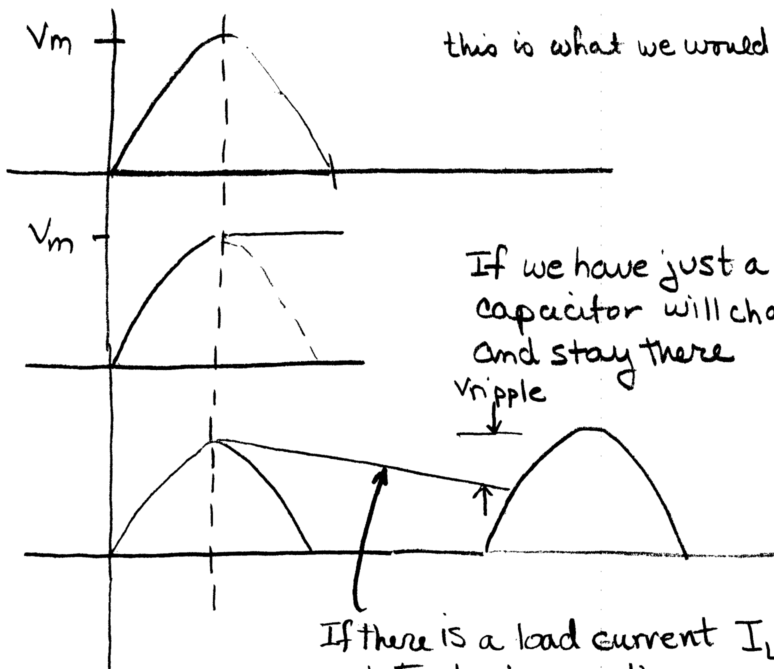
If you would actually measure $v_L(t)$ with a scope in the lab you would see.



It will look a lot like the original sine wave.

Simple half wave rectifier circuit (in power supplies, AM radio detectors)





this is what we would see if we had a resistor load.

If we have just a C as a load the capacitor will charge up to V_m and stay there

If there is a load current I_L this will act to discharge the capacitor.

Since capacitor is already at $+V_m$ there will be no current flow thru diode.

Let's estimate the voltage drop — called ripple — for a half-wave rectifier with smoothing capacitor.

charge removed from capacitor

$$\Delta Q \cong I_L T$$

T ← approximate by period, $\frac{1}{60\,Hz}$.

I_L ← <u>average</u> load current

definition of capacitance

$$C = \frac{Q}{V} \quad \text{or} \quad Q = CV$$

differentiating

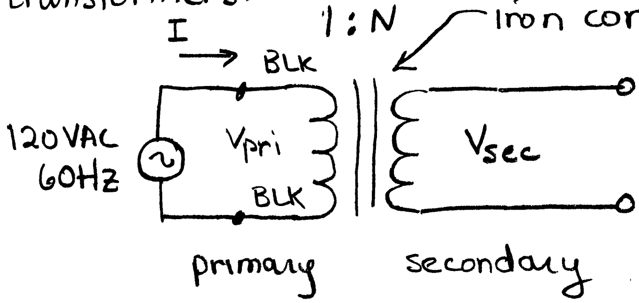
$$\Delta Q = C \Delta V$$

$$\therefore \quad I_L T = C \Delta V$$

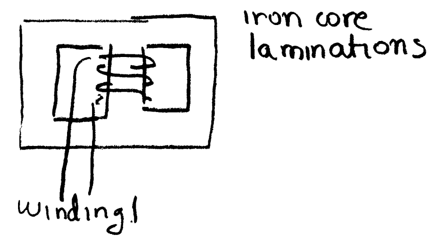
or

$$C = \frac{I_L T}{\Delta V}$$

Power supplies usually actually use full-wave rectifier or bridge rectifier circuits. To study these we need to look at transformers.



electrically isolated from power lines



$$V_{sec} = N \, V_{pri}$$

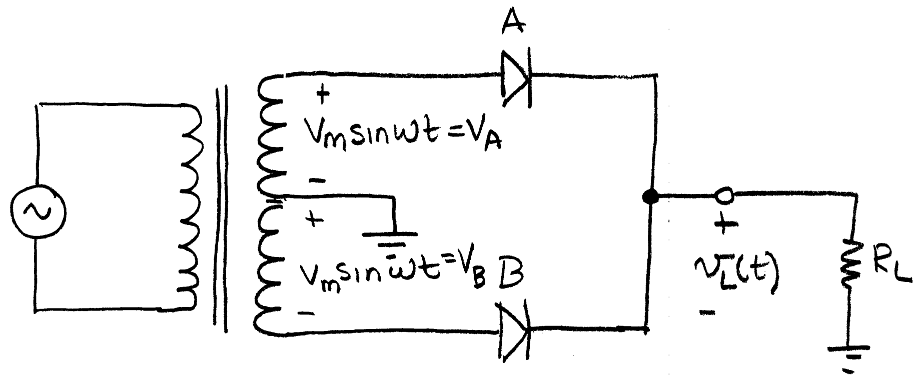
$$I_{sec} = \frac{1}{N} I_{pri}$$

$$V_{sec} I_{sec} = V_{pri} I_{pri}$$

transformers are usually very efficient

Transformers are used for:

1. changing voltages to more useful voltages efficiently
   - most efficient to transmit power at high voltages
2. electrical isolation from power lines
   - current can actually flow thru people!
   - can float output
3. impedance matching

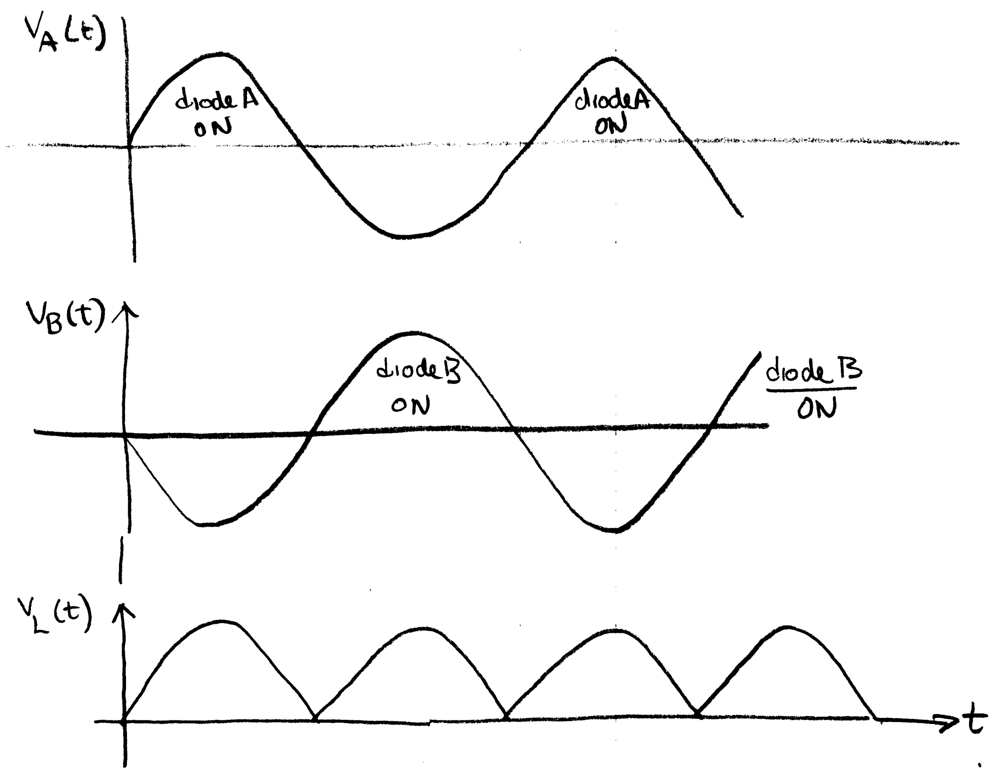


this is called a center-tap

The magnetic fields are in the same direction so the output looks like two sinusoidal sources in series.

When $V_A > 0$ diode A conducts, but $V_B < 0$ as seen by diode B so diode B is OFF

When $V_B > 0$ as seen by diode B it is conducting, but at that time $V_A < 0$

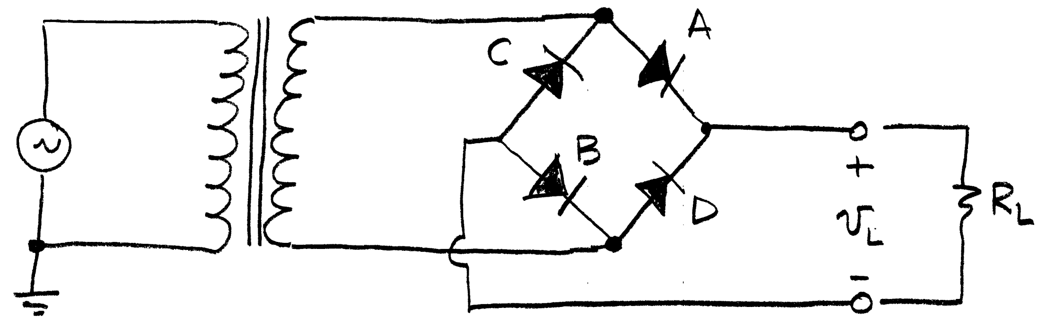


Much less "ripple" than half-wave rectifier

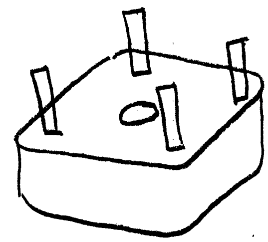
problems

1. requires center tapped transformer

diode bridge

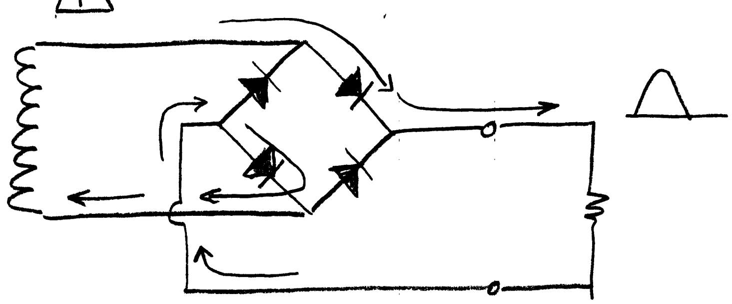


full wave rectifier without center-tapped transformer

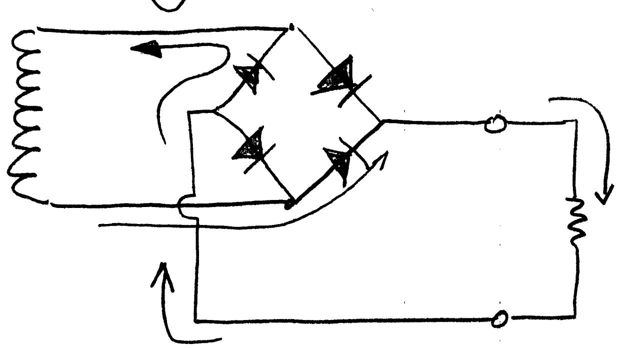


commercial diode bridge

positive half-cycle



negative half-cycle



Design choices p. 712 — 715

1. ripple — full-wave to reduce ripple
   capacitor size
2. maximum load current

   diode peak current

   diode surge current

   (diode PRV)

   transformer current

Example 10.8

design 5V DC @ 1A

line voltage 105 – 130 V rms

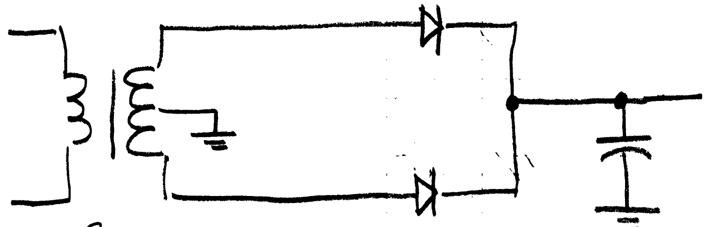
regulator ± 10% voltage tolerance, max dropout 2.5 V

Minimum allowed input to regulator to prevent dropout

$$\underbrace{5 \times 1.1}_{\text{upper limit of regulator}} + 2.5\text{ V} = 8\text{ V}$$

We will design power supply/filter to produce this.

1. use diode bridge.



2. select transformer current rating

   Fig. 10.37(c) $I_{t,rms} \cong 1.2\, I_{L,avg}$.

   since $I_L = 1A \Rightarrow I_{t,rms} = 1.2A$ pick larger transformer, maybe 1.5A

③ pick diodes. Look at 1N400x series.
identical except for PRV from 50V to 1000V.
since low voltage supply pick 1N4001

Power supply is 1A out average
⇒ each diode should be $\frac{1}{2}$A average forward current

However, peak currents several times larger.
measurements from test circuit give
peak diode currents 5–20A

data sheet says $V_{diode} \cong 1.5$ Volts for these currents.

④ Pick transformer voltage.

transformer resistance causes voltage drop
⇒ allow 10% drop near load current rating

$$V_{oc,peak} = V_{L,min} + V_{diode} + V_r + V_{drop}$$

- $V_{oc,peak}$: transformer secondary
- $V_{L,min}$: use 9 rather than 8 for device tolerance
- V_{diode}: 1.5V @ peak currents
- V_r: ripple $V_{r,p-p} = 2V$
- V_{drop}: transformer resistance $\approx 1V$

$$V_{oc,peak} = 9 + 1.5 + 2 + 1 = 13.5 \text{ Volts peak.}$$

Worse case: 105 input (lowest) producing $13.5V_{peak}$ (max).

At 120 Volts this transformer would produce

$$V_{oc,peak} = 13.5 \times \frac{120}{105} = 15.4 \text{ Volts.}$$

$$V_{oc,rms} = 15.4\,(0.707) \cong 10.9 \text{ Volts.}$$

For ± 10% regulation we pick minimum as $10.9 - 1.09 \cong 9.9V$.

⇒ we need at $9.9V_{rms}$ transformer.
(19.8V CT)

⑤ Now select capacitor

P-P ripple is 2 Volts.

$$C = \frac{I_L T}{2V_r} = \frac{(1A)(1/60)}{2(2)} = 4167\,\mu f$$

What is voltage rating

If we use an 10 volt ct transformer, 1.5A sec, with 10% regulation

From Example 10.7 Transformer model

$$\frac{V_{oc} - V_{fl}}{V_{fl}} \times 100\% = 10\%$$ ← regulation of transformer

V_{fl} = 10 volts rms (i.e. full load voltage)

Then $V_{oc} \cong 11$ Vrms (15.6 volts peak).

Use peak value under worse case.

$$15.6\left(\frac{130}{120}\right) = 16.9 \text{ volts},$$

∴ use 20V capacitors

<u>Computer model</u>

$$R_t = \frac{V_{oc} - V_{fl}}{I}$$

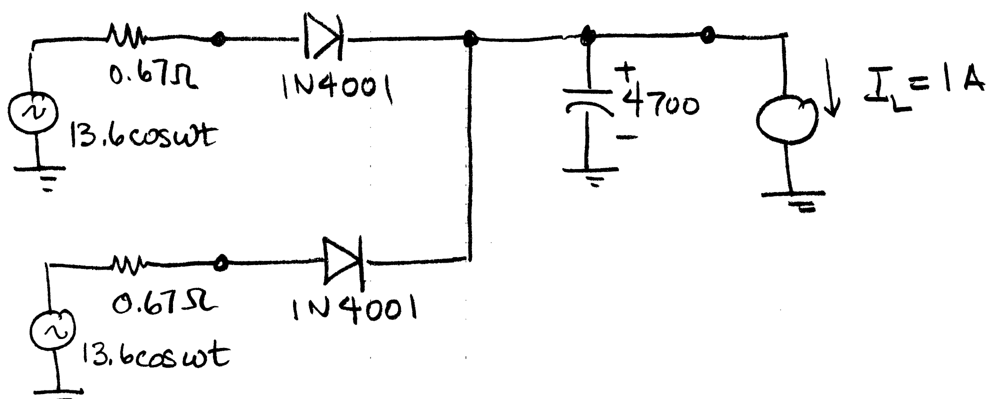
$$R_t = \frac{11 - 10}{1.5}$$

$R_t = 0.67\Omega$

use xfmr worse case i.e. 105 V.

Then peak reduces to

$$15.6\left(\frac{105}{120}\right) = 13.6$$



Thevenin

Reading T&R 3.4 (pgs. 105 – 109) Thevenin, Norton

(pgs. 115 – 118) non-linear loads

4.2 (pgs. 163 – 164) circuits w/ dependent sources.

Possible problems.

4.4, 4.5

Hambley problems: 3.17 (Ideal diode model)

3.20, 3.24 (Rectifier Circuits)

3.22, 3.35 (Wave-shaping circuits)

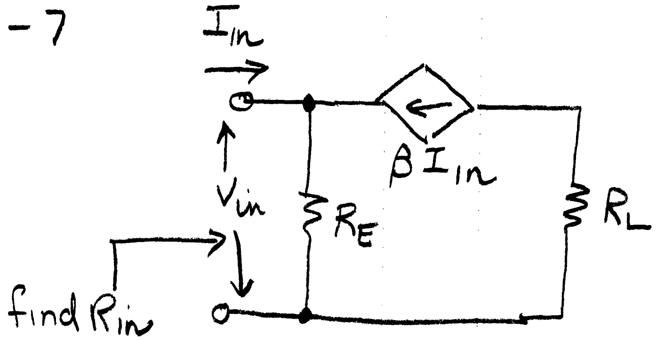
D3.38 (Design a clamp)

Thevenin Equivalent Circuits

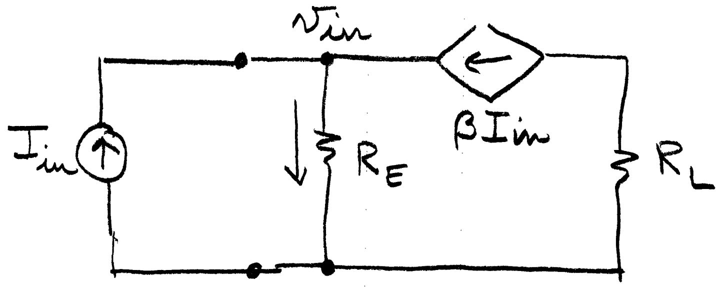
For circuits with active (controlled) circuits leave independent sources ON or use external test circuit.

⇒ find open circuit voltage
short circuit current

Example 4-7



Use a test source, calculate v_{IN}. Then $R_{in} = \dfrac{v_{IN}}{I_{in}}$



use KCL at input.

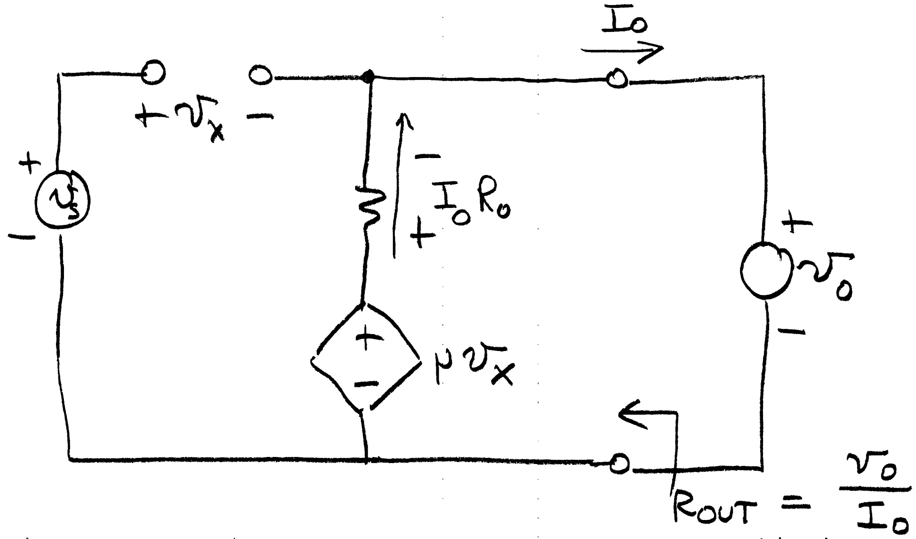
$$\sum_{+in} i = 0$$

$$+I_{in} + \beta I_{in} - \frac{v_{in}}{R_E} = 0$$

$$(\beta+1) I_{in} = \frac{v_{IN}}{R_E}$$

$$R_{in} \equiv \frac{v_{in}}{I_{in}} = (\beta+1) R_E$$

Example 4-8



can't use a test current source – try it!

do KVL on inner loop

$$-\mu v_x + I_o R_o + v_o = 0$$

↳ get rid of this variable by doing outer loop.

$$-v_s + v_x + v_o = 0$$

Eliminate v_x

$$-\mu(v_s - v_o) + I_o R_o + v_o = 0$$

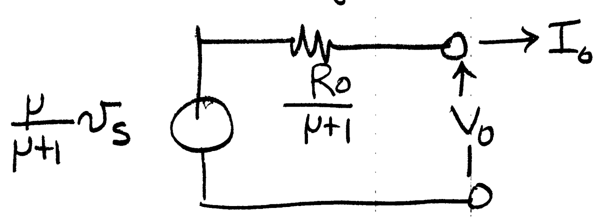
$$-\mu v_s + \mu v_o + I_o R_o + v_o = 0$$

$$-\mu v_s + (\mu+1) v_o + I_o R_o = 0$$

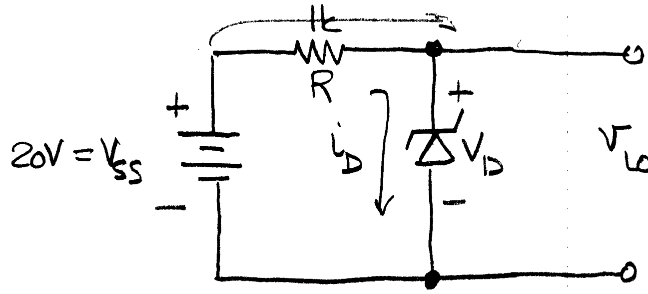
Since voltage source try writing v_o

$$v_o = \frac{\mu}{\mu+1} v_s - I_o \frac{R_o}{\mu+1}$$

$\frac{\mu}{\mu+1} v_s$ looks like a voltage source; $\frac{R_o}{\mu+1}$ looks like a resistance.



Sect. 3.7 Zener diode voltage regulator



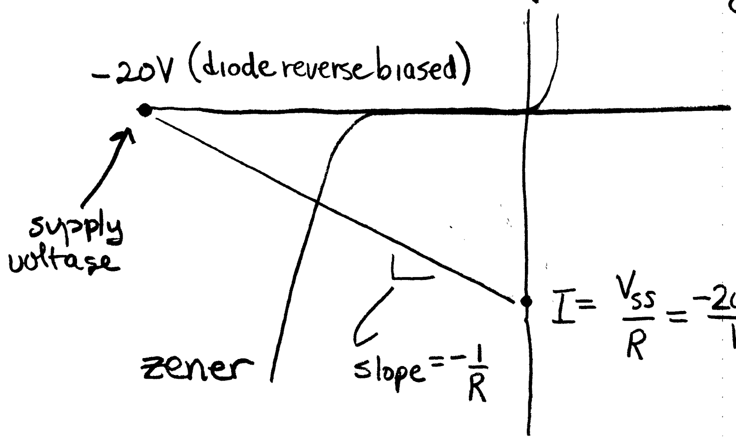
$v_{LOAD} = -v_D$ (negative since in 4th quadrant)

using KVL

$-V_{SS} + i_D R_D + v_D = 0$

↑ ↑ these are both negative

use load line analysis to find operating current.



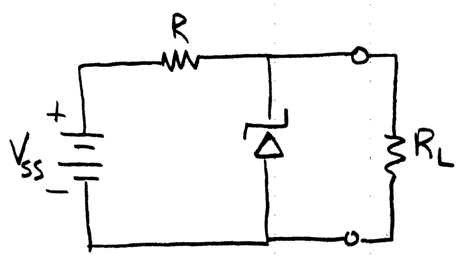
$I = \frac{V_{SS}}{R} = \frac{-20V}{1k} = -20\,mA$.

zener operates in 3rd quadrant

If you know V_Z the zener voltage, the supply voltage, and R you can always calculate I.

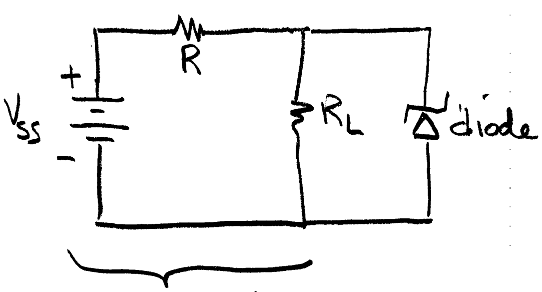
However if we must design a zener diode voltage regulator for a known load.

Practical circuit

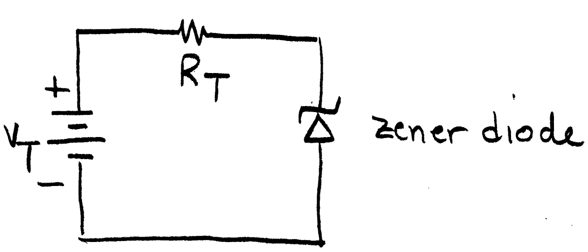


This represents the load. If $R_L \to \infty$ all current goes through the zener.

solution method



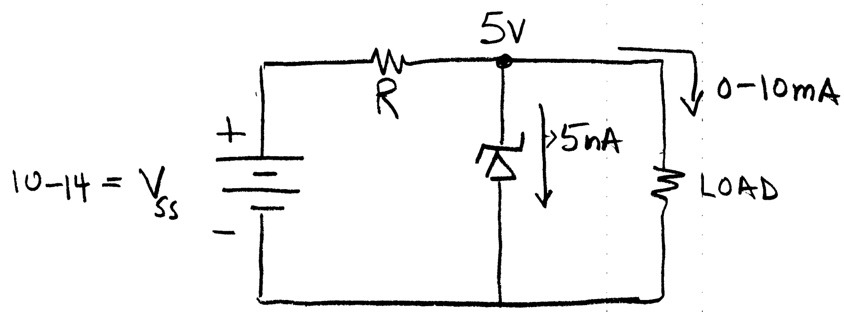
collect resistors & thevenize



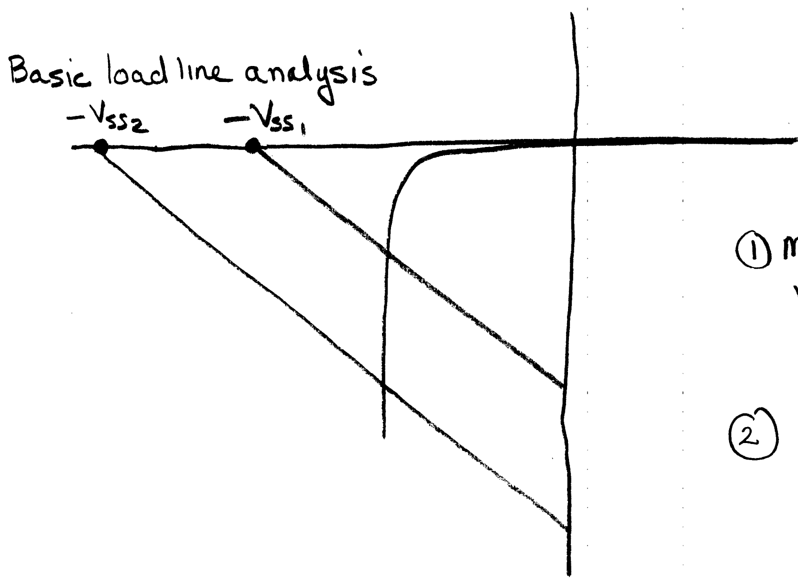
The design works best for relatively constant loads. If R_L should change this poses problems.

Prob 3.46 Design 5V zener diode regulator
operates from a source that varies 10−14V
load current varies from 0−10mA

Determine R so that $|I_d| \geq 5mA$



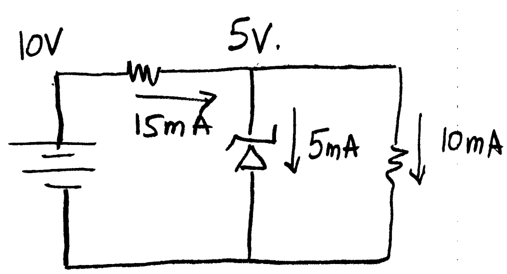
Consider that V_D = constant +5 volts.
R is fixed



① Minimum current for lowest V_{SS}. This should have been intuitive.

② Minimum I_d occurs when I_L = maximum. Since V_D is constant the total current is constant.
If $I_L = 0$ then $I_d = 15mA$
If $I_L = 10mA$ then $I_d = 5mA$.

design

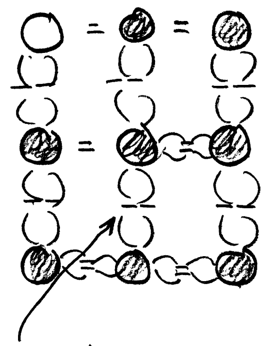


③ $R = \frac{V}{I} = \frac{10V - 5V}{15mA} = \frac{1}{3}k = 330\Omega$

3.9 Basic Semiconductor Concepts

- most semiconductor devices are silicon although others are possible

intrinsic silicon crystal
4 atoms in outermost valence band

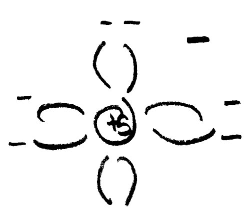


covalent bonds.

Thermal energy can break bond
fixed vacancy
free electron

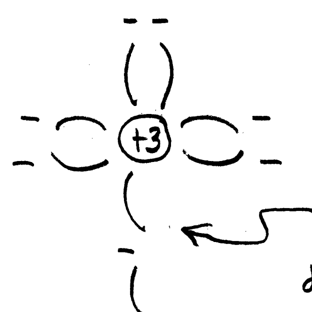
free electrons & holes generated by thermal energy → better conduction at high T's
(when a free electron encounters a hole recombination occurs.)

n-type semiconductor



spare free electron due to donor atom like phosphorus

p-type semiconductor



vacant bond due to +3 acceptor

Charge = 0

$$n = p + N_D$$

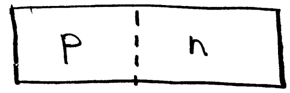
free electrons — holes — donor concentration

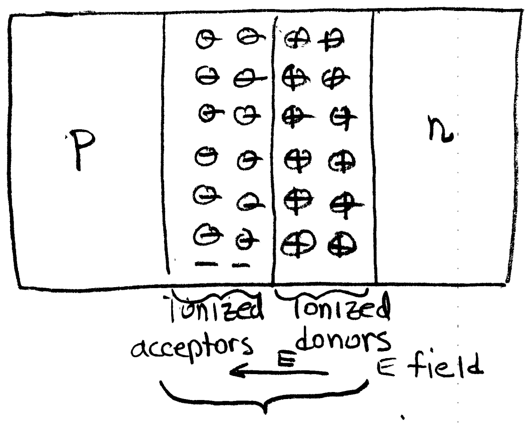
this is what tips the balance

$$p = N_A + n$$

holes — ionized acceptor atoms — free electrons.

3.10 unbiased p-n junction





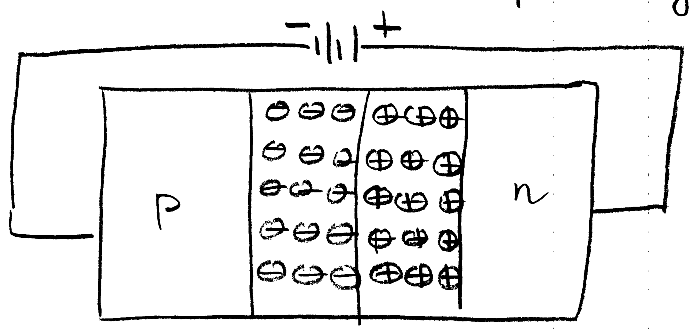
When we put the p & n materials together diffusion occurs

excess holes p → n

freeelectrons p ← n

The result is that the bound charges remain.

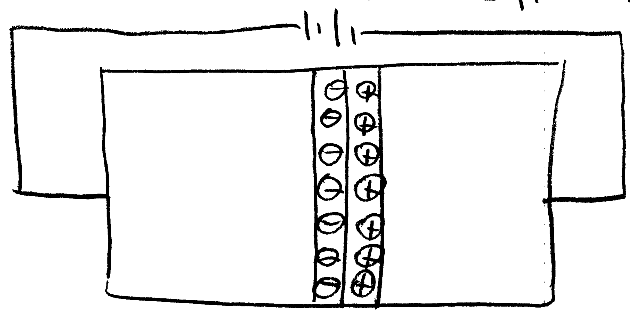
If we reverse bias the depletion region increases.



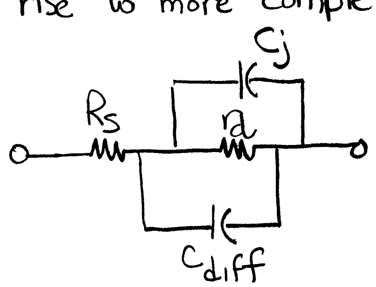
reverse bias pulls out the carries.

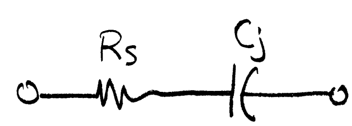
Increases the electric field making it harder for current to flow.

If we forward bias the depletion region decreases.



Gives rise to more complete diode model.





C_{diff} = forward bias

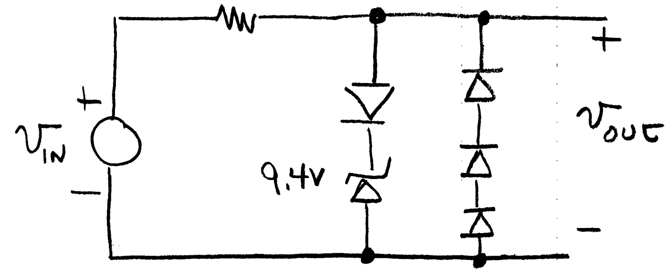
C_j = depletion capacitance

R_s = bulk ohmic resistance

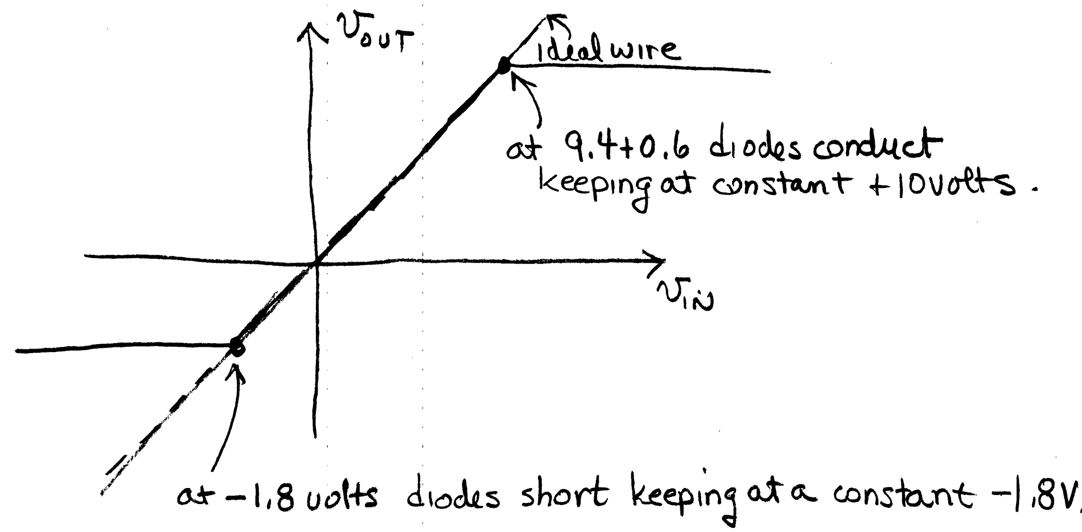
r_d = dynamic resistance

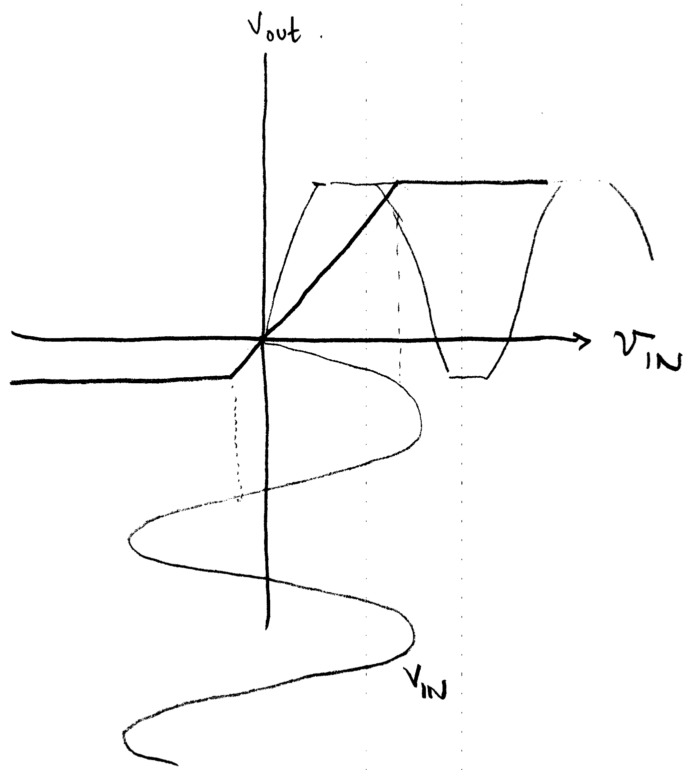
Clippers, Clamps, Diode Logic

3.17(a)



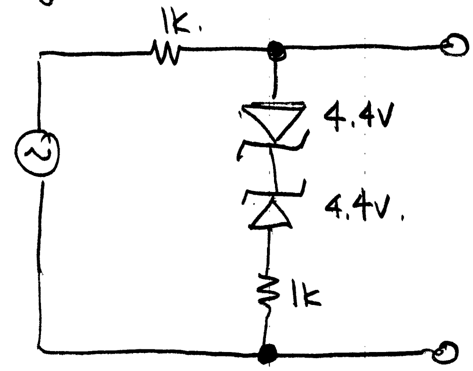
Assume ideal diodes with 0.6 volt offsets.



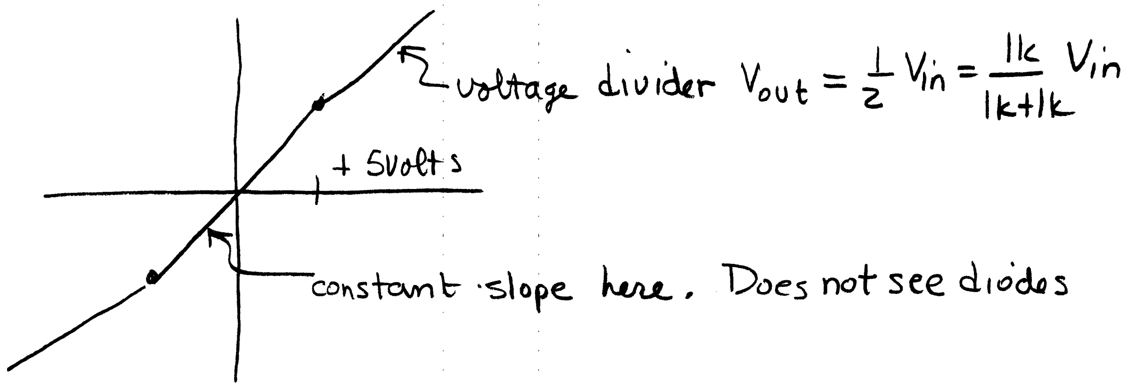


diodes can also change slope.

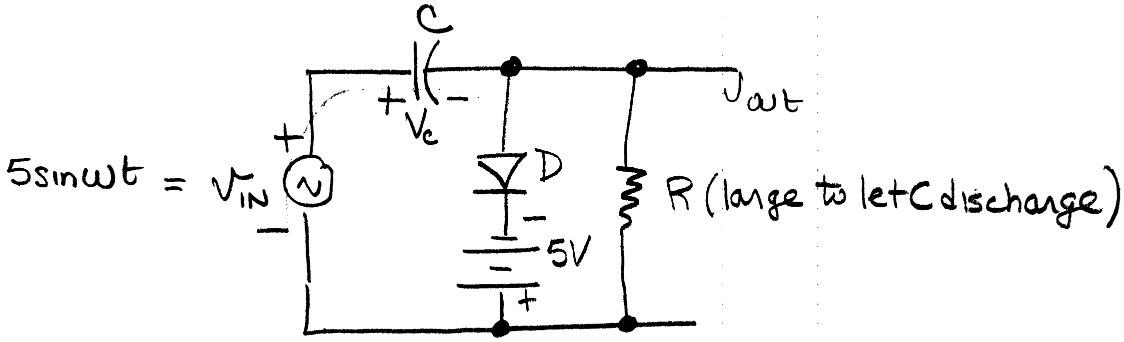
3.7(b)



what do the zeners do : conduct in forward direction with 0.6V drop and in reverse direction at 4.4 volts.

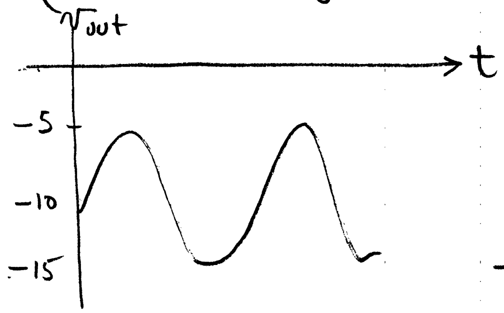


Clamps are circuits which insert DC components.



The capacitor is initially charged by the battery to +5 through D

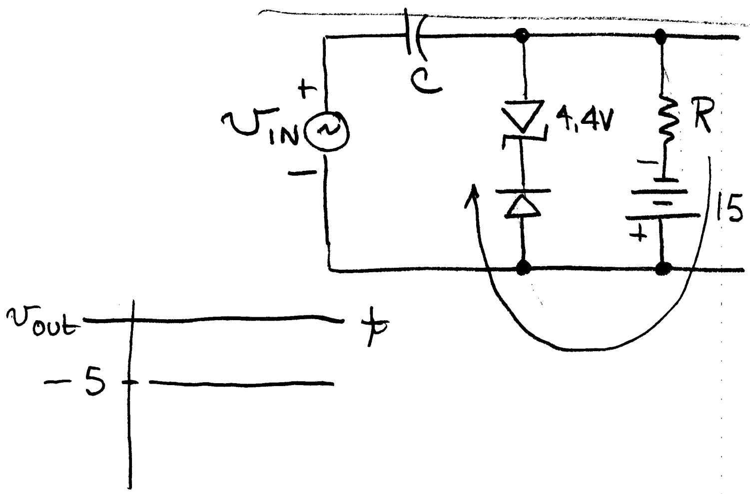
If v_{IN} increases above 5 volts. the diode conducts and V_c will charge to the peak input value. It (C) charges to the (peak value of the input + 5) volts



Capacitor always charges to V_{peak} of input

i.e. $V_C = V_p + V_R$

If V_{peak} = 5 volts then we get this out put.



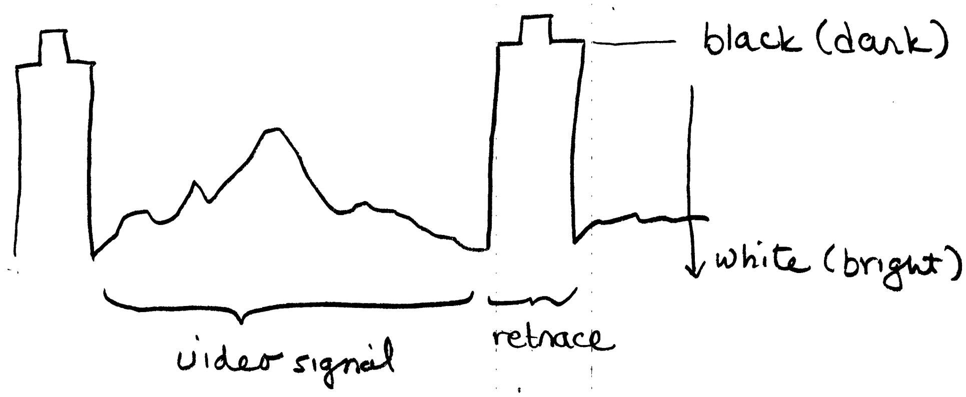
similar to above circuit but battery causes current flow through diodes. Diodes have a voltage drop which is 0.6 + 4.4 = 5 volts and is in parallel with C. Thus, C charges up to +5 volts as above from battery.

However, V_{IN} does not forward bias diode. That is done by the 15 volt battery. Thus, the battery keeps the diode branch at about 5 volts through a parallel brance.

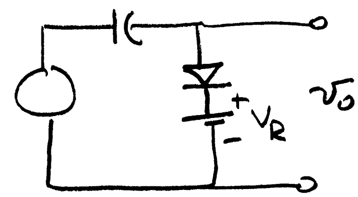
The difference between the two circuits is whether the battery is in series with v_{IN}.

Some exotic diode applications for a clamp

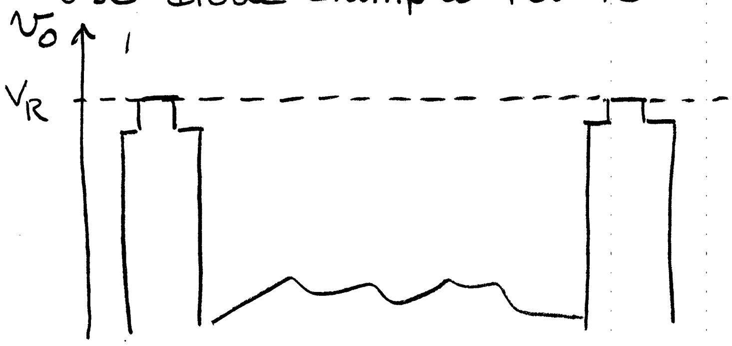
DC restoration in television circuits



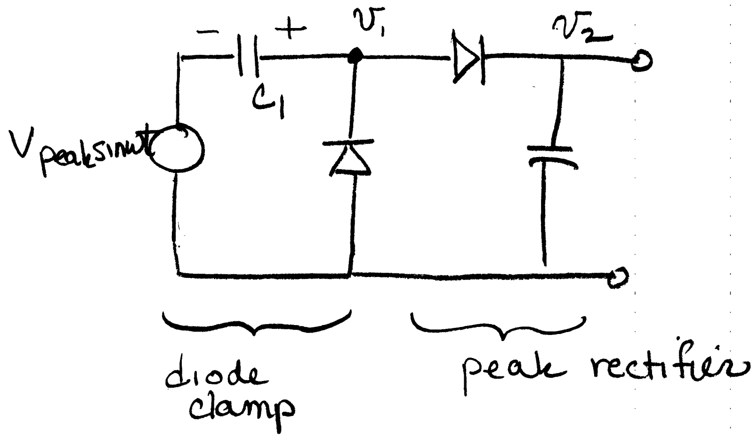
Running a video signal through an ac amplifier will shift its DC level. Yet television uses DC level to establish brightness. Use a clamp to restore proper DC levels.



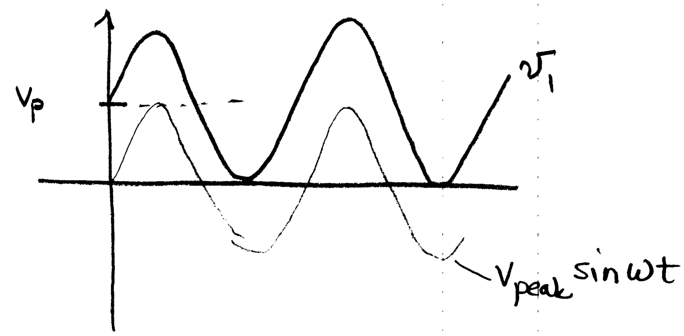
Use diode clamp to restore to



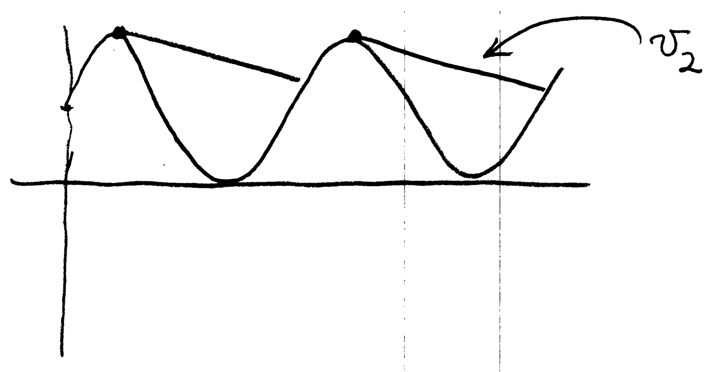
Voltage doubler



diode clamp charges to $+V_{peak}$ as shown.
This shifts ac waveform up as shown.



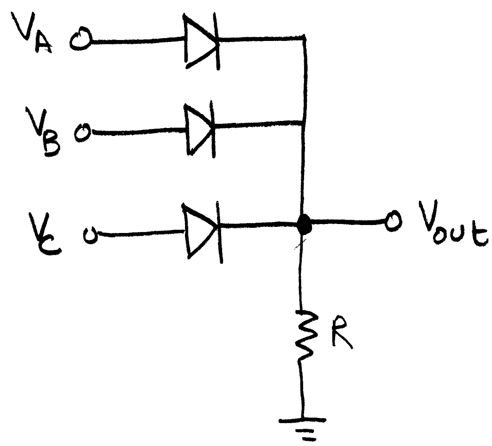
The peak rectifier operates just as discussed earlier.



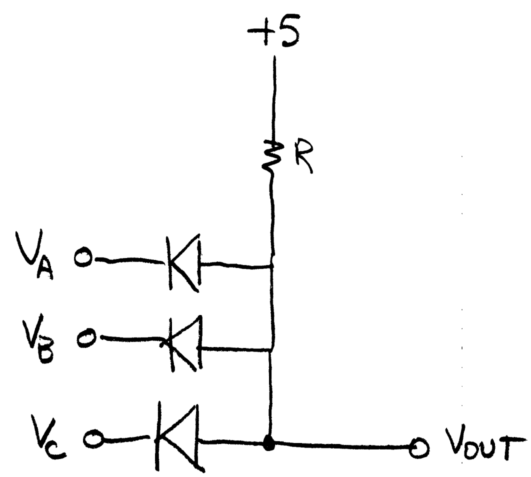
$$\Delta V = \frac{I_L T}{C}$$

(I_L: load current)

diode logic circuits



if V_A OR V_B OR V_C = +5 volts then V_{out} = 5 volts else V_{out} = 0.

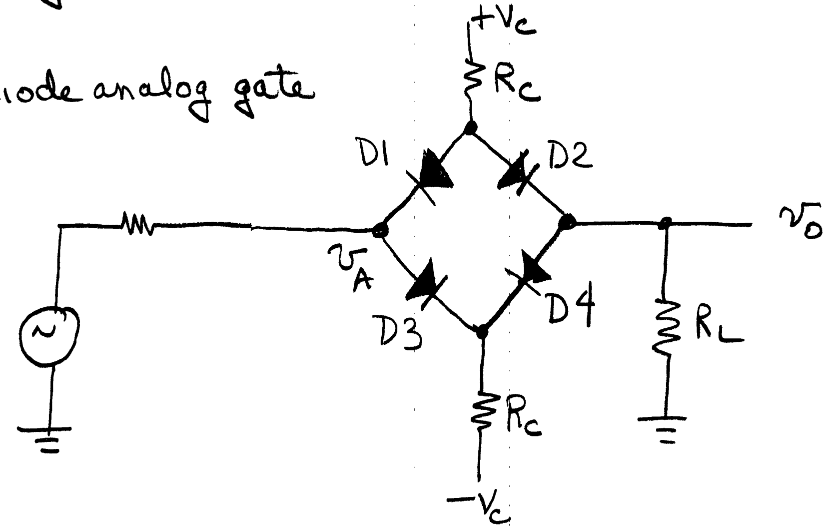


if V_A AND V_B AND V_C = +5 volts then V_{OUT} = +5 volts else V_{OUT} = 0

diode analog switches

usually done with transistors but diodes are faster

four-diode analog gate

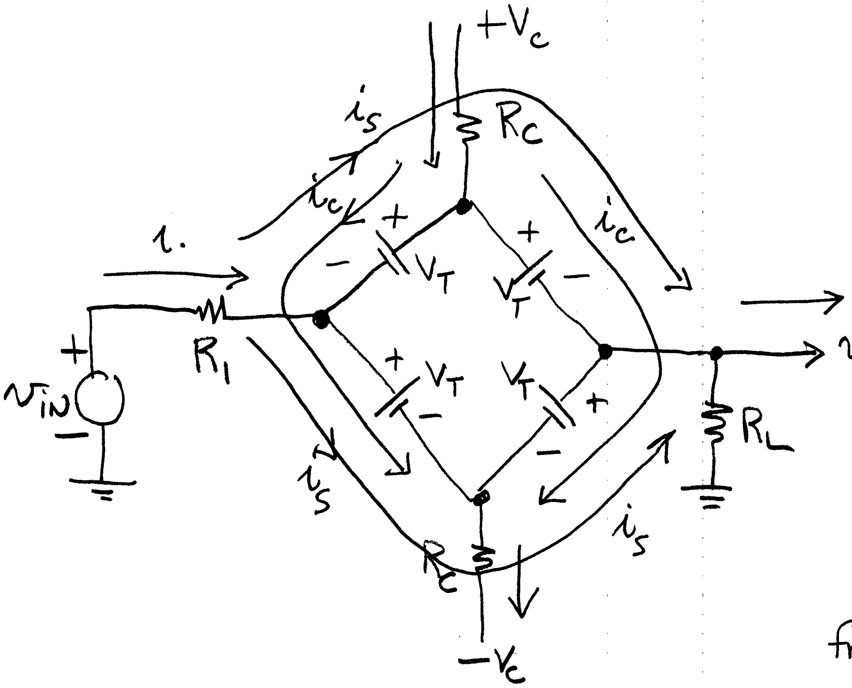


If $V_c > 0$ then then all diodes forward biased.

and $v_o = v_A$

If $v_c < 0$ Then diodes OFF (reversed biased and no output.

There are some restrictions such that the diodes remain forward biased.



$$i_c = \frac{2V_c - 2V_T}{2R_c}\left(\frac{1}{2}\right)$$

each current is $\frac{1}{2}$ since it splits

$$i_s = \frac{v_{IN}}{R_1 + R_L \| \frac{R_c}{2}}\left(\frac{1}{2}\right)$$

from R_1 load looks like $R_L \| \frac{1}{2} R_c$

Condition is that $i_s < i_c$ in D1 and D4.

for

Chapter 1

1.6 Power Supplies and Efficiency

$$P_i + P_s = P_o + P_d$$

- P_d ← power dissipated
- P_o ← output power
- P_s ← power from power supply
- P_i ← input power (usually small).

Efficiency of a power <u>amplifier</u> η is the percentage of the power supply that is converted into output power.

$$\eta = \frac{P_o}{P_s} \times 100\%$$

Example 1.4.

Power input to amplifier $= 10^{-11}$ watts.

Output voltage is 8V rms into 8 ohms.

$$P_o = \frac{V_o^2}{R_L} = \frac{(8)^2}{8} = 8 \text{ watts.}$$

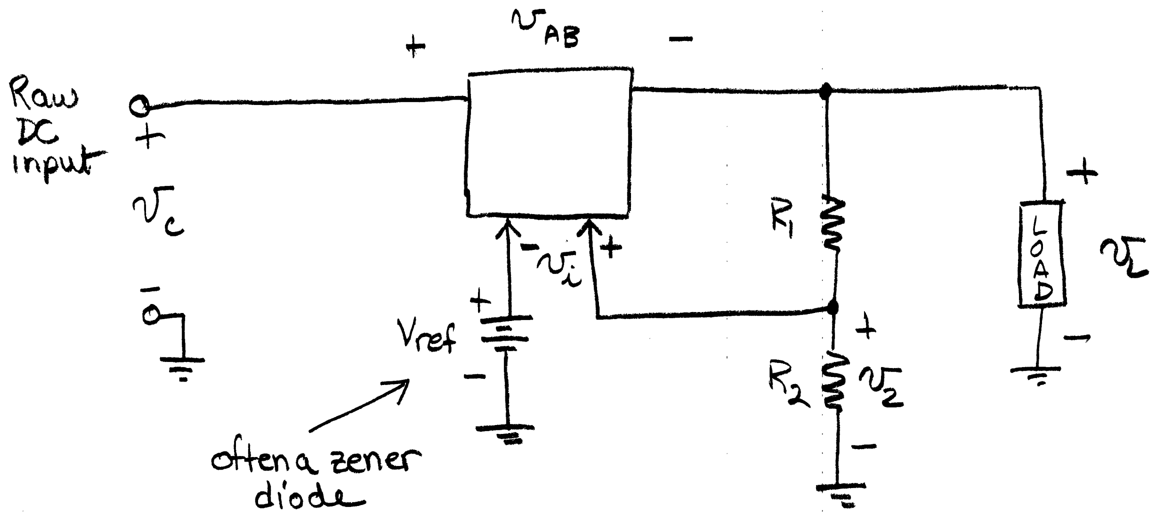
Power supply is supplying $+15V$ @ $1A$, $-15V$ @ $\frac{1}{2}A$

$$P_s = (15)(1) + (15)\left(\tfrac{1}{2}\right) = 22.5 \text{ Watts.}$$

$$\eta = \frac{8}{22.5} = 35.6\%$$ typical stereo amplifier

10.5 Linear Voltage Regulator

Series voltage regulator



$$v_2 = \frac{R_2}{R_2 + R_1} v_L = \beta v_L \qquad \beta \equiv \frac{R_2}{R_1 + R_2} \text{ voltage divider ratio}$$

$$v_i = \beta v_L - V_{ref}$$

Model the regulator as an amplifier (voltage)

$$v_{AB} = A v_i$$

$$v_{AB} = A(\beta v_L - V_{ref})$$

From input to output

$$v_c = v_{AB} + v_L$$

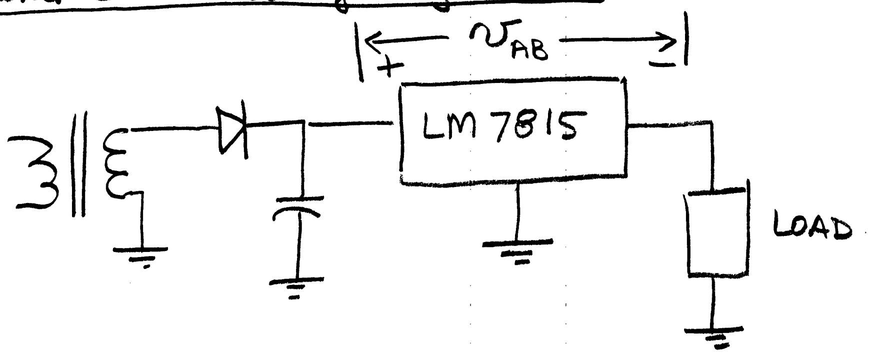
$$v_c = A(\beta v_L - V_{ref}) + v_L$$

Solve for v_L $\qquad v_c = A\beta v_L - AV_{ref} + v_L$

$$v_L = \frac{v_c}{A\beta + 1} + \frac{A \, V_{ref}}{A\beta + 1}$$

if $A\beta \gg 1$ $\qquad v_L \cong \dfrac{V_{ref}}{\beta}$

Integrated Circuit Voltage Regulators



Good for nominal output voltages of 2.6V to 15V.

minimum v_{AB} is known as the dropout voltage

Linear voltage regulators require $v_{AB} \geq$ minimum
This comes from regulator specs. Typically 2 to 2.5V for 78xx.

Diode Currents

When the capacitor is initially being charged there is a surge current.

As a result we must select diode for surge current.
1N4002 is rated for 30A surge for one cycle.

Steady state diode current is given by sum of
(1) load current
(2) regulator
(a) feedback network
(b) voltage reference
(c) power to electronics (amplifier)

Peak current is usualy several times steady state value. (5-20)

Transformer current rating should be several times average.
Remember winding resistance in modeling.