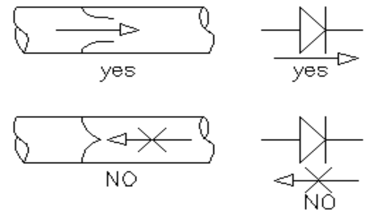
Diodes Notes

ECE 2210

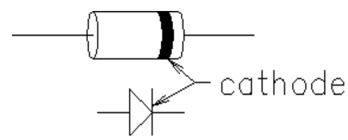
A. Stolp
4/8/03,
2/27/07

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



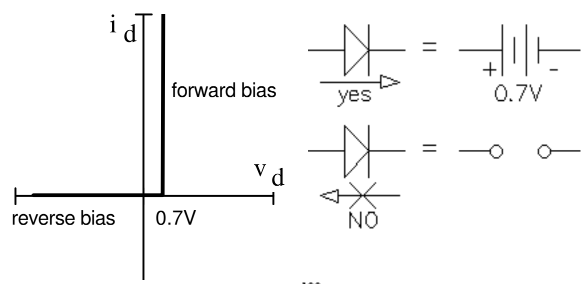
The electrical symbol for a diode looks like an arrow which shows the forward current direction and a small perpendicular line. The two sides of a diode are called the "anode" and the "cathode" (these names come from vacuum tubes). Most small diodes come in cylindrical packages with a band on one end 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.

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.

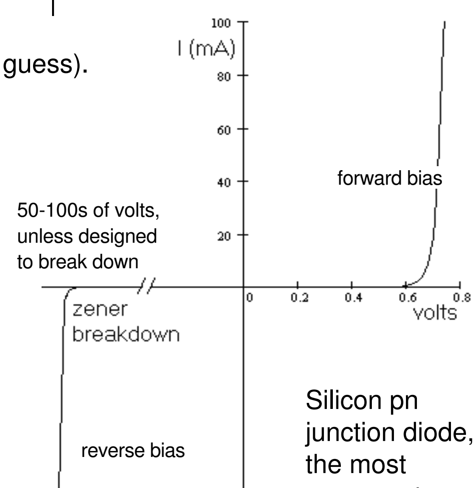


1 Assume the diode is operating in one of the linear regions (make an educated guess).

2 Analyze circuit with a linear model od the diode.

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

4 Repeat if necessary.

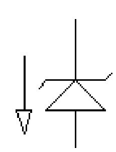


Silicon pn junction diode, the most common type.

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.

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.

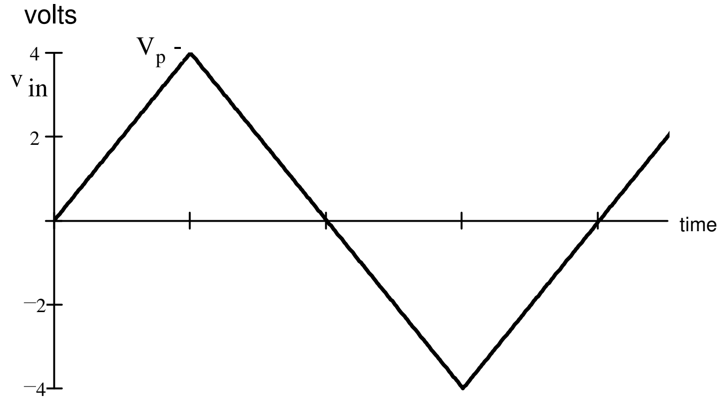


V_Z = zener voltage

I recommend that you try some of the DC analysis in the Diode Circuit Examples handout before you proceed here.

Diodes in AC Circuits

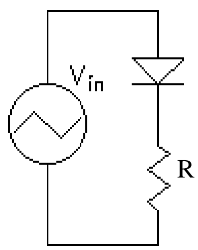
Diodes are often used to manipulate AC waveforms. We' ll start with some triangular waveforms to get the general idea.

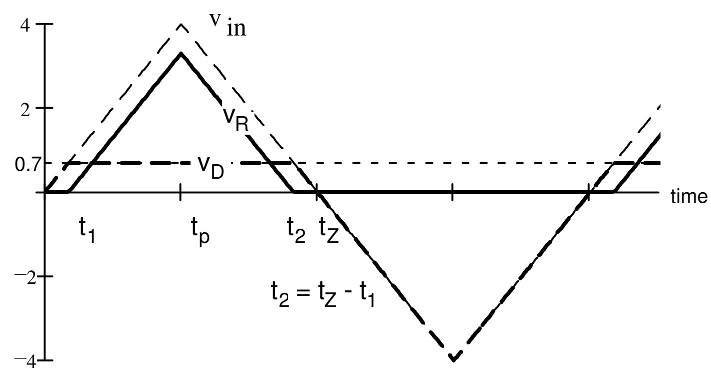


Diode doesn' t conduct until v_{in} reaches 0.7V, so 0.7V is a dividing line between the two models of the diode.

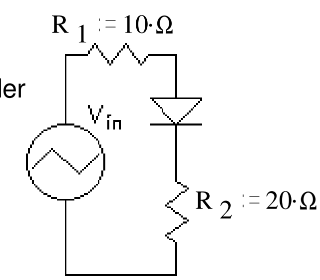
$$\text{slope} = \frac{0.7\cdot V}{t_1} = \frac{V_p}{t_p}$$

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

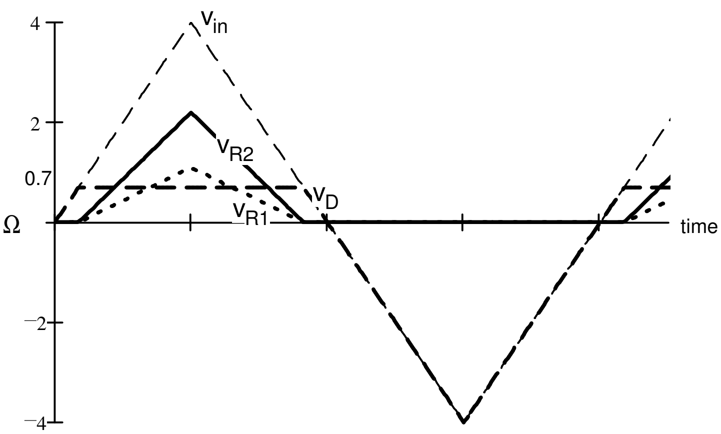




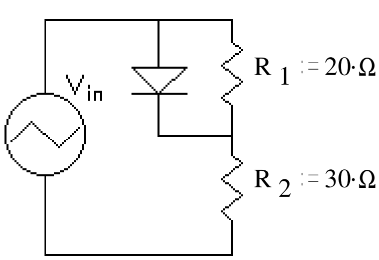
When the diode conducts, you' re left with a voltage divider



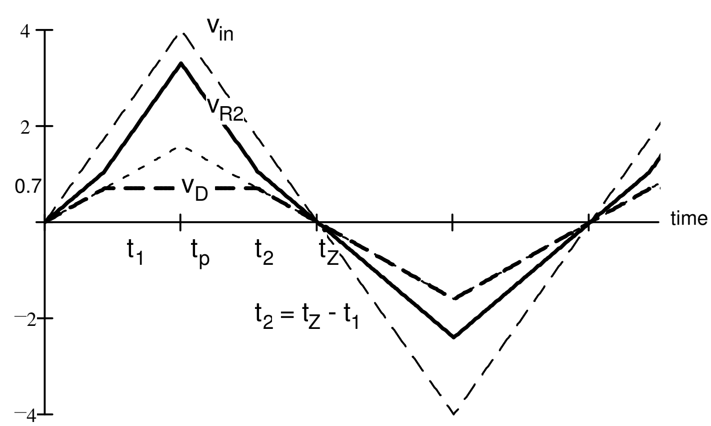
$$V_{R2peak} = \left(V_p - 0.7\cdot V\right)\cdot\frac{R_2}{R_1 + R_2}$$



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



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

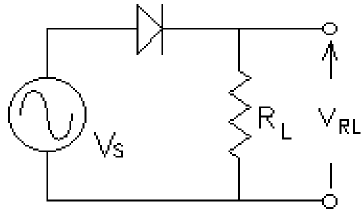


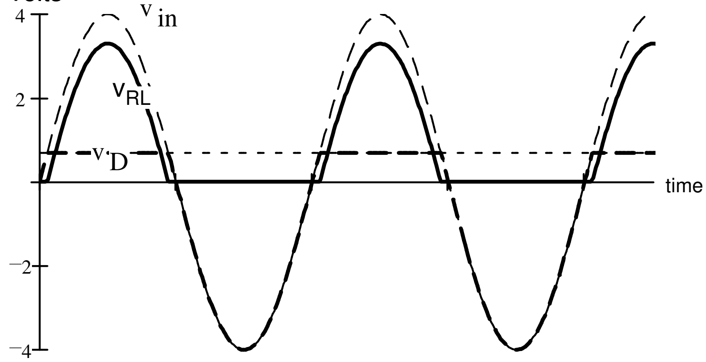
Rectifier Circuits & Power Supplies

Half-wave rectification

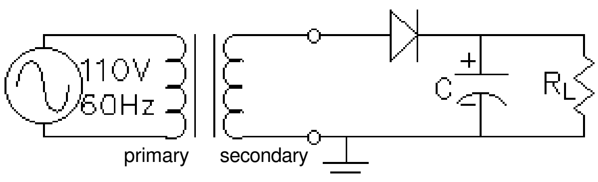
What if the input is a sine wave?

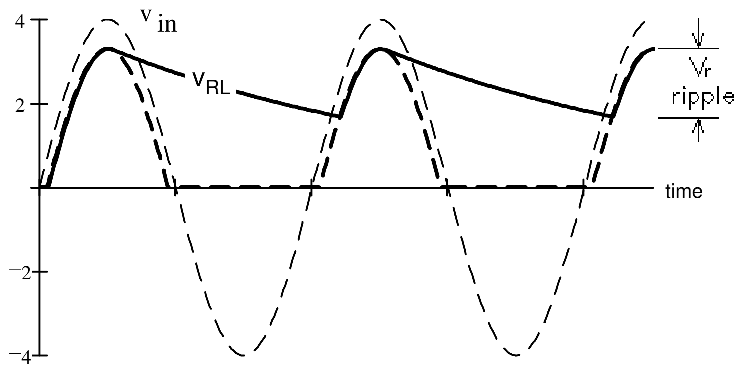
V_{RL} is now DC, although a bit bumpy. Some things are better if they' re bumpy, but not roads and not DC voltages.





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.

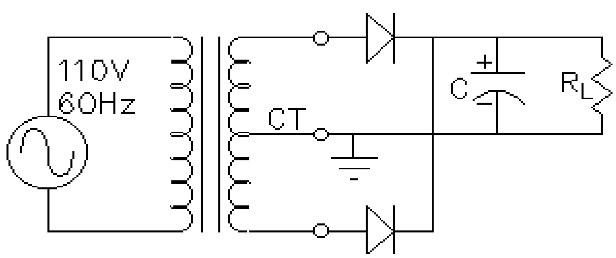


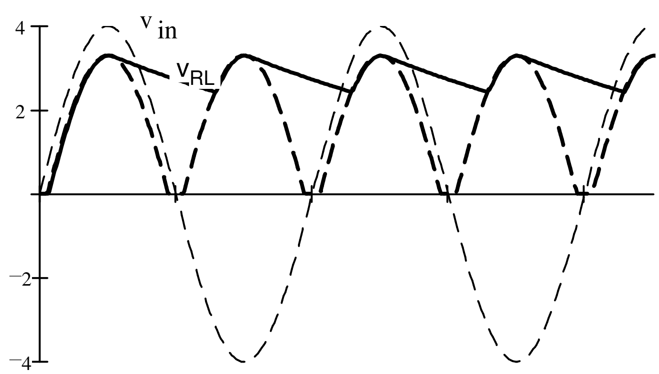


A "filter" capacitor (usually a big electrolytic) helps smooth out the bumps, although it sure looks like we could a bit bigger one here. The remaining bumpiness is called "ripple", V_r is peak-to-peak ripple

Full-wave rectification

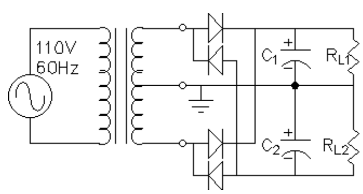
The "center tap" in the secondary of this transformer makes it easy to get full-wave rectification.



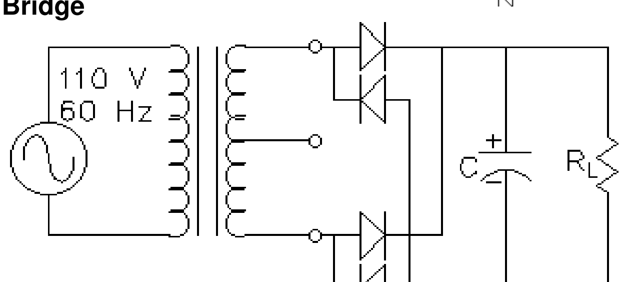


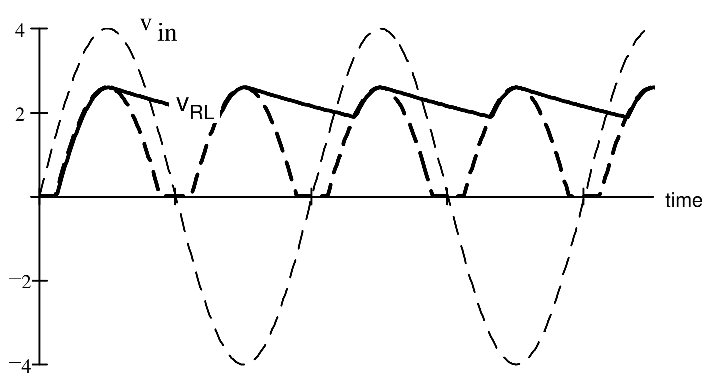
ripple is less

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



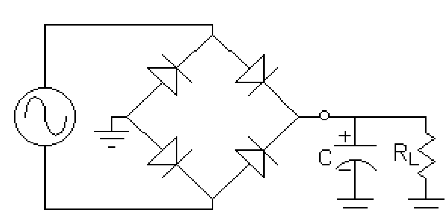
Bridge





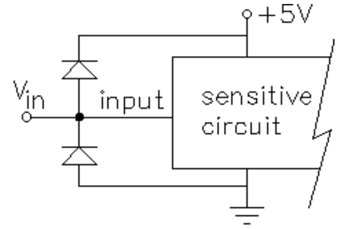
A "bridge" circuit or "bridge rectifier" can give you full-wave rectification without a center-tap transformer, but now you loose another "diode drop"

Bridge rectifiers are often drawn like this:



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.



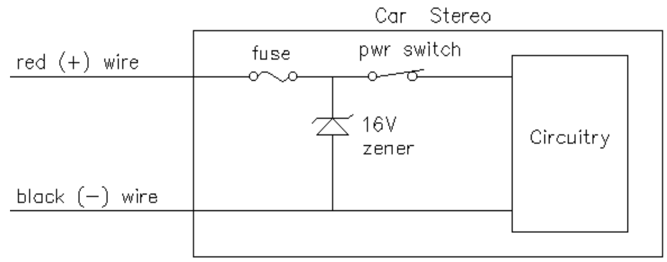
The input to the box marked "sensitive circuit" can' t get higher than the positive supply + 0.7V or lower than the negative supply - 0.7V.

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

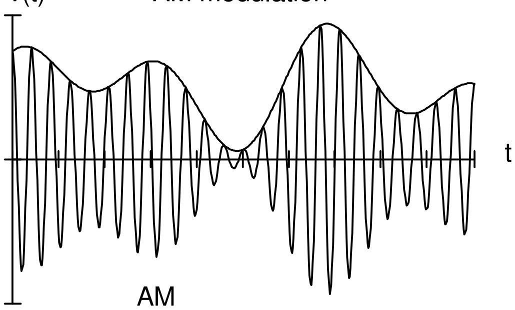
Another example of crowbar protection:

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

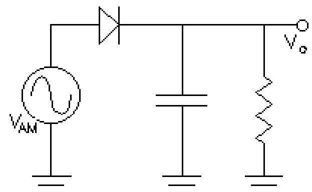
Or, If the input voltage is hooked up backwards the fuse will blow, protecting the circuitry.



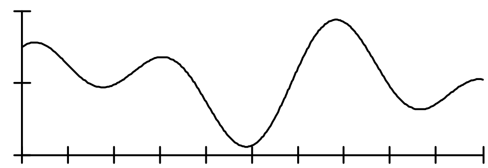
AM detector



A simple rectifier circuit



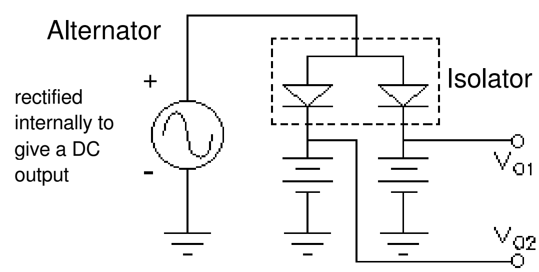
Returns the modulation signal



And a coupling capacitor can remove the DC

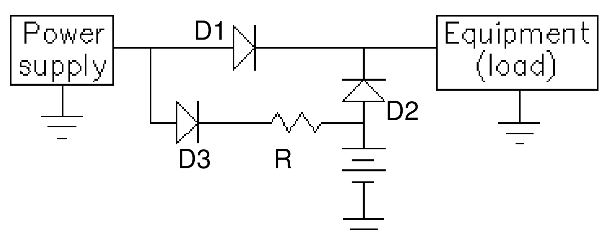
Battery Isolator

Like you might find in an RV. One alternator is used to charge two batteries. When the alternator is **not** charging, the batteries, 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

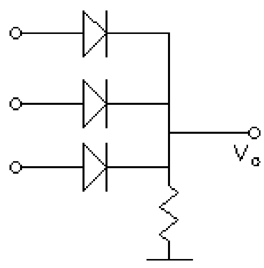
Normally the power supply powers the load through D1. However, if it fails, the load will remain powered by the battery through D2. Finally, D3 and R may be added to keep the battery charged when the power supply is working. These sorts of circuits are popular in hospitals.



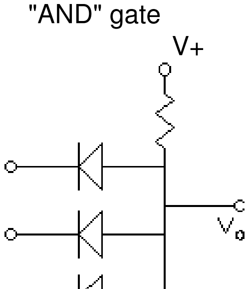
Diode Logic Circuits

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

"OR" gate

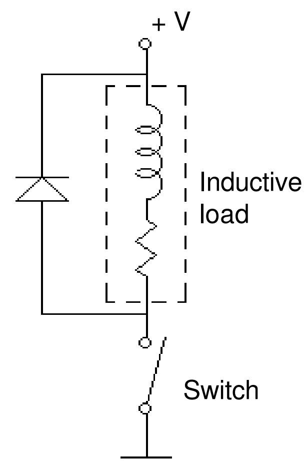


"AND" gate



"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.

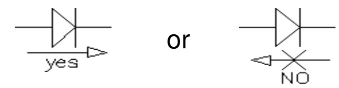


ECE 2210 Diode Circuit Examples

Basic diode circuit analysis

conducting — not conducting

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



2 Replace each diode with the appropriate model:

3 Redraw and analyze circuit.

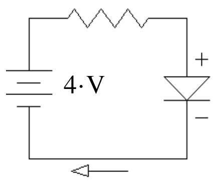
4 Make sure that each diode is actually in the state you assumed: current — $V_d < 0.7V$ Check

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.

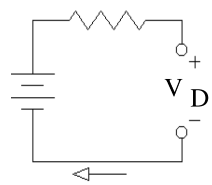
Ex1

$R := 1\cdot k\Omega$



I_D

Try reverse-biased, non-conducting model



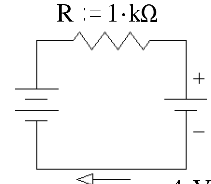
$V_D := 4\cdot V \quad > 0.7V$

$I_D := 0$

Doesn' t work, diode must be forward biased.

Try forward-biased, conducting model

$R := 1\cdot k\Omega$



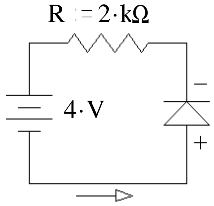
$V_D := 0.7\cdot V$

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

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

Ex2

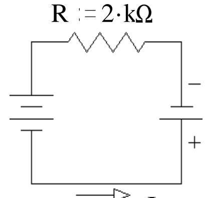
$R := 2\cdot k\Omega$



I_D

Try forward-biased, conducting model

$R := 2\cdot k\Omega$

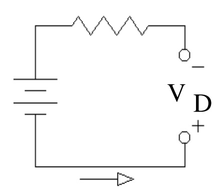


$V_D := 0.7\cdot V$

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

Doesn' t work, diode must be reverse biased.

Try reverse-biased, non-conducting model



Check the diode voltage

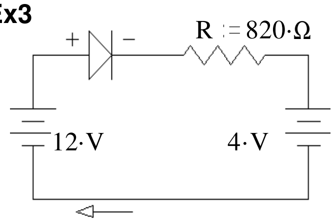
$V_D := -4\cdot V \quad < 0.7V$

Confirms diode is reverse biased

$I_D := 0\cdot mA$

Ex3

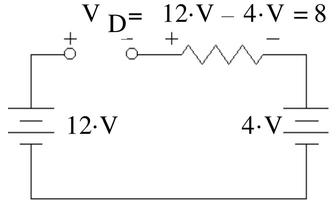
$R := 820\cdot\Omega$



Try reverse-biased, non-conducting model

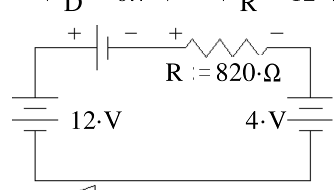
Doesn' t work, diode must be forward biased.

$V_D = 12\cdot V - 4\cdot V = 8\cdot V \quad > 0.7V$



Try forward-biased, conducting model

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



$V_R = 7.3\cdot V$

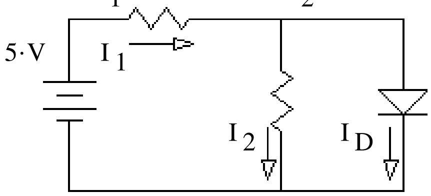
Check the diode current

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

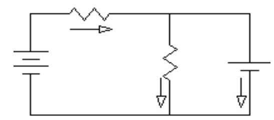
Confirms diode is forward biased

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

Ex4 $R_1 := 1\cdot k\Omega$ $R_2 := 1\cdot k\Omega$



Assume diode conducts:
Analyze



$V_D := 0.7\cdot V \quad = \quad V_{R2}$

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

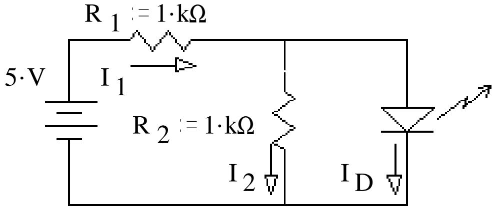
$V_{R1} := 5\cdot V - V_D \qquad V_{R1} = 4.3\cdot V \qquad I_1 := \dfrac{V_{R1}}{R_1} \qquad I_1 = 4.3\cdot mA$

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

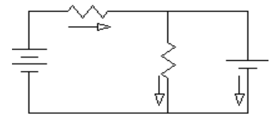
$I_D := I_1 - I_2 \qquad I_D = 3.6\cdot mA \quad > 0$, so assumption was correct

Ex5 Now with an LED

$R_1 := 1\cdot k\Omega$



Assume diode conducts



$V_D := 2\cdot V \quad = \quad V_{R2}$

Analyze

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

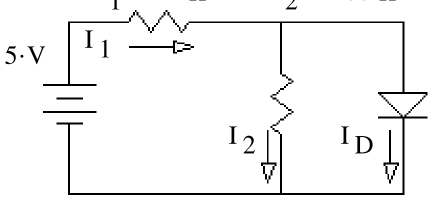
$V_{R1} := 5\cdot V - V_D \qquad V_{R1} = 3\cdot V \qquad I_1 := \dfrac{V_{R1}}{R_1} \qquad I_1 = 3\cdot mA$

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

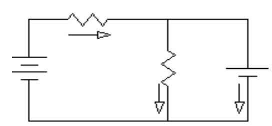
$I_D := I_1 - I_2 \qquad I_D = 1\cdot mA \quad > 0$, so assumption was correct, but the current is probably too small to create noticeable light

Ex6 Regular diode, but smaller R_1

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



Assume diode conducts



$V_D := 0.7\cdot V = \quad V_{R2}$

Analyze

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

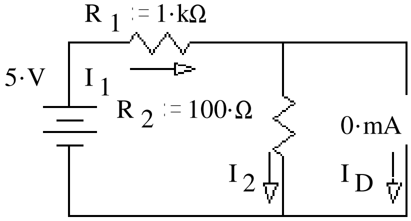
$V_{R1} := 5\cdot V - V_D \qquad V_{R1} = 4.3\cdot V \qquad I_1 := \dfrac{V_{R1}}{R_1} \qquad I_1 = 4.3\cdot mA$

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

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

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

$R_1 := 1\cdot k\Omega$



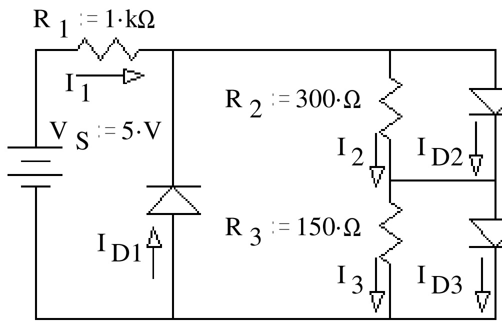
Analyze $\qquad I_1 := \dfrac{5\cdot V}{R_1 + R_2} \qquad I_2 := I_1$

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

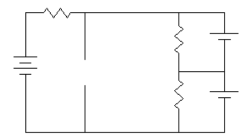
$V_{R2} := I_2\cdot R_2 \qquad V_{R2} = 0.455\cdot V \quad < 0.7V$, so assumption was correct

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

Ex7



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.



$V_{D2} := 0.7 \cdot V$

$V_{D3} := 0.7 \cdot V$

Assume both D_2 and D_3 conduct.

Analyze $\quad V_{R1} := V_S - V_{D2} - V_{D2}$

$V_{R1} = 3.6 \cdot V$

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

$$I_2 := \frac{V_{D2}}{R_2} \qquad I_2 = 2.333 \cdot mA$$

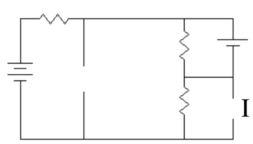
$$I_3 := \frac{V_{D3}}{R_3} \qquad I_3 = 4.667 \cdot mA$$

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

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

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

Assume D_2 conducts and D_3 doesn' t.



$V_{D2} := 0.7 \cdot V$

$I_{D3} := 0 \cdot mA$

Analyze $\quad I_2 := \dfrac{V_{D2}}{R_2} \qquad I_2 = 2.333 \cdot mA$

$$I_1 := \frac{V_S - V_{D2}}{R_1 + R_3} \qquad I_1 = 3.739 \cdot mA$$

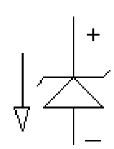
Assumed D_2 conducts, so check D_2 current. $\quad I_{D2} := I_1 - I_2 \qquad I_{D2} = 1.406 \cdot mA \quad > 0,$ so assumption OK

Assumed D_3 doesn' t conduct, so checD_3 voltage. $\quad V_{R3} := I_1 \cdot R_3 \qquad V_{R3} = 0.561 \cdot V \quad < 0.7V,$ so OK

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

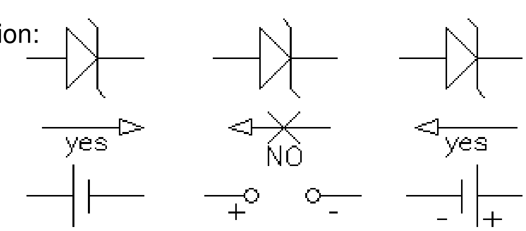
Zener Diodes

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:



$V_D = 0.7V \qquad 0.7V > V_D > V_Z \qquad V_Z$

Same basic diode circuit analysis

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

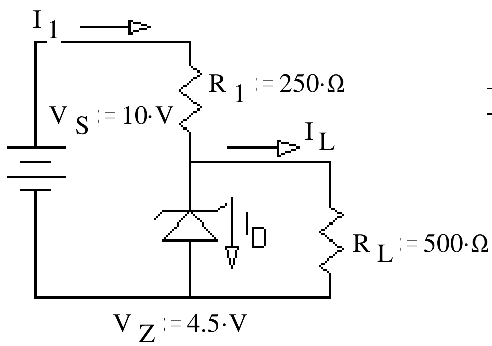
2 Replace each diode with the appropriate model:

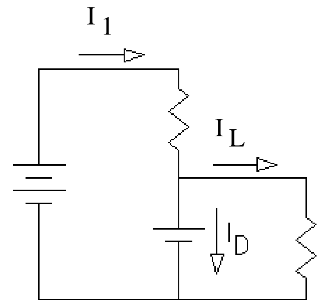
3 Redraw and analyze circuit.

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

Zener Diode Circuit Examples

Ex1 Typical shunt regulator circuit:





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

Assume conducting in breakdown region

$V_D := V_Z$

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

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

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

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

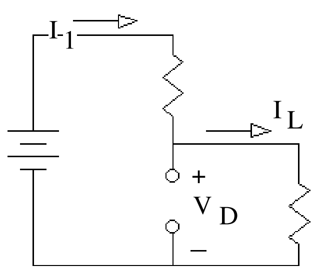
Ex2 What if R_L is smaller? $\qquad R_L := 150 \cdot \Omega$

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

$I_1 := \dfrac{V_S - V_Z}{R_1}$ $\qquad I_1 = 22 \cdot mA$ $\qquad I_D := I_1 - I_L$ $\qquad I_D = -8 \cdot mA$ < 0, so assumption is **WRONG !**

Circuit "falls out of regulation"

Assume not conducting



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

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

$V_D := \dfrac{R_L}{R_1 + R_L} \cdot V_S$ $\qquad V_D = 3.75 \cdot V$ $<$ $V_Z = 4.5 \cdot V$

so this assumption is OK

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

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

$I_1 := \dfrac{V_S - V_Z}{R_1}$ $\qquad I_1 = 6 \cdot mA$ $\qquad I_D := I_1 - I_L$ $\qquad I_D = -3 \cdot mA$ < 0, so assumption is **WRONG !**

Circuit "falls out of regulation"

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

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

$V_D := \dfrac{R_L}{R_1 + R_L} \cdot V_S$ $\qquad V_D = 4 \cdot V$ $<$ $V_Z = 4.5 \cdot V$

so this assumption is OK

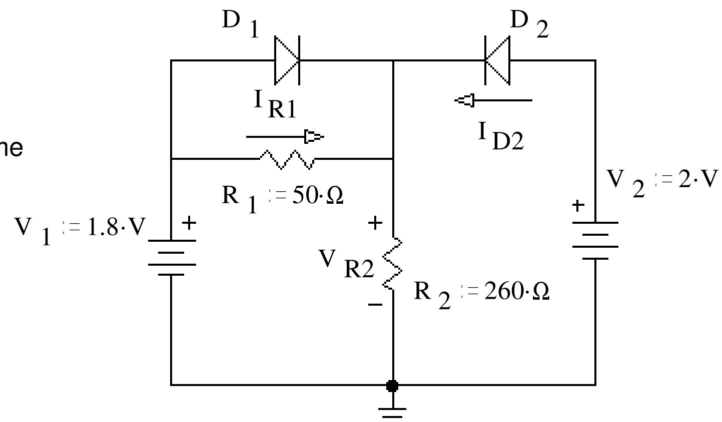
Exam-type Diode Circuit Examples

On an exam, I usually tell you what assumptions to make about the diodes, then you can show that you know how to analyze the circuit and test those assumptions. Since everyone starts with the same assumptions, everyone should do the same work.

In the circuit shown, use the constant-voltage-drop model for the silicon diode.

a) Assume that diode D_1 does NOT conduct.
Assume that diode D_2 does conduct.

Find V_{R2}, V_{R1}, I_{R1}, & I_{D2}, based on these assumptions. Stick with these assumptions even if your answers come out absurd. Hint: think in nodal voltages.



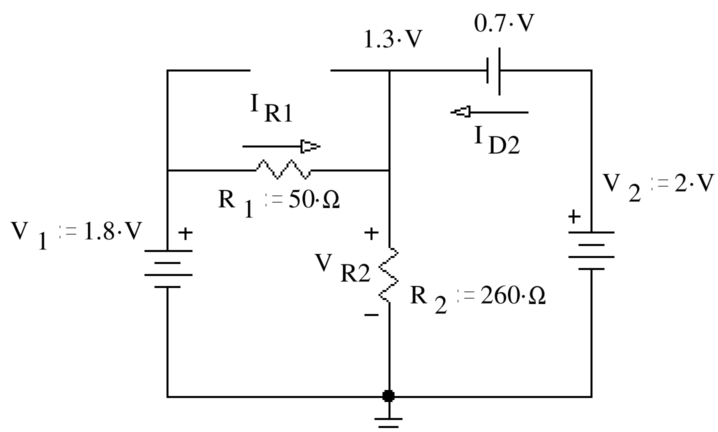
$V_{R2} =$ __________

$V_{R1} =$ __________

$I_{R1} =$ __________

$I_{D2} =$ __________

Solution to a)



$V_{R2} := V_2 - 0.7 \cdot V$ $\qquad V_{R2} = 1.3 \cdot V$

$V_{R1} := V_1 - V_{R2}$ $\qquad V_{R1} = 0.5 \cdot V$

$I_{R1} := \dfrac{V_{R1}}{R_1}$ $\qquad I_{R1} = 10 \cdot mA$

$I_{R2} := \dfrac{V_{R2}}{R_2}$ $\qquad I_{R2} = 5 \cdot mA$

$I_{D2} := I_{R2} - I_{R1}$ $\qquad I_{D2} = -5 \cdot mA$

b) Based on your numbers above, does it look like the assumption about D_1 was correct? yes no (circle one)
How do you know? (Specifically show a value which is or is not within a correct range.)

yes $\quad V_{D1} = V_{R1} = 0.5 \cdot V < 0.7V$

c) Based on your numbers above, does it look like the assumption about D_2 was correct? yes no (circle one)
How do you know?

no $\quad I_{D2} = -5 \cdot mA < 0$

d) Based on your answers to b) and c), which (if any) of the following was not correctly calculated in part a.

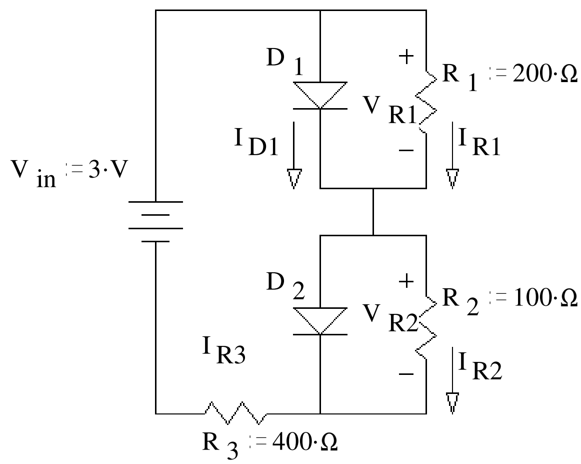
V_{R2} $\qquad V_{R1}$ $\qquad I_{R1}$ $\qquad I_{D2}$

(circle any number of answers)

Circle all in this case

Assume that diode D_1 is conducting and that diode D_2 is not conducting.

a) Find V_{R1}, I_{R1}, I_{R3}, I_{D1}, V_{R2} based on these assumptions.
Do not recalculate if you find the assumptions are wrong.



$V_{R1} =$ ________

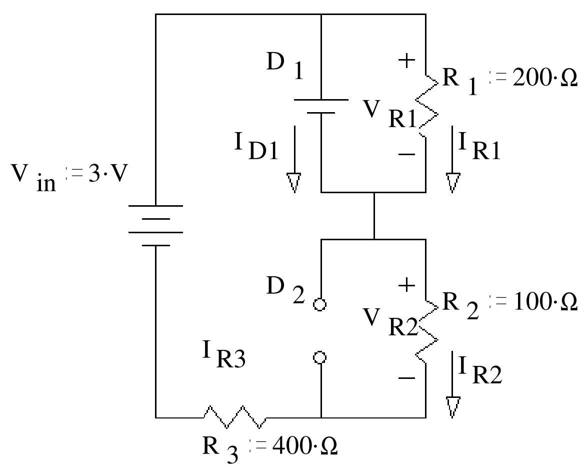
$I_{R1} =$ ________

$I_{R3} =$ ________

$I_{D1} =$ ________

$V_{R2} =$ ________

Solution:



$V_{R1} := 0.7 \cdot V$

$I_{R1} := \dfrac{V_{R1}}{R_1}$ $\quad I_{R1} = 3.5 \cdot mA$

$I_{R3} := \dfrac{V_{in} - 0.7 \cdot V}{R_2 + R_3}$ $\quad I_{R3} = 4.6 \cdot mA$

$I_{D1} := I_{R3} - I_{R1}$ $\quad I_{D1} = 1.1 \cdot mA$

$I_{R2} := I_{R3}$

$V_{R2} := I_{R2} \cdot R_2$ $\quad V_{R2} = 0.46 \cdot V$

(circle one)

b) Was the assumption about D_1 correct? yes no

How do you know? (Specifically show a value which is or is not within a correct range.)

yes $\quad I_{R2} = 4.6 \cdot mA > 0$

c) Was the assumption about D_2 correct? yes no

(circle one)

How do you know?

yes $\quad V_{D2} = V_{R2} = 0.46 \cdot V < 0.7V$

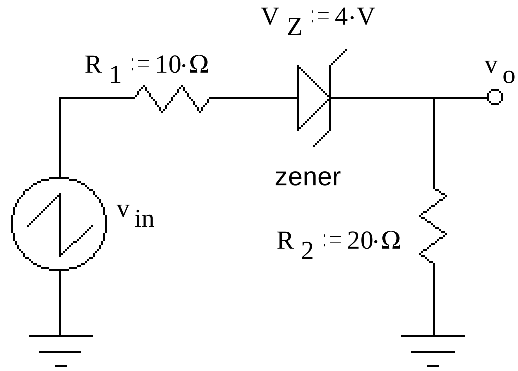
d) Based on your answers to b) and c), which (if any) of the following was not correctly calculated in part a.

V_{R1} $\quad I_{R1}$ $\quad I_{R3}$ $\quad I_{D2}$ $\quad V_{R2}$

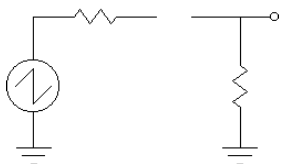
(circle any number of answers)

Circle none in this case

A voltage waveform (dotted line) is applied to the circuit shown.
<u>Accurately</u> draw the output waveform (v_o) you expect to see.
Label important times **<u>and</u>** voltage levels.



If diode doesn't conduct:

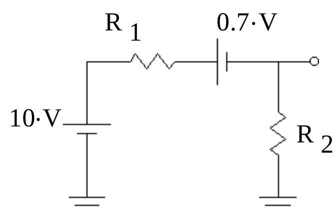


$v_o := 0$

Positive half

Diode conducts at: $0.7 \cdot V$ input   at time: $\frac{0.7 \cdot V}{10 \cdot V} \cdot 10 \cdot ms = 0.7 \cdot ms$

Maximum:

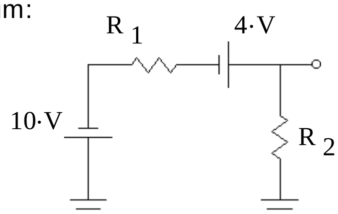


$v_o := (10 \cdot V - 0.7 \cdot V) \cdot \frac{R_2}{R_1 + R_2}$ $v_o = 6.2 \cdot V$

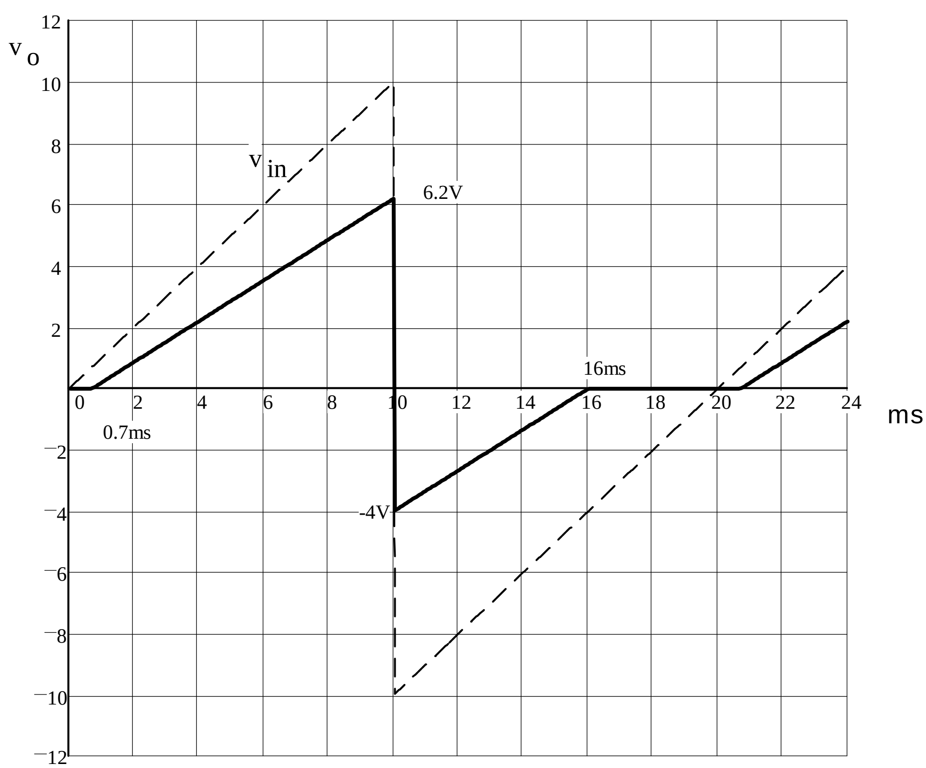
Negative half

Diode conducts at: $-4 \cdot V$ input   at time: $20 \cdot ms - \frac{4 \cdot V}{10 \cdot V} \cdot 10 \cdot ms = 16 \cdot ms$

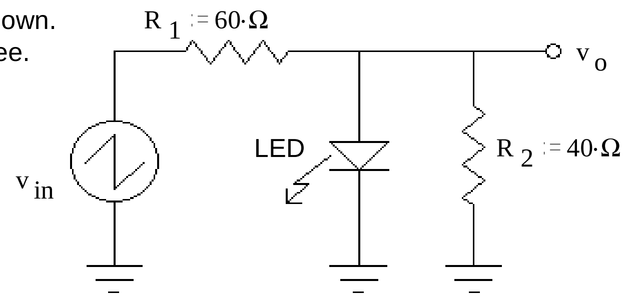
Maximum:



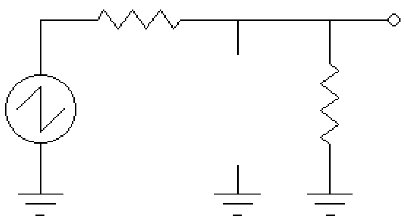
$v_o := -(10 \cdot V - 4 \cdot V) \cdot \frac{R_2}{R_1 + R_2}$ $v_o = -4 \cdot V$



A voltage waveform (dotted line) is applied to the circuit shown. <u>Accurately</u> draw the output waveform (v_o) you expect to see. Label important times **<u>and</u>** voltage levels.



If diode doesn't conduct:

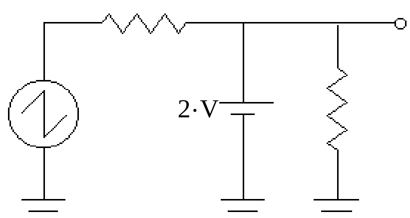


$$v_o = \frac{R_2}{R_1 + R_2} \cdot v_{in}$$

$$\frac{R_2}{R_1 + R_2} \cdot 10 \cdot V = 4 \cdot V$$

When: $v_{in} := \frac{R_1 + R_2}{R_2} \cdot 2 \cdot V$ $\quad v_{in} = 5 \cdot V$ $\quad$ at: $5 \cdot ms$ $\quad$ Diode begins to conduct

When diode conducts:



$$v_o = 2 \cdot V$$