Diodes Notes

Diodes are basically electrical check valves. They allow current to flow freely in one direction, but not the other. Check valves require a small forward pressure to open the valve. Similarly, a diode requires a small forward voltage (bias) to "turn on". This is called the forward voltage drop. There are many different types of diodes, but the two that you are most likely to see are silicon diodes and light-emitting diodes (LEDs). These two have forward voltage drops of about 0.7V and 2V respectively.

Mechanical check valve

Diode

silicon diode   LED
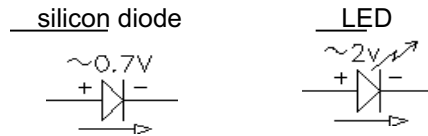
The electrical symbol for a diode looks like an arrow which shows the forward current direction and a small perpendicular line. The two sides of a diode are called the "anode" and the "cathode" (these names come from vacuum tubes). Most small diodes come in cylindrical packages with a band on one end that corresponds to the small perpendicular line, and shows the polarity, see the picture. Normal diodes are rated by the average forward current and the peak reverse voltage that they can handle. Diodes with significant current ratings are known as "rectifier" or "power" diodes. (Rectification is the process of making AC into DC.) Big power diodes come in a variety of packages designed to be attached to heat sinks. Small diodes are known as "signal" diodes because they're designed to handle small signals rather than power.

cathode
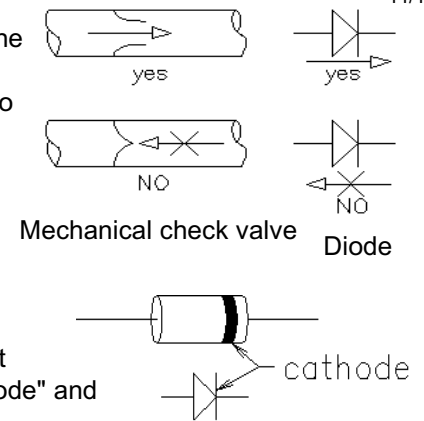
Diodes are nonlinear parts

So far in this class we've only worked with linear parts. The diode is definitely NOT linear, but it can be modeled as linear in its two regions of operation. If it's forward biased, it can be replaced by battery of 0.7V (2V for LEDs) which opposes the current flow. Otherwise it can be replaced by an open circuit. These are "models" of the actual diode. If you're not sure of the diode's state in a circuit, guess. Then replace it with the appropriate model and analyze the circuit. If you guessed the open, then the voltage across the diode model should come out less than +0.7V (2V for LEDs). If you guessed the battery, then the current through the diode model should come out in the direction of the diode's arrow. If your guess doesn't work out right, then you'll have to try the other option. In a circuit with multiple diodes (say "n" diodes), there will be 2^n possible states, all of which may have to be tried until you find the right one. Try to guess right the first time.
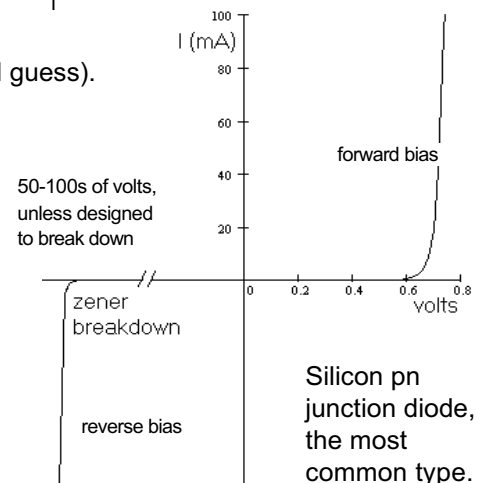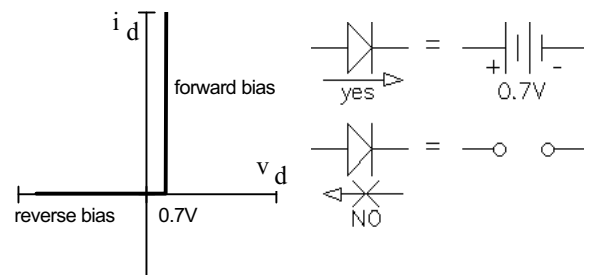
Constant-voltage-drop model

This is the most common diode model and is the only one we'll use in this class. It gives quite accurate results in most cases.

i_d forward bias v_d

reverse bias   0.7V

1 Assume the diode is operating in one of the linear regions (make an educated guess).
2 Analyze circuit with a linear model od the diode.
3 Check to see if the diode was really in the assumed region.
4 Repeat if necessary.

Actual diode curve

The characteristics of real diodes are actually more complicated than the constant-voltage-drop model. The forward voltage drop is not quite constant at any current and the diode "leaks" a little current when the voltage is in the reverse direction. If the reverse voltage is large enough, the diode will "breakdown" and let lots of current flow in the reverse direction. A mechanical check valve will show similar characteristics. Breakdown does not harm the diode as long as it isn't overheated.

I (mA)

50-100s of volts, unless designed to break down

zener breakdown

forward bias

reverse bias

Silicon pn junction diode, the most common type.

Zener diodes are special diodes designed to operate in the reverse breakdown region. Since the reverse breakdown voltage across a diode is very constant for a large range of current, it can be used as a voltage reference or regulator. Zener diodes are also used for over-voltage protection. In the forward direction zeners work the same as regular diodes.
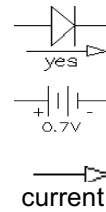
V_Z = zener voltage
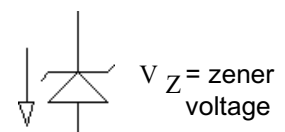
Diode Circuit Examples

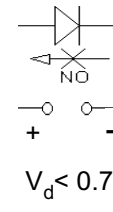**Basic diode circuit analysis**

1 Make an educated guess about each diode's state.

2 Replace each diode with the appropriate model:

3 Redraw and analyze circuit.

4 Make sure that each diode is actually in the state you assumed:

conducting   not conducting

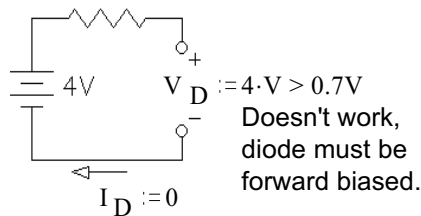yes   or   NO

0.7V   +   -

current $V_d < 0.7V$

Note: 0.7V is for silicon junction diodes & will be different for other types. (2V for LED)

If any of your guesses don't work out right, then you'll have to start over with new guesses. In a circuit with n diodes there will be 2^n possible states, all of which may have to be tried until you find the right one. Try to guess right the first time.
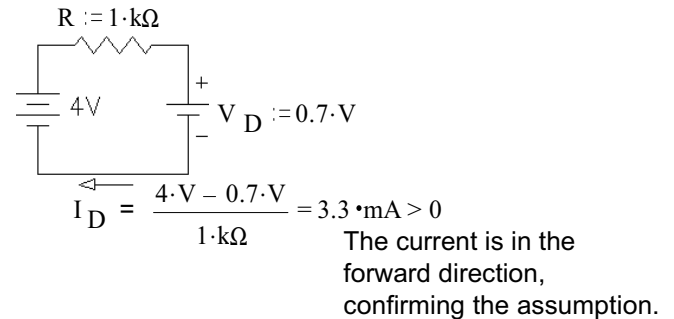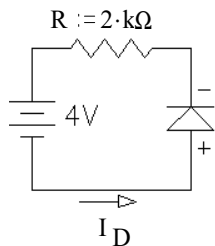
Ex1
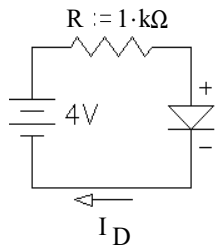
$R := 1 \cdot k\Omega$ 4V I_D

Try reverse-biased, non-conducting model

4V $V_D := 4 \cdot V > 0.7V$
Doesn't work, diode must be forward biased.
$I_D := 0$

Try forward-biased, conducting model

$R := 1 \cdot k\Omega$ 4V $V_D := 0.7 \cdot V$

$I_D = \dfrac{4 \cdot V - 0.7 \cdot V}{1 \cdot k\Omega} = 3.3 \cdot mA > 0$

The current is in the forward direction, confirming the assumption.

Ex2

$R := 2 \cdot k\Omega$ 4V I_D

Try forward-biased, conducting model

$R := 2 \cdot k\Omega$ 4V $V_D := 0.7 \cdot V$

$I_D = \dfrac{-4 \cdot V - 0.7 \cdot V}{1 \cdot k\Omega} = -4.7 \cdot mA < 0$

Doesn't work, diode must be reverse biased.

Try reverse-biased, non-conducting model

Check the diode voltage

4V $V_D := -4 \cdot V < 0.7V$

Confirms diode is reverse biased

$I_D := 0 \cdot mA$

Ex3

$R := 820 \cdot \Omega$ 12V   4V

Try reverse-biased, non-conducting model

$V_D = 12 \cdot V - 4 \cdot V = 8 \cdot V > 0.7V$
Doesn't work, diode must be forward biased.

12V   4V

Try forward-biased, conducting model

$V_D := 0.7 \cdot V$ $V_R := 12 \cdot V - 4 \cdot V - V_D$

$R := 820 \cdot \Omega$ $V_R = 7.3 \cdot V$

12V   4V

Check the diode current

$I = \dfrac{V_R}{R} = 8.9 \cdot mA > 0$

Confirms diode is forward biased
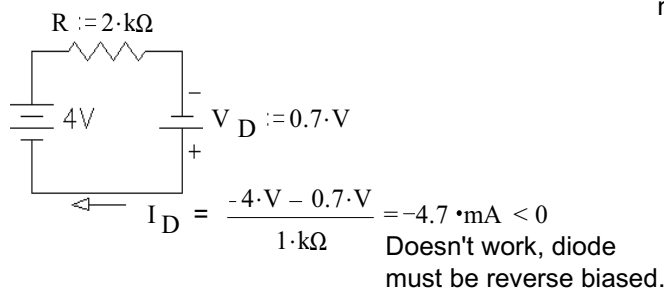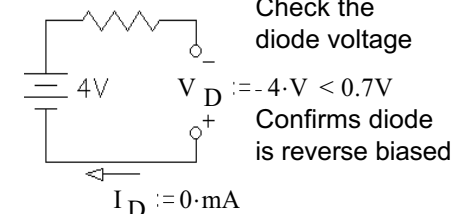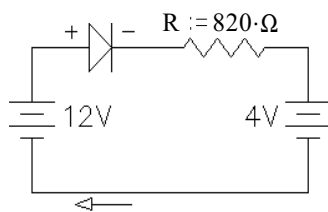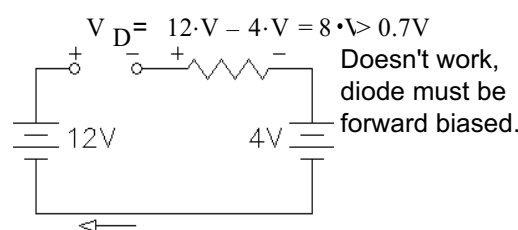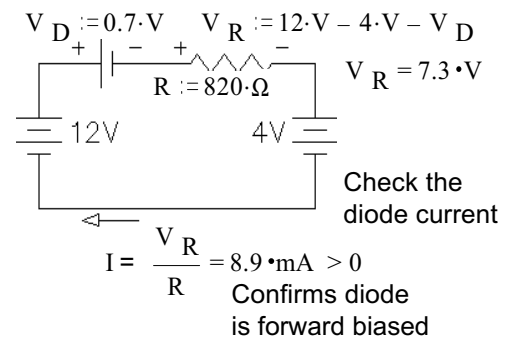
In each of the previous examples, the first guess I made was pretty stupid.

Ex4

$R_1 := 1 \cdot k\Omega$ $R_2 := 1 \cdot k\Omega$

$V_S := 5 \cdot V$ I_1 I_2 I_D
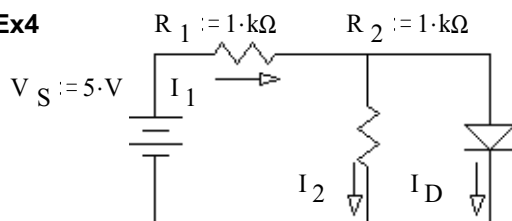
Assume diode conducts:
Analyze

$V_D := 0.7 \cdot V$

$= V_{R2}$

$V_{R2} := V_D$ $I_2 := \dfrac{V_{R2}}{R_2}$ $I_2 = 0.7 \cdot mA$

$V_{R1} := V_S - V_D$ $V_{R1} = 4.3 \cdot V$ $I_1 := \dfrac{V_{R1}}{R_1}$ $I_1 = 4.3 \cdot mA$

We assumed conducting (assuming a voltage), so check the current.

ECE 2210   Diode Notes   p2

$I_D := I_1 - I_2$ $I_D = 3.6 \cdot mA > 0$, so assumption was correct

Ex5 With an LED

$R_1 := 1 \cdot k\Omega$

$V_S := 5 \cdot V$ I_1

$R_2 := 1 \cdot k\Omega$
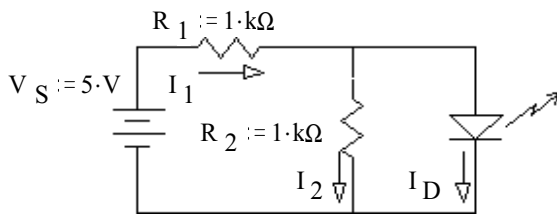
I_2 I_D

Assume diode conducts $V_D := 2 \cdot V$ $= V_{R2}$
Analyze

$V_{R2} := V_D$ $I_2 := \dfrac{V_{R2}}{R_2}$ $I_2 = 2 \cdot mA$

$V_{R1} := V_S - V_D$ $V_{R1} = 3 \cdot V$ $I_1 := \dfrac{V_{R1}}{R_1}$ $I_1 = 3 \cdot mA$

We assumed conducting (assuming a voltage), so check the current.

$I_D := I_1 - I_2$ $I_D = 1 \cdot mA$ > 0, so assumption was correct,
but the current is probably too
small to create noticeable light

Ex6   Smaller R_1

$R_1 := 1 \cdot k\Omega$ $R_2 := 100 \cdot \Omega$

$V_S := 5 \cdot V$ I_1
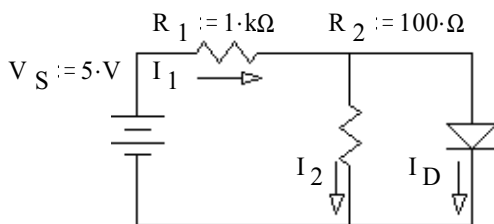
I_2 I_D

Assume diode conducts $V_D := 0.7 \cdot V$ $= V_{R2}$
Analyze

$V_{R2} := V_D$ $I_2 := \dfrac{V_{R2}}{R_2}$ $I_2 = 7 \cdot mA$

$V_{R1} := V_S - V_D$ $V_{R1} = 4.3 \cdot V$ $I_1 := \dfrac{V_{R1}}{R_1}$ $I_1 = 4.3 \cdot mA$

We assumed conducting (assuming a voltage), so check the current.

$I_D := I_1 - I_2$ $I_D = -2.7 \cdot mA$ < 0, so assumption was **WRONG !**

$R_1 := 1 \cdot k\Omega$

$V_S := 5 \cdot V$ I_1

$R_2 := 100 \cdot \Omega$ $0 \cdot mA$

I_2 I_D

Assume diode does not conduct $I_D := 0 \cdot mA$

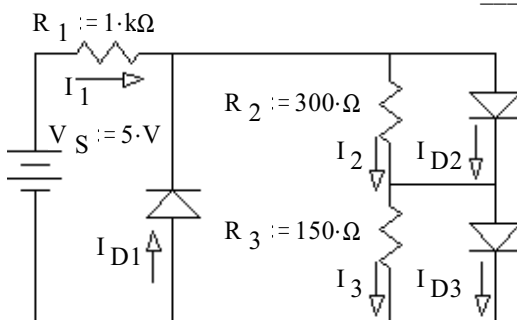Analyze $I_1 := \dfrac{V_S}{R_1 + R_2}$ $I_2 := I_1$

We assumed not conducting (assuming a current), so check the voltage.

$V_{R2} := I_2 \cdot R_2$ $V_{R2} = 0.455 \cdot V$ $< 0.7V$, so assumption was correct

Actually, this final check isn't necessary, since first assumption didn't
work, so this one had to.

Ex7   _____

$R_1 := 1 \cdot k\Omega$

I_1

$R_2 := 300 \cdot \Omega$

$V_S := 5 \cdot V$

I_2 I_{D2}

I_{D1} $R_3 := 150 \cdot \Omega$

I_3 I_{D3}

You can safety say that diode D_1 doesn't conduct without rechecking
later because no supply is even trying to make current flow through
that diode the right way.

Assume both D_2 and D_3 conduct. $V_{D2} := 0.7 \cdot V$
                                                   $V_{D3} := 0.7 \cdot V$
Analyze $V_{R1} := V_S - V_{D2} - V_{D2}$

$V_{R1} = 3.6 \cdot V$ $I_1 := \dfrac{V_{R1}}{R_1}$ $I_1 = 3.6 \cdot mA$

$I_2 := \dfrac{V_{D2}}{R_2}$ $I_2 = 2.333 \cdot mA$ $I_3 := \dfrac{V_{D3}}{R_3}$ $I_3 = 4.667 \cdot mA$

We assumed D_1 & D_2 conduct (assumed a voltage), so check currents.

$I_{D2} := I_1 - I_2$ $I_{D2} = 1.267 \cdot mA$ > 0, so assumption OK

$I_{D3} := I_1 - I_3$ $I_{D3} = -1.067 \cdot mA$ < 0, so assumption **wrong**

_____

Assume D_2 conducts and D_3 doesn't. $V_{D2} := 0.7 \cdot V$

Analyze $I_2 := \dfrac{V_{D2}}{R_2}$ $I_2 = 2.333 \cdot mA$ $I_1 := \dfrac{V_S - V_{D2}}{R_1 + R_3}$ $I_1 = 3.739 \cdot mA$ $I_{D3} := 0 \cdot mA$

Assumed D_2 conducts, so check D_2 current. $I_{D2} := I_1 - I_2$ $I_{D2} = 1.406 \cdot mA$ > 0, so assumption OK

Assumed D_3 doesn't conduct, so check D_3 voltage. $V_{R3} := I_1 \cdot R_3$ $V_{R3} = 0.561 \cdot V$ $< 0.7V$, so OK

Once you find one case that works, you don't have to try any others.
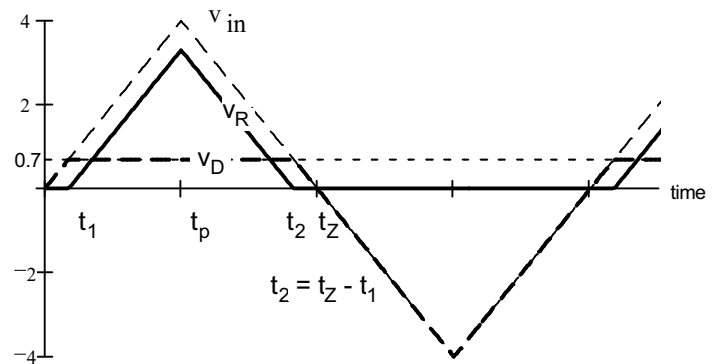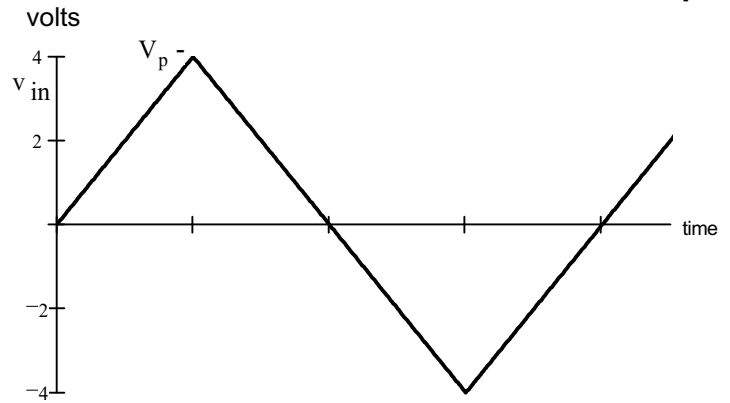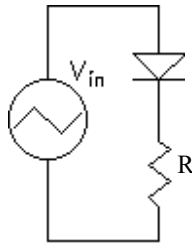
So far, we've only analyzed DC circuits with diodes. Naturally, you know what's next. We'll start with some triangular waveforms to get the general idea.
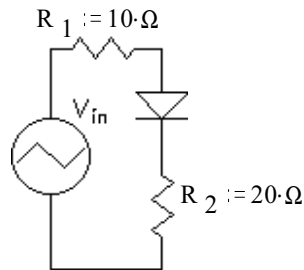
volts

Diode doesn't conduct until v_{in} reaches $0.7V$, so $0.7V$ is a dividing line between the two models of the diode.

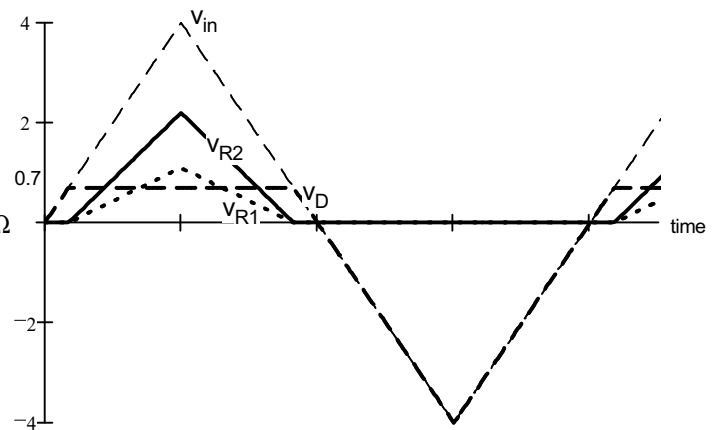$$\text{slope} = \frac{0.7 \cdot V}{t_1} = \frac{V_p}{t_p}$$

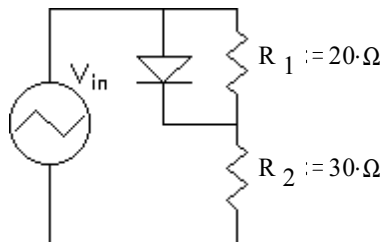$$t_1 = \frac{0.7 \cdot V}{V_p} \cdot t_p$$

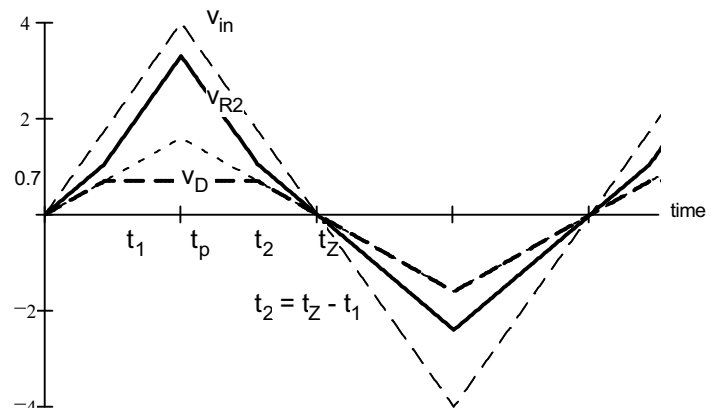$$t_2 = t_z - t_1$$

When the diode conducts, you're left with a voltage divider

$R_1 := 10 \cdot \Omega$

$R_2 := 20 \cdot \Omega$

$$V_{R2peak} = \left(V_p - 0.7 \cdot V\right) \cdot \frac{R_2}{R_1 + R_2}$$

Sometimes it's helpful to figure out what the voltage across the diode would be if it never conducted (light dotted line).

$R_1 := 20 \cdot \Omega$

$R_2 := 30 \cdot \Omega$

$$t_1 = \frac{0.7 \cdot V}{V_p \cdot \dfrac{R_1}{R_1 + R_2}} \cdot t_p$$

$$t_2 = t_z - t_1$$

Rectifier Circuits & Power Supplies

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Half-wave rectification

What if the input is a sine wave?

V_{RL} is now DC, although a bit bumpy. Some things are better if they're bumpy, but not roads and not DC voltages.
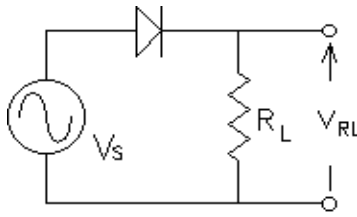
Rectification is the process of making DC from AC. Usually the AC is derived from the AC wall outlet (often through a transformer) and the DC is needed for electronic circuitry modeled by R_L here.
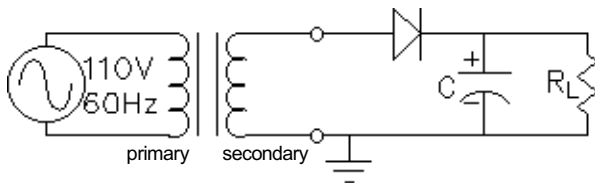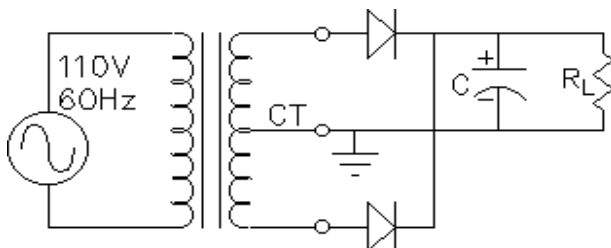

A "filter" capacitor (usually a big electrolytic) helps smooth out the bumps, although it sure looks like we could a bit bigger one here. The remaining bumpiness is called "ripple", V_r is peak-to-peak ripple
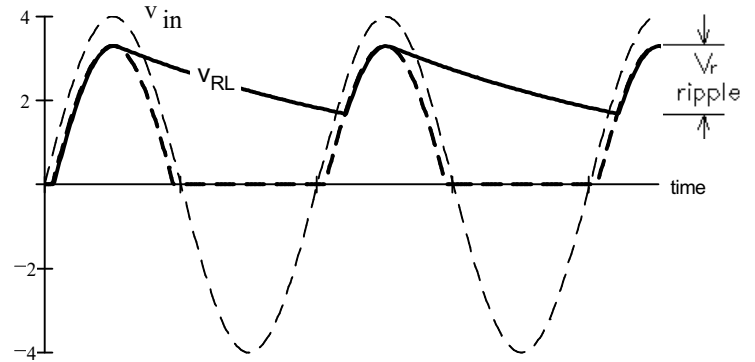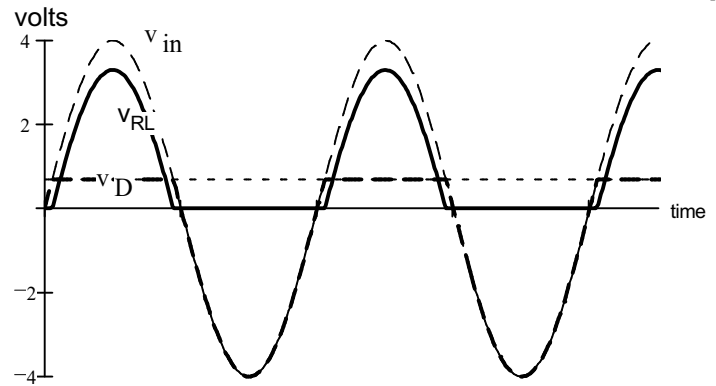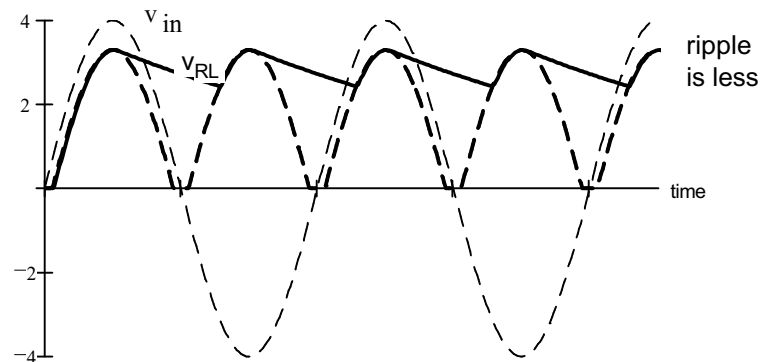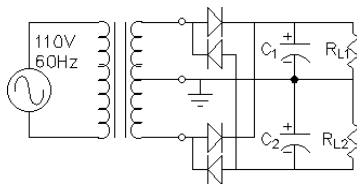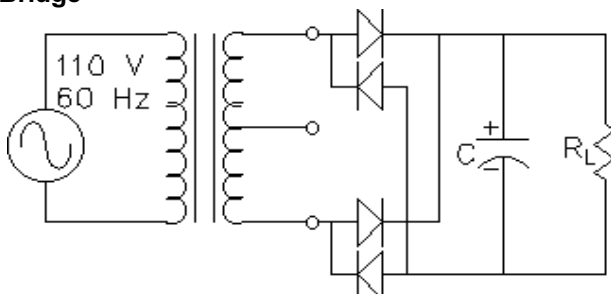
Full-wave rectification

The "center tap" in the secondary of this transformer makes it easy to get full-wave rectification.
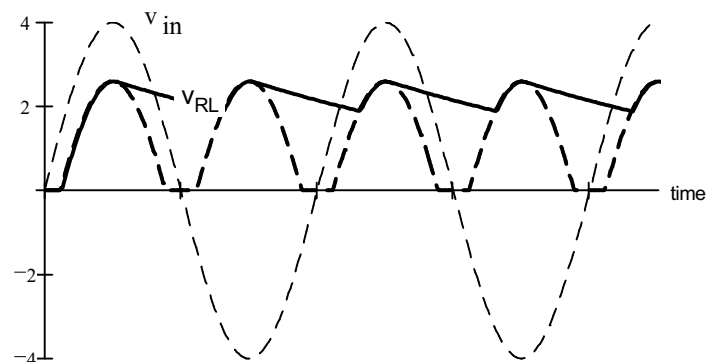

The center-tap transformer is also good for making $\pm$ supplies
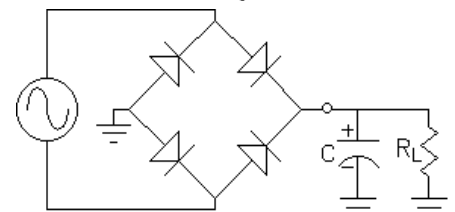

Bridge

A "bridge" circuit or "bridge rectifier" can give you full-wave rectification without a center-tap transformer, but now you loose another "diode drop"

Bridge rectifiers are often drawn like this:


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Zener Diodes

Zener diodes are special diodes designed to operate in the reverse breakdown region. Since the reverse breakdown voltage across the diode is very constant for a large range of current, it can be used as a voltage reference or regulator. Diodes are not harmed by operating in this region as long as their power rating isn't exceeded. In the forward direction zeners work the same as regular diodes.

V_Z = zener voltage
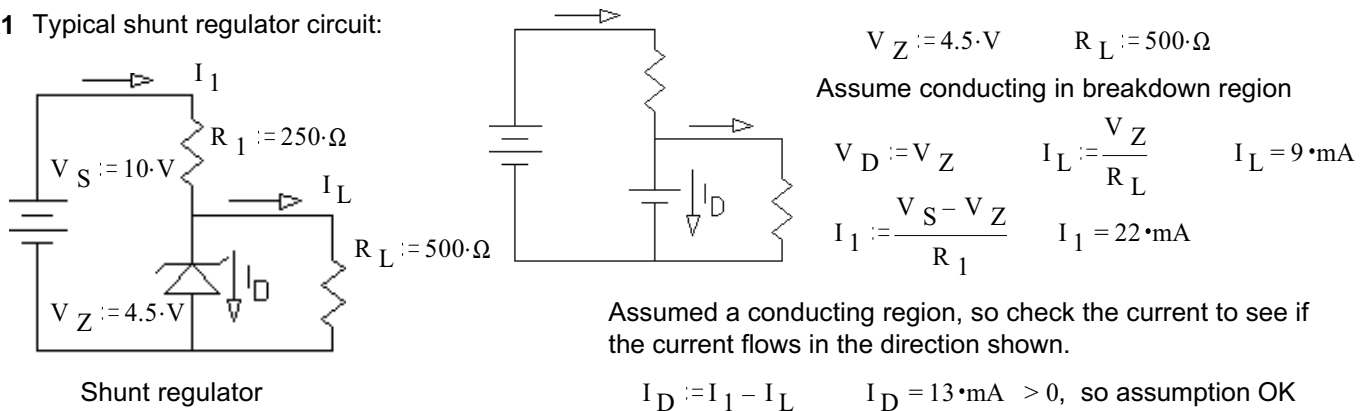
Now there are three possible regions of operation:

Same basic diode circuit analysis

1 Make an educated guess about each diode's state.

2 Replace each diode with the appropriate model:

3 Redraw and analyze circuit.

yes   NO   yes

4 Make sure that each diode is actually in the state you assumed:

$V_D = 0.7V$ $0.7V > V_D > V_Z$ V_Z
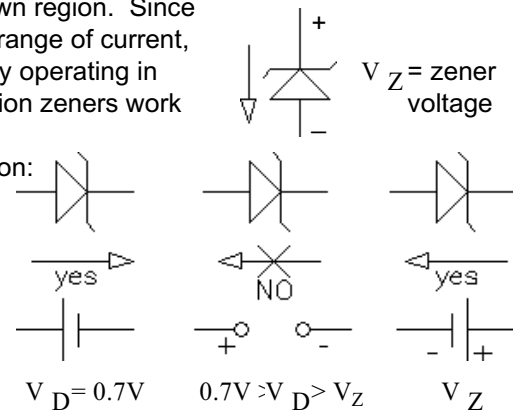
Zener Diode Circuit Examples

Ex1 Typical shunt regulator circuit:

$V_Z := 4.5 \cdot V$ $R_L := 500 \cdot \Omega$

Assume conducting in breakdown region

I_1

$R_1 := 250 \cdot \Omega$

$V_S := 10 \cdot V$

I_L

$R_L := 500 \cdot \Omega$

$V_Z := 4.5 \cdot V$

Shunt regulator

$V_D := V_Z$ $I_L := \dfrac{V_Z}{R_L}$ $I_L = 9 \cdot mA$

$I_1 := \dfrac{V_S - V_Z}{R_1}$ $I_1 = 22 \cdot mA$

Assumed a conducting region, so check the current to see if the current flows in the direction shown.

$I_D := I_1 - I_L$ $I_D = 13 \cdot mA \ > 0$, so assumption OK

Ex2 What if R_L is smaller? $R_L := 150 \cdot \Omega$

Assume conducting in breakdown region $V_D := V_Z$ $I_L := \dfrac{V_Z}{R_L}$ $I_L = 30 \cdot mA$

$I_1 := \dfrac{V_S - V_Z}{R_1}$ $I_1 = 22 \cdot mA$ $I_D := I_1 - I_L$ $I_D = -8 \cdot mA$ < 0, so assumption is **WRONG !**
                                                                        Circuit "falls out of regulation"

Assume not conducting

I_1

I_L

V_D

$I_L = I_1 := \dfrac{V_S}{R_1 + R_L}$ $I_1 = 25 \cdot mA$

Assumed a non-conducting region, so check the voltage to see if it's in the right range.

$V_D := \dfrac{R_L}{R_1 + R_L} \cdot V_S$ $V_D = 3.75 \cdot V < \ V_Z = 4.5 \cdot V$
                                                        so this assumption is OK

Ex3 What if V_S is smaller instead of R_L? $V_S := 6 \cdot V$ $R_L := 500 \cdot \Omega$

Assume conducting in breakdown region $V_D := V_Z$ $I_L := \dfrac{V_Z}{R_L}$ $I_L = 9 \cdot mA$

$I_1 := \dfrac{V_S - V_Z}{R_1}$ $I_1 = 6 \cdot mA$ $I_D := I_1 - I_L$ $I_D = -3 \cdot mA$ < 0, so assumption is **WRONG !**
                                                                        Circuit "falls out of regulation"

Assume not conducting $I_L = I_1 := \dfrac{V_S}{R_1 + R_L}$ $I_1 = 8 \cdot mA$

Assumed a non-conducting region, so check the voltage to see if it's in the right range. $V_D := \dfrac{R_L}{R_1 + R_L} \cdot V_S$ $V_D = 4 \cdot V < \ V_Z = 4.5 \cdot V$
                                                                        so this assumption is OK

Other Useful Diode Circuits

Simple limiter circuits can be made with diodes.
A common input protection to protect circuit from excessive input voltages
such as static electricity.

The input to the box marked "sensitive circuit" can't get higher than
the positive supply + 0.7V or lower than the negative supply - 0.7V.

Put a fuse in the V_{in} line and the diodes can make it blow, providing
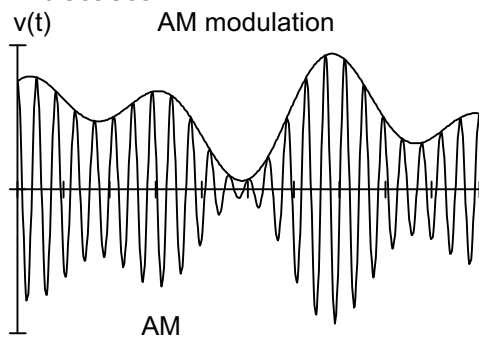what's known as "crowbar" protection.

Another example of crowbar protection:

   If the input voltage goes above 16 V. the fuse will
   blow, protecting the circuitry.

   Or, If the input voltage is hooked up backwards the
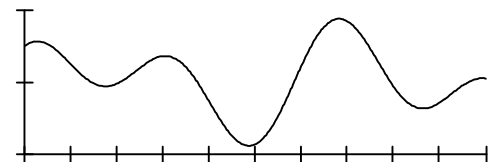   fuse will blow, protecting the circuitry.
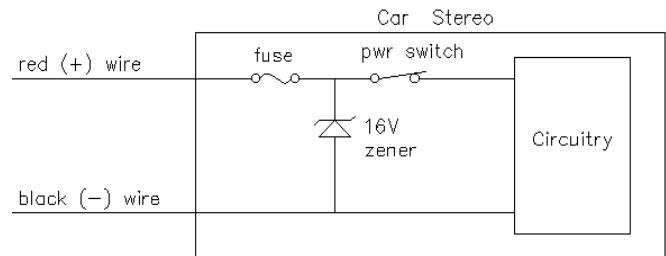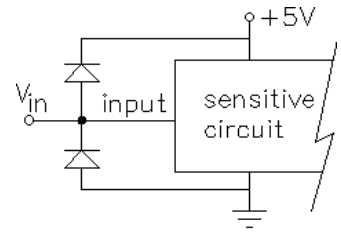
AM detector
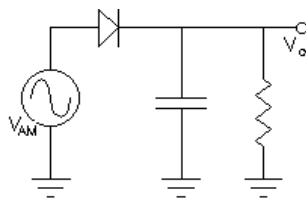
Battery Isolator

Like you might find in an RV. One alternator is used to charge two
batteries. When the alternator is **not** charging, the batteries, the
circuits they are hooked to should be isolated from one another. If
not, then one battery might discharge through the second,
especially if second is bad. Also, you wouldn't want the
accessories in the RV to drain the starting battery, or your uncle
George from South Dakota might never leave your driveway.
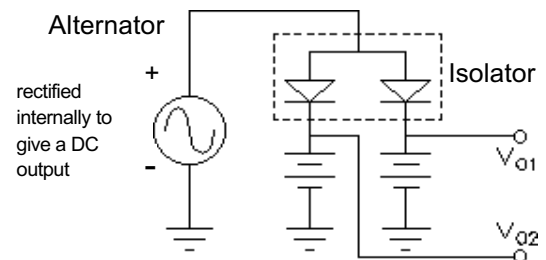
Battery Backup Power

Normally the power supply powers the load through D1.
However, if it fails, the load will remain powered by the
battery through D2. Finally, D3 and R may be added to
keep the battery charged when the power supply is
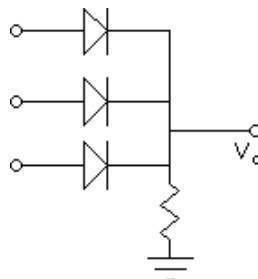working. These sorts of circuits are popular in hospitals.
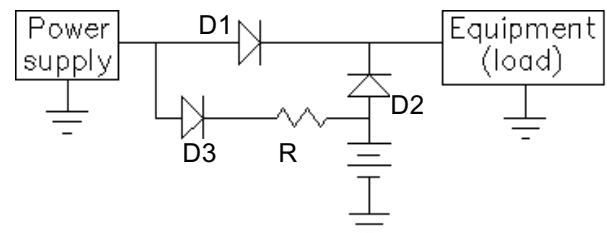
Diode Logic Circuits

Actually, both of the
previous circuits are logic
circuits as well.
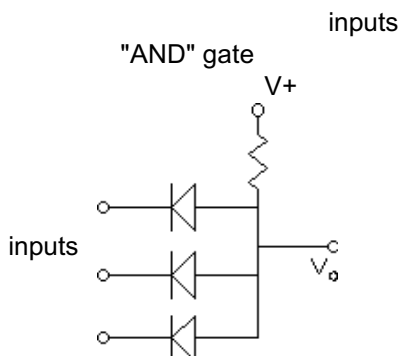
"Flyback" Diode

Every time the switch
opens the inductor current
continues to flow through
the diode for a moment. If
the diode weren't there,
then the current would arc
across the switch.