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.

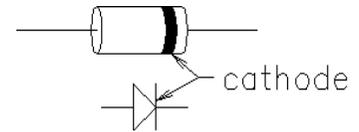Mechanical check valve   Diode

silicon diode   LED
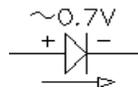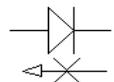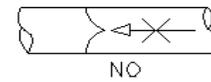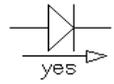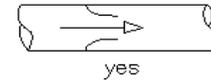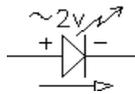
cathode

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.

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.

1. Assume the diode is operating in one of the linear regions (make an educated guess).

2. Analyze circuit with a linear model of the diode.

3. Check to see if the diode was really in the assumed region.
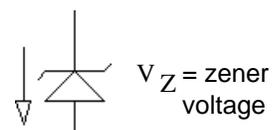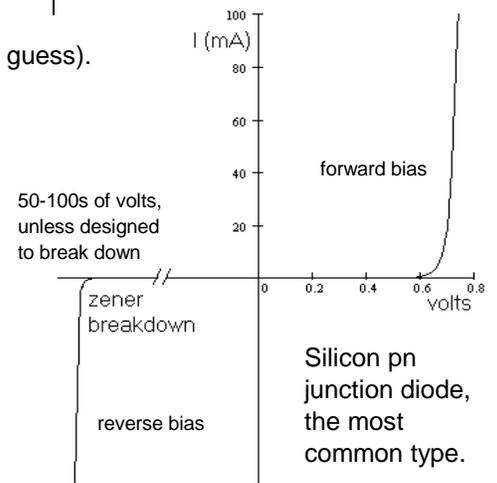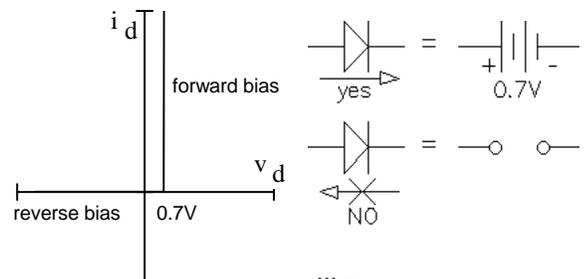
4. Repeat if necessary.

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.

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

Basic Diode DC 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.

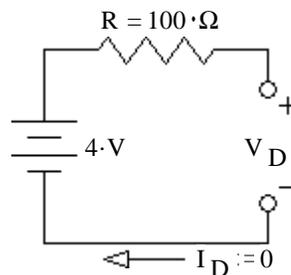4. Make sure that each diode is actually in the state you assumed:

   $V_D < 0.7V$ Check
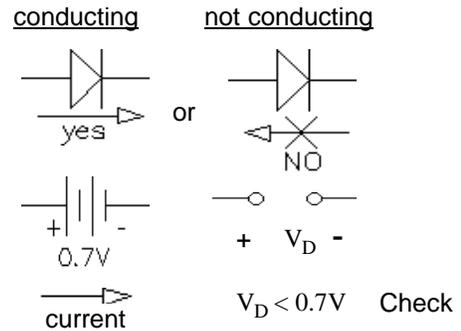
   Note: $0.7V$ is for silicon junction diodes & is different for other types. (2V for LED)

5. 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 2ⁿ possible states, all of which may have to be tried
   until you find the right one. Try to guess right the first time.
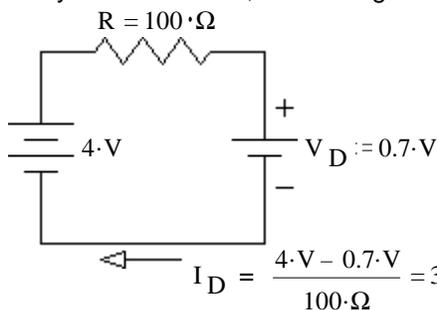
Ex. 1 $R := 100 \cdot \Omega$
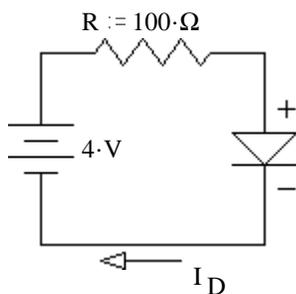
Try reverse-biased, nonconducting model
(Bad choice but done here to illustrate method)

$R = 100 \cdot \Omega$

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

$I_D := 0$

Try forward-biased, conducting model

$R = 100 \cdot \Omega$

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

$I_D = \dfrac{4 \cdot V - 0.7 \cdot V}{100 \cdot \Omega} = 33 \cdot mA \ > 0$ The current *is* in the forward direction,
confirming the assumption.

Ex. 2 $R := 100 \cdot \Omega$
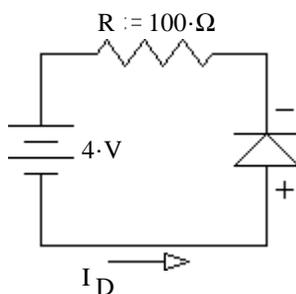
Try forward-biased, conducting model
(Bad choice but done here to illustrate method)

$R = 100 \cdot \Omega$

$4.7 \cdot V$

$4 \cdot V$ $V_D := 0.7 \cdot V$
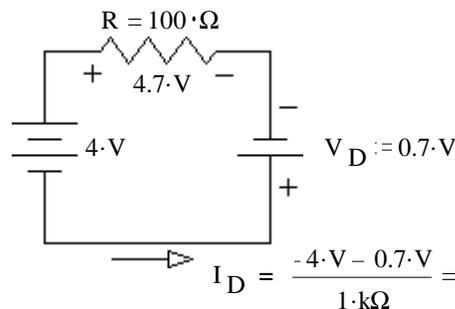
$I_D = \dfrac{-4 \cdot V - 0.7 \cdot V}{1 \cdot k\Omega} = -4.7 \cdot mA < 0$ Doesn't work, diode
must be reverse biased.

Try reverse-biased,
nonconducting model

$R = 100 \cdot \Omega$
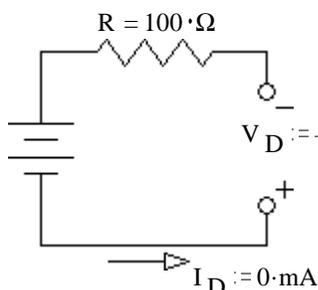
Check the diode voltage

$V_D := -4 \cdot V \ < \ 0.7V$ Confirms diode *is* reverse biased

$I_D := 0 \cdot mA$

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Ex. 3

Try reverse-biased, nonconducting model

$V_D = 12 \cdot V - 2 \cdot V = 10 \cdot V > 0.7\ V$ Doesn't work, diode must be forward biased.

$R = 300 \cdot \Omega$
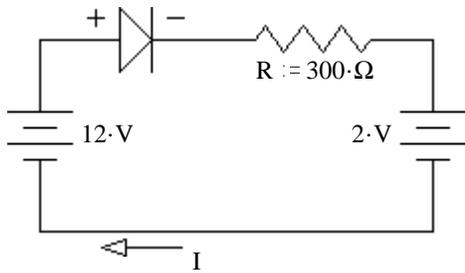
$12 \cdot V$ $2 \cdot V$

Try forward-biased, conducting model

$V_D := 0.7 \cdot V$ $V_R = 12 \cdot V - 2 \cdot V - V_D = 9.3 \cdot V$
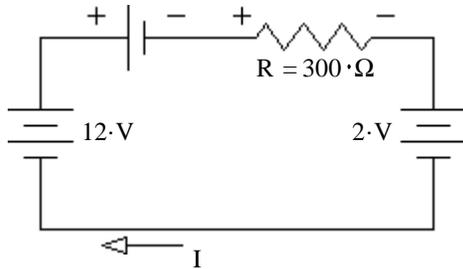
$R = 300 \cdot \Omega$

$12 \cdot V$ $2 \cdot V$
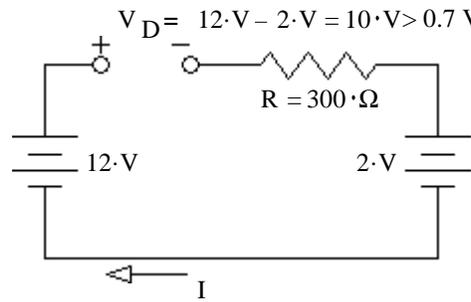
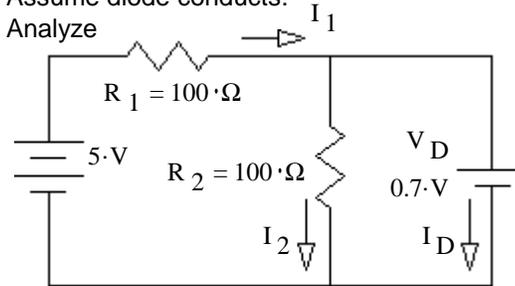Check the diode current $I = \dfrac{9.3 \cdot V}{R} = 31 \cdot mA > 0$

Confirms diode is forward biased

In each of these examples so far, my first guess was pretty stupid. I did that intentionally to show the process.
I suspect that you can make better guesses and thus save yourself some work.

Ex. 4
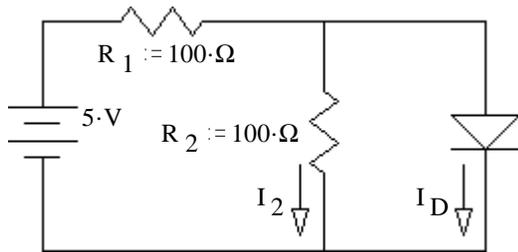
Assume diode conducts:
Analyze

$R_1 = 100 \cdot \Omega$

$5 \cdot V$ $R_2 = 100 \cdot \Omega$ V_D $0.7 \cdot V$

$V_{R1} := 5 \cdot V - V_D$
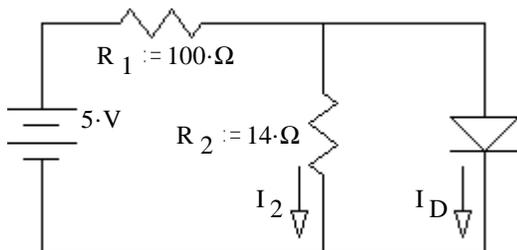$V_{R1} = 4.3 \cdot V$

$I_1 := \dfrac{V_{R1}}{R_1}$

$I_1 = 43 \cdot mA$

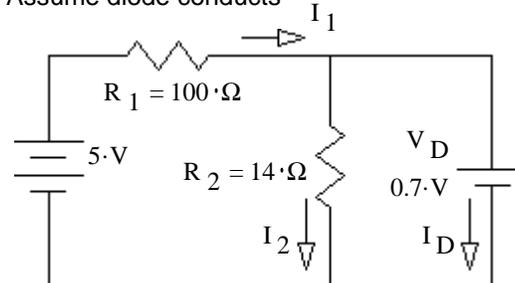$V_{R2} := V_D$ $I_2 := \dfrac{V_{R2}}{R_2}$ $I_2 = 7 \cdot mA$

We assumed conducting (assuming a voltage),
so check the current: $I_D = I_1 - I_2 = 36 \cdot mA > 0$, so assumption was correct

Ex. 5 Same circuit again, but with smaller R_2

Assume diode conducts

$R_1 = 100 \cdot \Omega$

$5 \cdot V$ $R_2 = 14 \cdot \Omega$ V_D $0.7 \cdot V$

$V_{R1} := 5 \cdot V - V_D$
$V_{R1} = 4.3 \cdot V$

$I_1 := \dfrac{V_{R1}}{R_1}$

$I_1 = 43 \cdot mA$

$V_{R2} := V_D$ $I_2 := \dfrac{V_{R2}}{R_2}$ $I_2 = 50 \cdot mA$

$I_D = I_1 - I_2 = -7 \cdot mA$ < 0, so assumption was **WRONG !**

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Try again with diode not conducing

$$R_1 = 100 \cdot \Omega$$

$$5 \cdot V$$

$$R_2 = 14 \cdot \Omega$$

$$I_2 \qquad I_D := 0 \cdot mA \qquad I_2 := \frac{5 \cdot V}{R_1 + R_2}$$
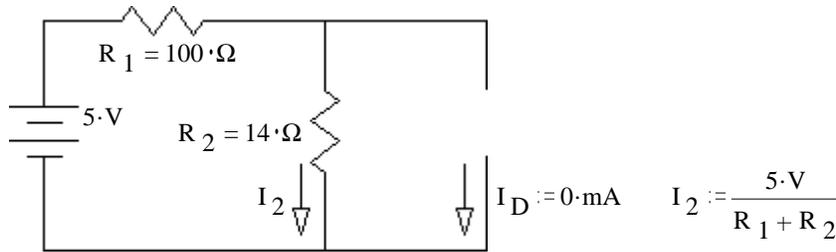
We assumed not conducting (assuming a current),

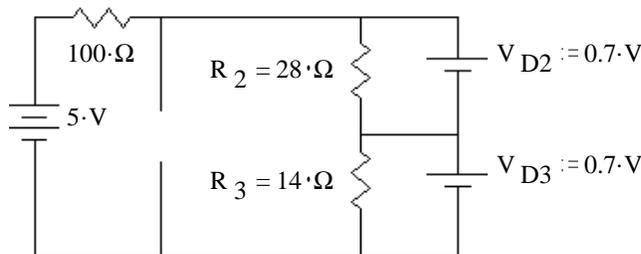so check the voltage: $\quad V_{R2} := I_2 \cdot R_2 \qquad V_{R2} = 0.614 \cdot V \quad < 0.7 \text{ V, so assumption was correct.}$

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

Ex. 6

$$R_1 := 100 \cdot \Omega$$

$$I_1$$
$$V_S := 5 \cdot V \qquad R_2 := 28 \cdot \Omega$$
$$I_2 \qquad I_{D2}$$
$$I_{D1} \qquad R_3 := 14 \cdot \Omega$$
$$I_3 \qquad I_{D3}$$
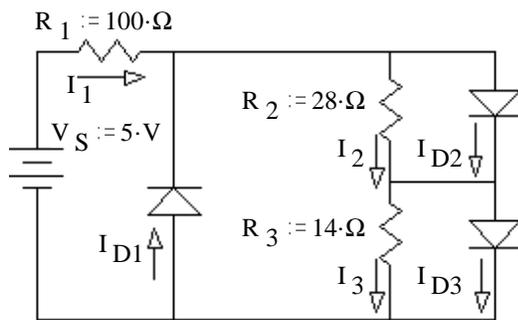
You can safety say that diode D_1 doesn't conduct without rechecking later because no supply is even trying to make current flow through that diode the right way.

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

$$100 \cdot \Omega$$
$$R_2 = 28 \cdot \Omega \qquad V_{D2} := 0.7 \cdot V$$
$$5 \cdot V$$
$$R_3 = 14 \cdot \Omega \qquad V_{D3} := 0.7 \cdot V$$

$$V_{R1} = 3.6 \cdot V \qquad I_1 := \frac{V_{R1}}{R_1} \qquad I_1 = 36 \cdot mA$$

$$I_2 := \frac{V_{D2}}{R_2} \qquad I_2 = 25 \cdot mA$$
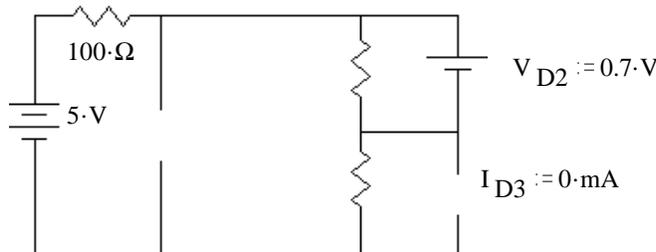
$$I_3 := \frac{V_{D3}}{R_3} \qquad I_3 = 50 \cdot mA$$

We assumed D_1 & D_2 conduct (assumed a voltage), $I_{D2} = I_1 - I_2 = 11 \cdot mA \qquad > 0, \text{ so assumption OK}$

so check currents: $I_{D3} = I_1 - I_3 = -14 \cdot mA \qquad < 0, \text{ so assumption is } \textbf{wrong}$

_____

Assume D_2 conducts and D_3 doesn't.   Analyze

$$100 \cdot \Omega$$
$$5 \cdot V$$

$$V_{D2} := 0.7 \cdot V \qquad I_2 := \frac{V_{D2}}{R_2} \qquad I_2 = 25 \cdot mA$$

$$I_{D3} := 0 \cdot mA \qquad I_3 = I_1 := \frac{V_S - V_{D2}}{R_1 + R_3} \qquad I_1 = 37.72 \cdot mA$$

Assumed D_2 conducts, so check D_2 current: $I_{D2} = I_1 - I_2 = 12.72 \cdot mA \quad > 0, \text{ so assumption OK}$

Assumed D_3 doesn't conduct, so check D_3 voltage: $V_{R3} := I_1 \cdot R_3 \qquad V_{R3} = 0.528 \cdot V \quad < 0.7 \text{ V, so OK}$

Once you find a case that works, you don't have to try any others.

LEDs (**L**ight - **E**mitting **D**iodes)

An LED has a higher voltage drop when forward biased, more like $2V$ for red, yellow or green LEDs, even more for blue or white (often well over $3V$). In this class we'll assume $2V$ for all LEDs.
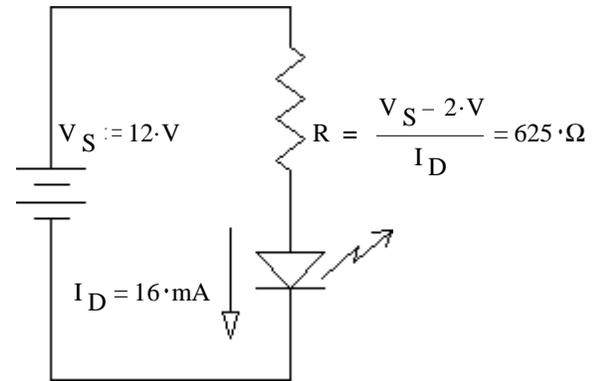
The symbol for an LED is like a regular diode but with one or more arrows that represent the light emission.
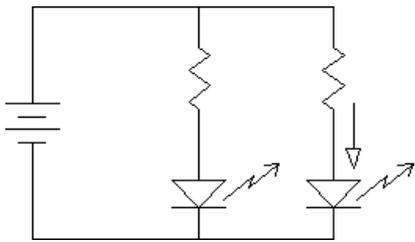
$\sim 2v$

Light
Emitting
Diode
LED

cathode
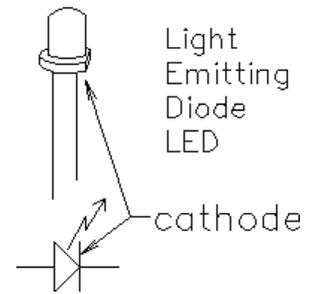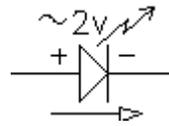
As a simple rule-of-thumb, you usually want between 10 and 20 mA of current for decent light.
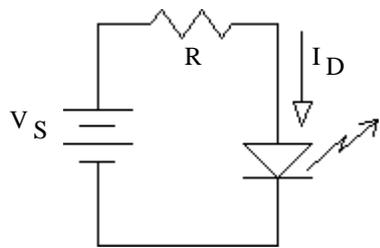
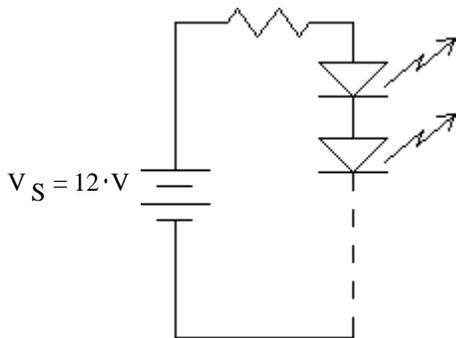For example, in a car, you might design for: $I_D := 16 \cdot mA$

$V_S := 12 \cdot V$

$R = \dfrac{V_S - 2 \cdot V}{I_D} = 625 \cdot \Omega$

$I_D = 16 \cdot mA$

For more lights, you might do this: OR:

R

$500 \cdot \Omega$

$V_S = 12 \cdot V$ $I_D = 16 \cdot mA$

$R := \dfrac{V_S - 2 \cdot (2 \cdot V)}{I_D}$ $R = 500 \cdot \Omega$
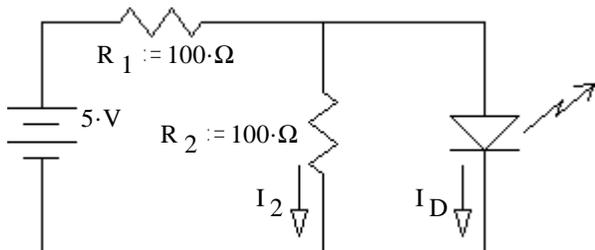
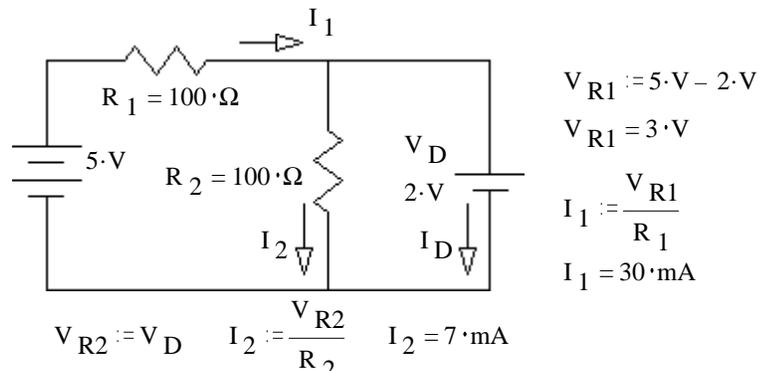$V_S = 12 \cdot V$
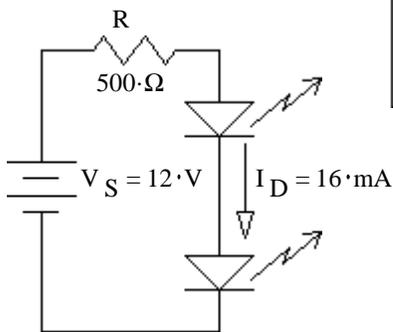
How many LEDs could you place in series?

You may be tempted to say 6, but that would be unwise for two reasons:

1. $2V$ forward drop is not all that accurate and even a small difference in the voltage across a diode can make a huge difference in the current.

2. If the $12V$ is for a car, then it's not all that accurate either
   At times it could go as high as $14.5V$.

**Ex.** Similar to earlier example, but now with an LED

$R_1 := 100 \cdot \Omega$

$5 \cdot V$ $R_2 := 100 \cdot \Omega$

I_2 I_D

Assuming conduction:

I_1

$R_1 = 100 \cdot \Omega$

$5 \cdot V$ $R_2 = 100 \cdot \Omega$ V_D $2 \cdot V$

I_2 I_D

$V_{R1} := 5 \cdot V - 2 \cdot V$

$V_{R1} = 3 \cdot V$

$I_1 := \dfrac{V_{R1}}{R_1}$

$I_1 = 30 \cdot mA$

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

Check the current: $I_D = I_1 - I_2 = 23 \cdot mA > 0$, so assumption was correct

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.
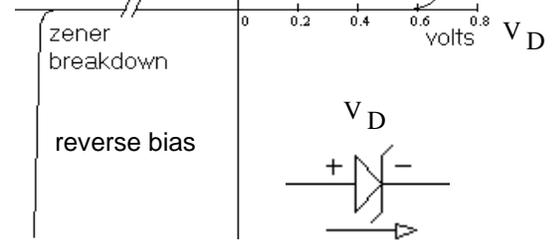
zener breakdown voltage = V_Z
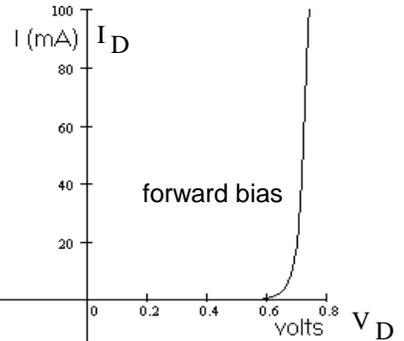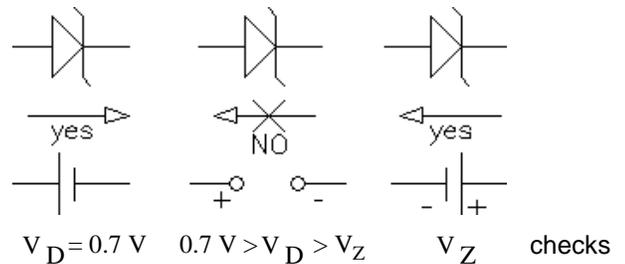
The symbol for a zener diode
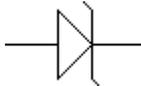
note how the cathode line is
modified to look a little like a "Z"

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.

4. Make sure that each diode is actually in the state you assumed: $V_D = 0.7\,V$ $0.7\,V > V_D > V_Z$ V_Z checks

yes   NO   yes

Zener diodes are often used in voltage regulation circuits. The objective of a voltage regulator is to provide a constant voltage to a load even when the load changes or supply voltage changes. Real voltage regulators can only maintain regulation for a limited range of load current (or load resistance) and for a limited range of supply voltages.
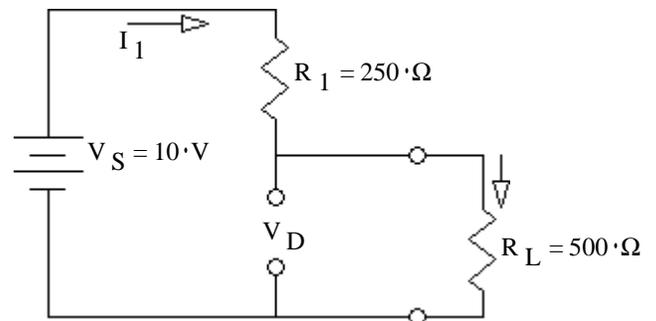
The simplest type of voltage regulator is the "shunt regulator", covered below. In more complicated regulator circuits the zener is only used as a reference voltage and is not directly connected to the load.

Zener Diode Circuit Examples

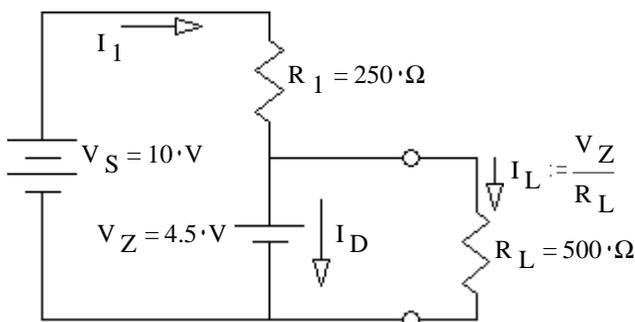**Ex. 1** Typical shunt regulator circuit:

Assume not conducting

Assume conducting in breakdown region
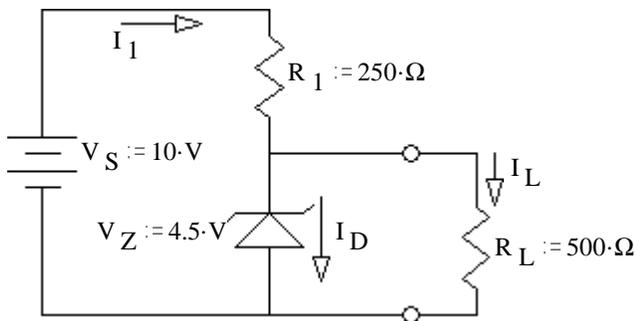
$$I_L := \frac{V_Z}{R_L} \qquad I_L = 9\,mA \qquad I_1 := \frac{V_S - V_Z}{R_1} \qquad I_1 = 22\,mA$$

$$V_D = V_S \cdot \frac{R_L}{R_1 + R_L} = 6.67\,V > \quad V_Z = 4.5\,V$$

so assumption is **wrong**

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

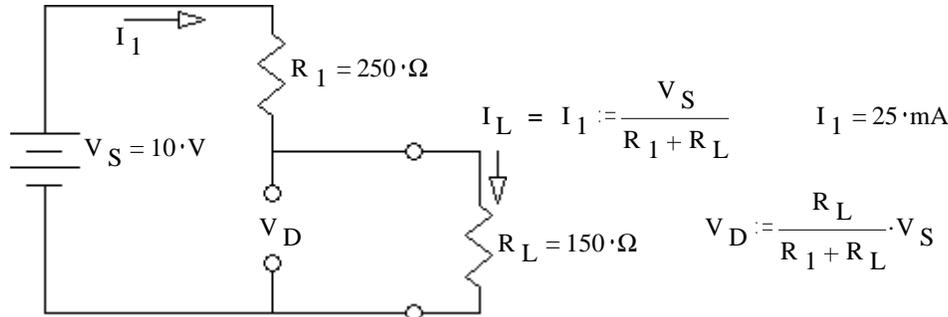$$I_D = I_1 - I_L = 13\,mA \; > 0, \text{ so assumption OK}$$

Ex. 2 What if R_L is smaller? $R_L := 150 \cdot \Omega$
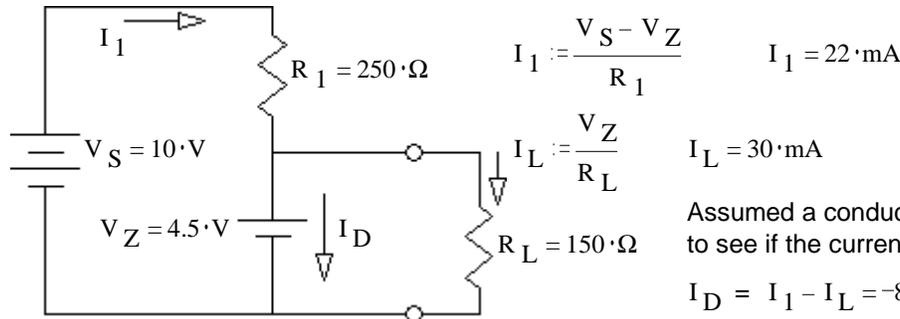
$R_1 = 250 \cdot \Omega$

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

$V_S = 10 \cdot V$

$I_L := \dfrac{V_Z}{R_L}$ $I_L = 30 \cdot mA$

$V_Z = 4.5 \cdot V$ I_D $R_L = 150 \cdot \Omega$

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

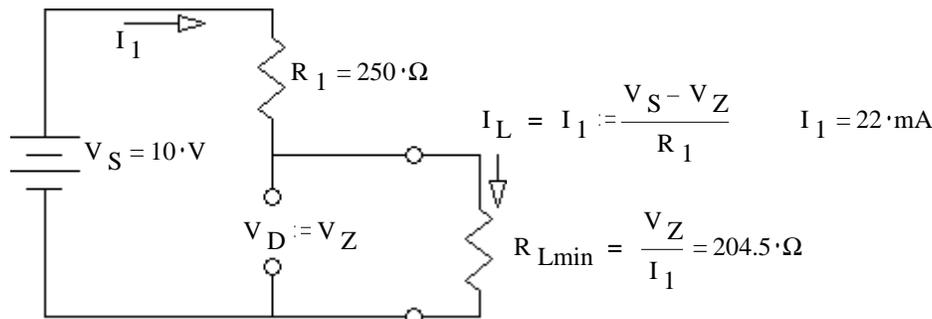$I_D = I_1 - I_L = -8 \cdot mA < 0$, so assumption is **WRONG !**

Assume not conducting   Circuit "falls out" of regulation

$R_1 = 250 \cdot \Omega$

$V_S = 10 \cdot V$

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

V_D $R_L = 150 \cdot \Omega$ $V_D := \dfrac{R_L}{R_1 + R_L} \cdot V_S$

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

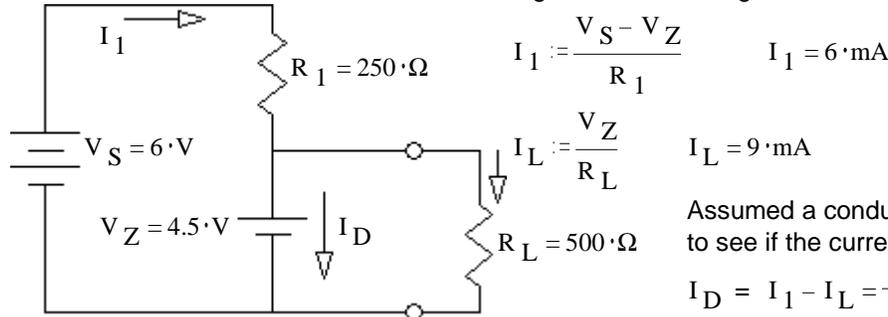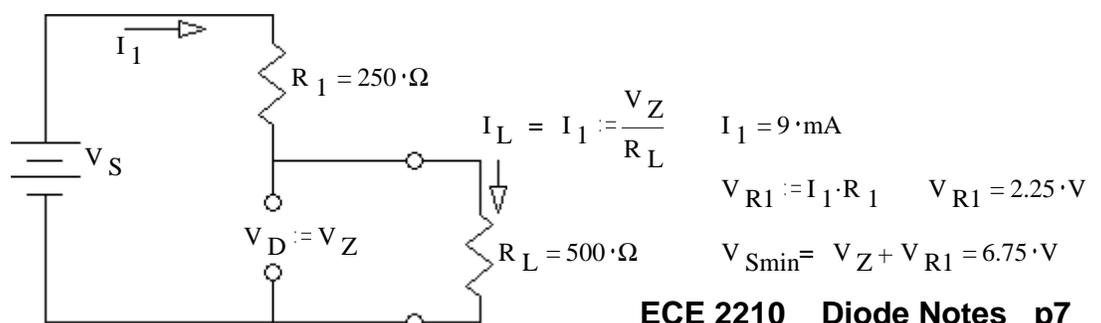$V_D = 3.75 \cdot V < V_Z = 4.5 \cdot V$

so this assumption is OK

How small can R_L be and still maintain regulation?
 Assume both nonconducting AND $V_D = V_Z$ at the same time.

$R_1 = 250 \cdot \Omega$

$V_S = 10 \cdot V$

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

$V_D := V_Z$

$R_{Lmin} = \dfrac{V_Z}{I_1} = 204.5 \cdot \Omega$

Ex. 3 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

$R_1 = 250 \cdot \Omega$

$I_1 := \dfrac{V_S - V_Z}{R_1}$ $I_1 = 6 \cdot mA$

$V_S = 6 \cdot V$

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

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

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

$I_D = I_1 - I_L = -3 \cdot mA < 0$, so assumption is **WRONG !**

How small can V_S be and still maintain regulation?

 Assume both non-conduction AND $V_D = V_Z$ at the same time.

V_S

$R_1 = 250 \cdot \Omega$

$I_L = I_1 := \dfrac{V_Z}{R_L}$ $I_1 = 9 \cdot mA$

$V_D := V_Z$ $R_L = 500 \cdot \Omega$

$V_{R1} := I_1 \cdot R_1$ $V_{R1} = 2.25 \cdot V$

$V_{Smin} = V_Z + V_{R1} = 6.75 \cdot V$

Rectifier Circuits & Power Supplies

Electronic circuits all work on DC power, yet we would often like to use AC power from an outlet to run them. A very common type of "power supply" is a device or circuit which converts AC input power to DC power, usually at a lower voltage. You are certainly familiar with power supplies for laptops and phones, but other devices, like audio amplifiers, monitors and TVs that plug directly into AC sockets, have built-in power supplies. Most modern power supplies are more complex than the ones I will show here, but still incorporate some of the same parts and concepts.

In the circuits below, I assume the input is sinusoidal AC and the desired output is DC. Where the DC output voltage is lower than the AC input, a transformer can be used on the AC side to first lower the AC voltage. Diodes are used as "rectifiers", allowing current to flow in only one direction and converting the AC to DC.
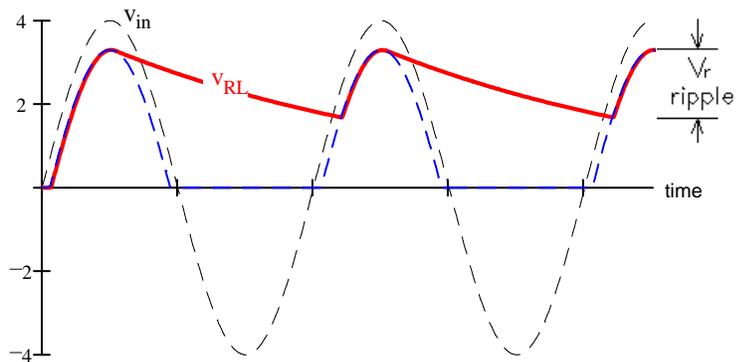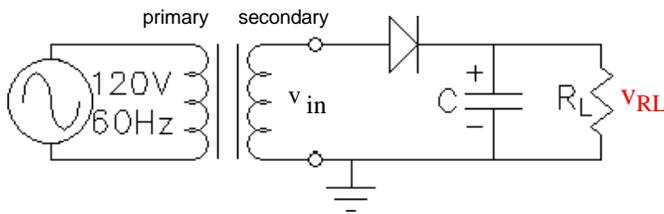
Half-wave rectification
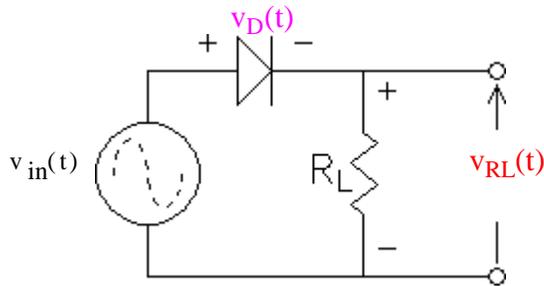
I show the input as a dashed line so it's easier to see the other waveforms.

R_L is the load and may actually be far more than just a resistor
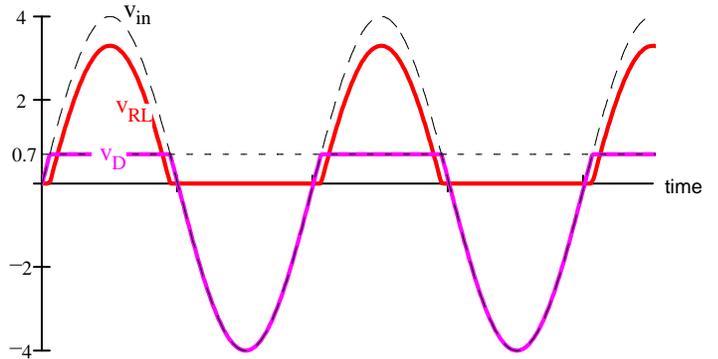
V_{RL} is now DC, although a bit bumpy. Some things are better if they're bumpy, but not roads and not DC voltages.

Usually the AC is derived from the AC wall outlet (often through a transformer) and a capacitors are used to smooth out the bumps.
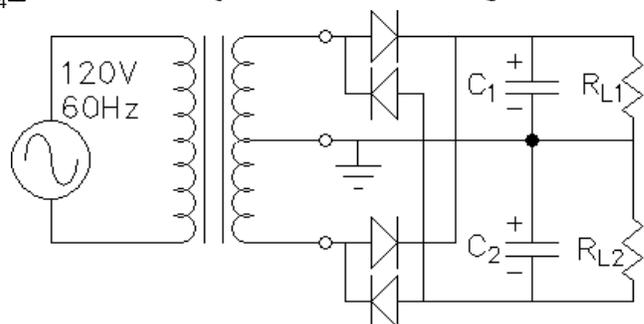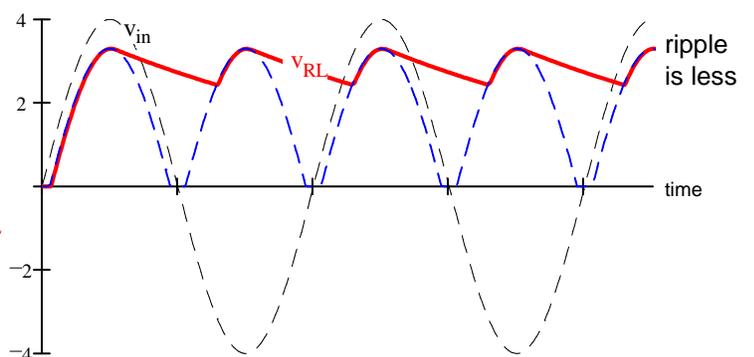
primary   secondary

Full-wave rectification

If the negative half of the input is also used, then it's called "full-wave" rectification. The "center tap" in the secondary of this transformer makes it easy to get full-wave rectification.
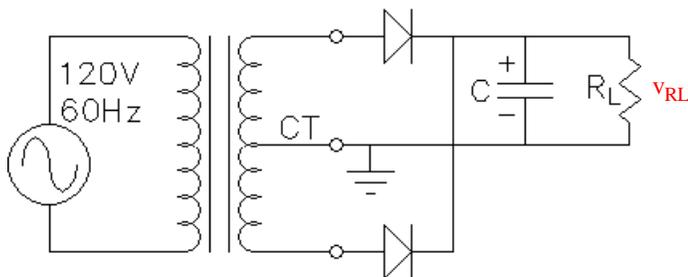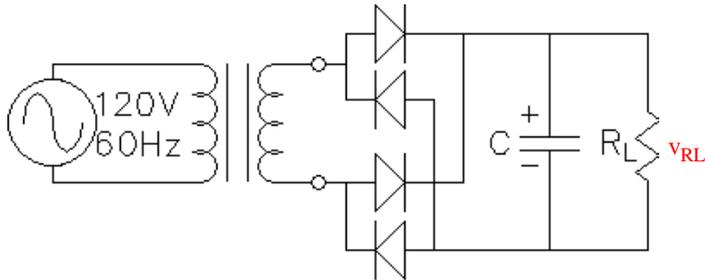
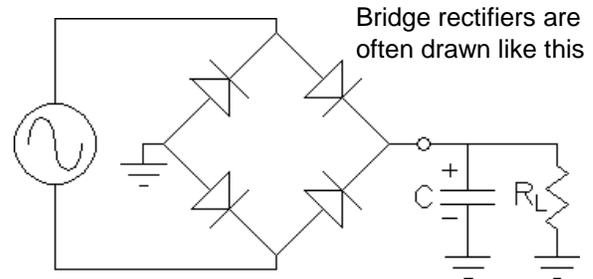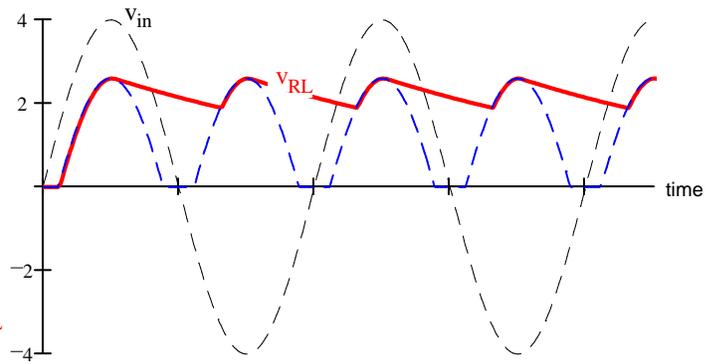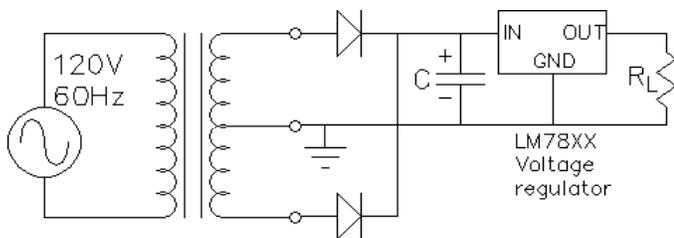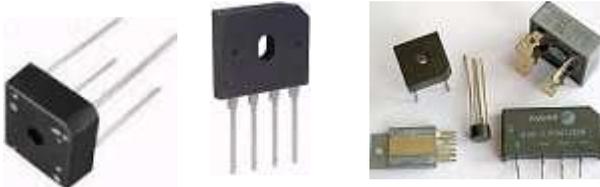The center-tap transformer is also good for making $\pm$ supplies

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"

The four diodes of a bridge rectifier are often packaged in a
single package.

Bridge rectifiers are
often drawn like this

In all of these power supplies a
three-terminal voltage regulator
may be used to further regulate
and smooth out the DC voltage.

So clearly, it is important to understand how diodes work in AC circuits.

Diode AC Circuit Analysis

1. Replace the diode with an open (nonconducting model) and redraw the circuit.

2. Determine the waveform across the open.

3. Compare that waveform to the conduction-region voltage of the diode (typically $0.7V$) to determine time region(s)
   when the diode will conduct.

4. Draw the "output" waveform for non-conduction times using the circuit drawing made in step 1.

5. Draw the circuit with the conducting diode model and draw the "output" waveform for conduction times. Usually you
   start by determining the output when the input is at a peak value and then follow-up by filling in between there and the
   conducting waveform section(s) you've already drawn.

Triangular Waveforms

My examples and problems use input waveforms
made of straight lines and triangular pieces. I do
this to make the waveforms easier to draw. It also
makes it easier to determine the times when
important events occur.

Real waveforms are almost never triangular !!

It's just that many of us are not very good at
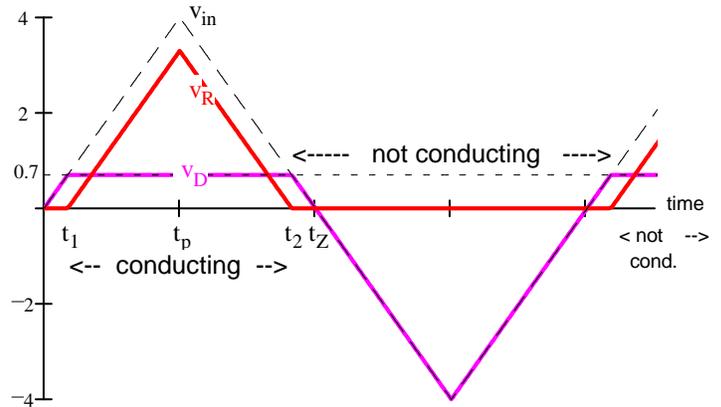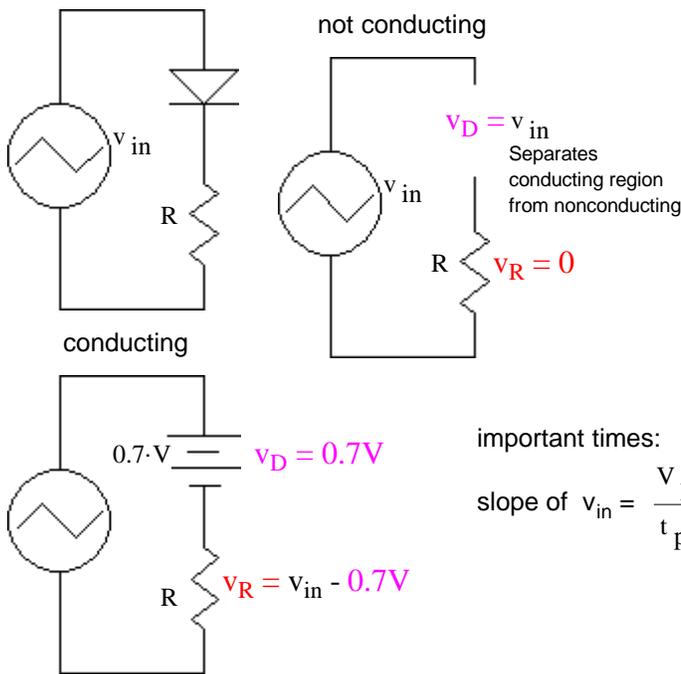drawing sine waves and partial sine waves.

Input waveforms are drawn as dashed lines so
that we can draw over them.
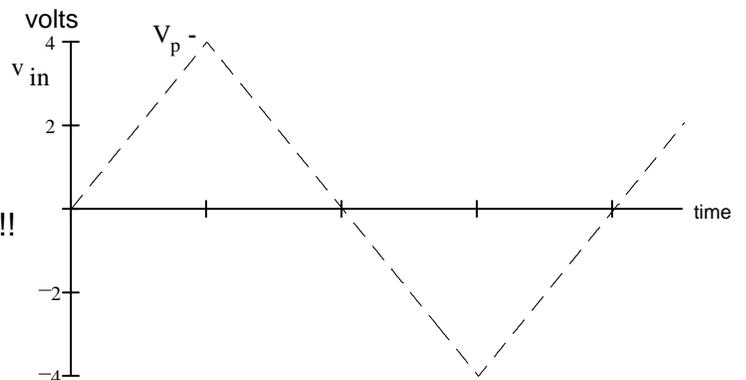
The input for the next 2 examples

Ex. 1 The first example is very similar to the Half-wave rectifier you saw earlier, only the resulting waveforms are easier to draw because they consist of simple straight lines.

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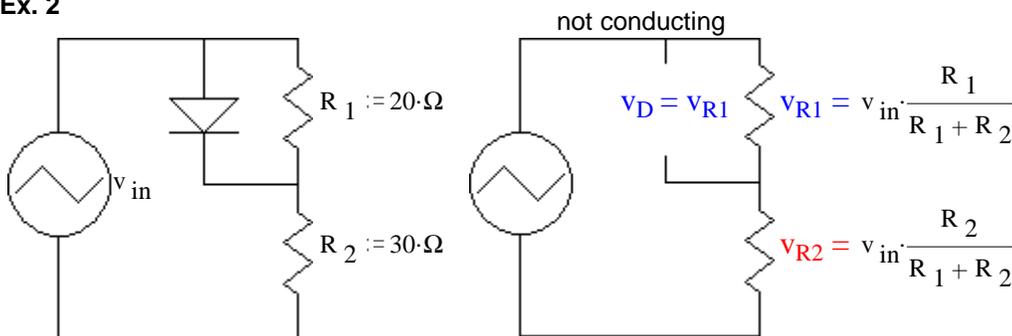
not conducting

$v_D = v_{in}$
Separates conducting region from nonconducting

$v_R = 0$

conducting

$v_D = 0.7V$

$v_R = v_{in} - 0.7V$

important times:

slope of $v_{in} = \dfrac{V_p}{t_p} = \dfrac{0.7 \cdot V}{t_1}$ $t_1 = \dfrac{0.7 \cdot V}{V_p} \cdot t_p$ $t_2 = t_z - t_1$

Ex. 2

not conducting

$R_1 := 20 \cdot \Omega$

$R_2 := 30 \cdot \Omega$

$v_D = v_{R1}$ $v_{R1} = v_{in} \cdot \dfrac{R_1}{R_1 + R_2}$ dashed line below that peaks at:

$$4 \cdot V \cdot \dfrac{20 \cdot \Omega}{20 \cdot \Omega + 30 \cdot \Omega} = 1.6 \cdot V$$

$v_{R2} = v_{in} \cdot \dfrac{R_2}{R_1 + R_2}$

conducting

$0.7 \cdot V$ $v_{R1} = v_D = 0.7V$

$v_{R2} = v_{in} - 0.7V$

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

$t_2 = t_z - t_1$
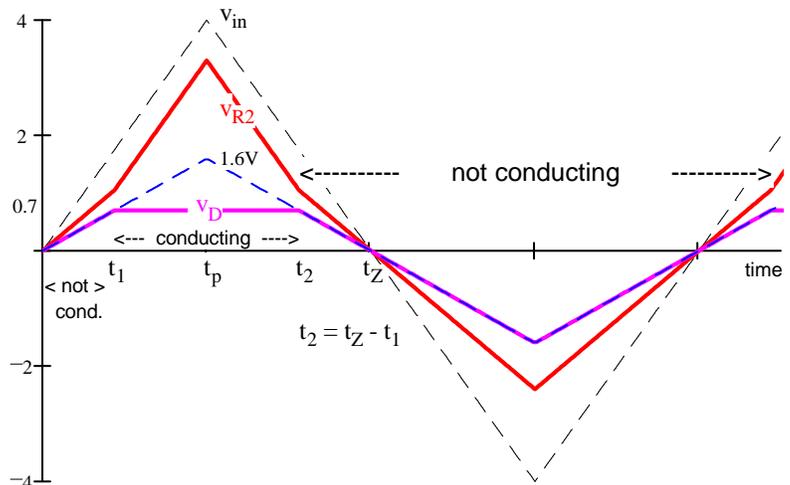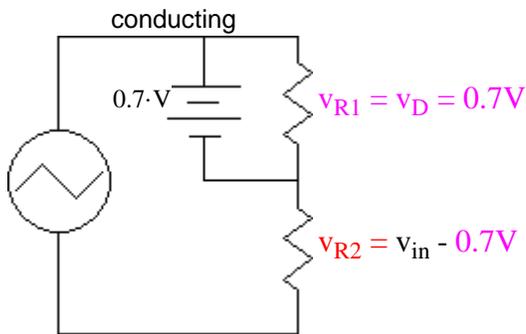
Other Useful Diode Circuits

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.
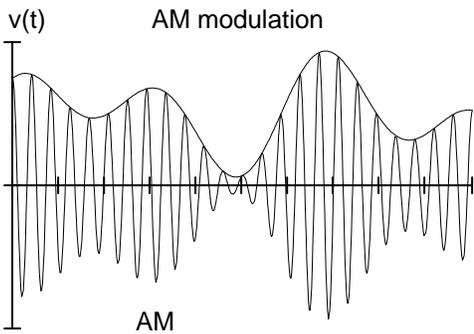
Another example of crowbar protection:

> If the input voltage goes above 16 V. the fuse will blow, protecting the circuitry.
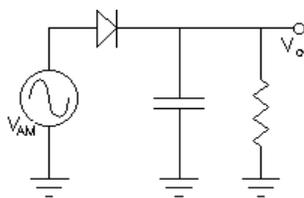
> Or, If the input voltage is hooked up backwards the fuse will blow, protecting the circuitry.
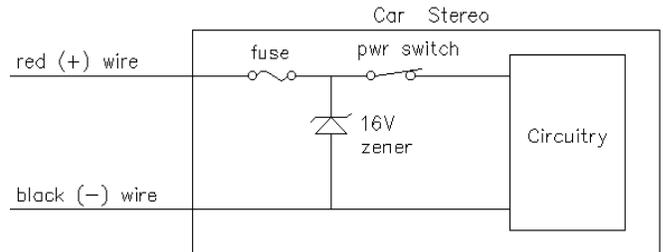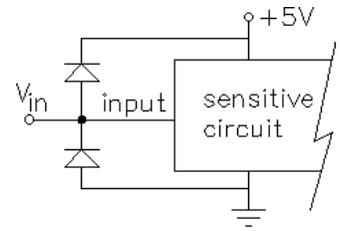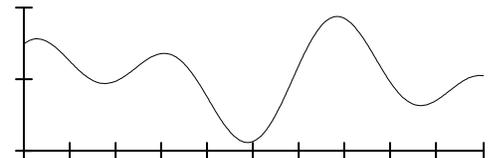
AM detector

A simple rectifier circuit

Returns the modulation signal

And a coupling capacitor can remove the DC

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 and 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.
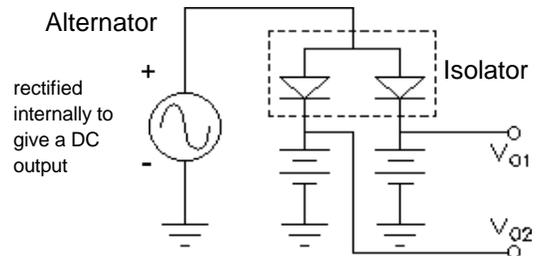
Battery Backup Power

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.
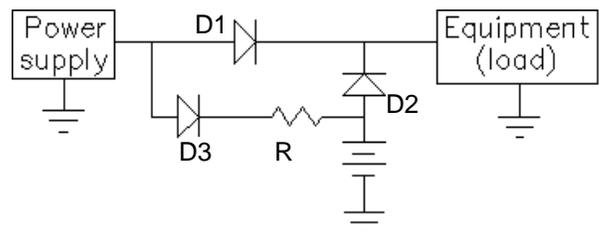
Diode Logic Circuits

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

"OR" gate
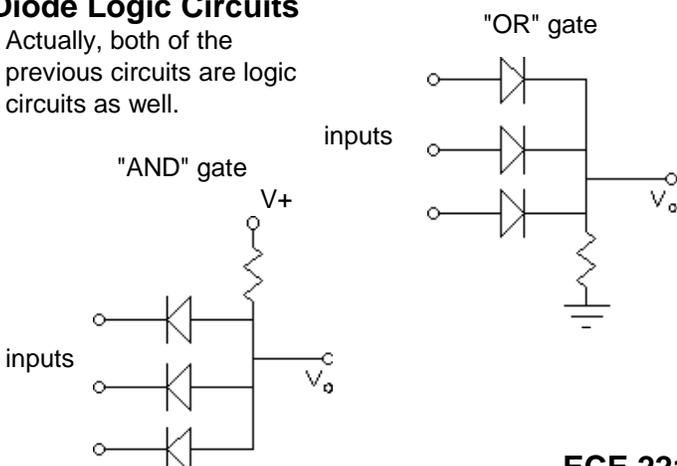
"Flyback" Diode

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.