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.

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.

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.

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.

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.

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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 \( v_{\text{in}} \) 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

\[
V_{R2\text{peak}} = (V_p - 0.7 \cdot V) \left( \frac{R_2}{R_1 + R_2} \right)
\]

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

\[
t_1 = \frac{0.7 \cdot V}{V_p} \cdot t_p
\]

\[
V_p \left( \frac{R_1}{R_1 + R_2} \right)
\]
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.

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 lose 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 circuit.

Or, if the input voltage is hooked up backwards the fuse will blow, protecting the circuit.

AM detector

\[
v(t) \quad \text{AM modulation}
\]

A simple rectifier circuit

\[
\text{Returns the modulation signal}
\]

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.

"AND" gate

"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.
ECE 2210  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:

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

Try reverse-biased, non-conducting model

Try forward-biased, conducting model

Ex2

Try forward-biased, conducting model

Try reverse-biased, non-conducting model

Ex3

Try reverse-biased, non-conducting model

Try forward-biased, conducting model

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 guesses and thus save yourself some work.

ECE 2210  Diode Circuit Examples  p1
Ex4

Assume diode conducts:

\[ V_{D} := 0.7 \cdot V = V_{R2} \]

\[ V_{R2} := V_{D} \quad I_{2} := \frac{V_{R2}}{R_{2}} \quad I_{2} = 0.7 \cdot mA \]

\[ V_{R1} := 5 \cdot V - V_{D} \quad V_{R1} = 4.3 \cdot V \quad I_{1} := \frac{V_{R1}}{R_{1}} \quad I_{1} = 4.3 \cdot mA \]

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

\[ I_{D} := I_{1} - I_{2} \quad I_{D} = 3.6 \cdot mA > 0, \text{ so assumption was correct} \]

Ex5

Now with an LED

Assume diode conducts:

\[ V_{D} := 2 \cdot V = V_{R2} \]

\[ V_{R2} := V_{D} \quad I_{2} := \frac{V_{R2}}{R_{2}} \quad I_{2} = 2 \cdot mA \]

\[ V_{R1} := 5 \cdot V - V_{D} \quad V_{R1} = 3 \cdot V \quad I_{1} := \frac{V_{R1}}{R_{1}} \quad I_{1} = 3 \cdot mA \]

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

\[ I_{D} := I_{1} - I_{2} \quad I_{D} = 1 \cdot mA > 0, \text{ so assumption was correct, but the current is probably too small to create noticeable light} \]

Ex6

Regular diode, but smaller \( R_{1} \)

Assume diode conducts:

\[ V_{D} := 0.7 \cdot V = V_{R2} \]

\[ V_{R2} := V_{D} \quad I_{2} := \frac{V_{R2}}{R_{2}} \quad I_{2} = 7 \cdot mA \]

\[ V_{R1} := 5 \cdot V - V_{D} \quad V_{R1} = 4.3 \cdot V \quad I_{1} := \frac{V_{R1}}{R_{1}} \quad I_{1} = 4.3 \cdot mA \]

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

\[ I_{D} := I_{1} - I_{2} \quad I_{D} = 2.7 \cdot mA < 0, \text{ so assumption was WRONG!} \]

Assume diode does not conduct

\[ I_{D} := 0 \cdot mA \]

\[ \text{We assumed not conducting (assuming a current), so check the voltage.} \]

\[ V_{R2} := I_{2} \cdot R_{2} \quad V_{R2} = 0.455 \cdot V < 0.7V, \text{ so assumption was correct} \]

Actually, this final check isn’t necessary, since first assumption didn’t work, so this one had to.
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
\[
V_{R1} := V_S - V_{D2} - V_{D2} \\
V_{R1} = 3.6 \cdot V
\]

\[
I_1 := \frac{V_{R1}}{R_1} \quad I_1 = 3.6 \cdot mA
\]

\[
I_2 := \frac{V_{D2}}{R_2} \quad I_2 = 2.333 \cdot mA
\]

\[
I_3 := \frac{V_{D3}}{R_3} \quad I_3 = 4.667 \cdot mA
\]

We assumed \( D_1 \) & \( D_2 \) conduct (assumed a voltage), so check currents.
\[
I_{D2} := I_1 - I_2 \quad I_{D2} = 1.267 \cdot mA > 0, \text{ so assumption OK}
\]
\[
I_{D3} := I_1 - I_3 \quad I_{D3} = -1.067 \cdot mA < 0, \text{ so assumption wrong}
\]

Assume \( D_2 \) conducts and \( D_3 \) doesn’t.

Analyze
\[
I_2 := \frac{V_{D2}}{R_2} \quad I_2 = 2.333 \cdot mA
\]

\[
I_1 := \frac{V_S - V_{D2}}{R_1 + R_3} \quad I_1 = 3.739 \cdot mA
\]

Assumed \( D_2 \) conducts, so check \( D_2 \) current.
\[
I_{D2} := I_1 - I_2 \quad I_{D2} = 1.406 \cdot mA > 0, \text{ so assumption OK}
\]

Assumed \( D_3 \) doesn’t conduct, so check \( D_3 \) voltage.
\[
V_{R3} := I_1 \cdot R_3 \quad V_{R3} = 0.561 \cdot V < 0.7V, \text{ so OK}
\]

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.

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.
4. Make sure that each diode is actually in the state you assumed:
Zener Diode Circuit Examples

**Ex1** Typical shunt regulator circuit:

\[ V_Z = 4.5 \text{ V} \]
\[ R_L = 500 \text{ } \Omega \]
\[ V_S = 10 \text{ V} \]
\[ I_1 = 250 \text{ } \Omega \]
\[ I_L \]

Assume conducting in breakdown region

\[ V_D = V_Z \]
\[ I_L = \frac{V_Z}{R_L} \]
\[ I_L = 9 \text{ mA} \]
\[ I_1 = \frac{V_S - V_Z}{R_1} \]
\[ I_1 = 22 \text{ mA} \]

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

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

**Ex2** What if \( R_L \) is smaller? \( R_L = 150 \text{ } \Omega \)

Assume conducting in breakdown region

\[ I_1 = \frac{V_S - V_Z}{R_1} \]
\[ I_1 = 22 \text{ mA} \]
\[ I_D = I_1 - I_L \]
\[ I_D = -8 \text{ mA} < 0, \text{ so assumption is WRONG!} \]

Circuit "falls out of regulation"

Assume not conducting

\[ I_L = I_1 = \frac{V_S}{R_1 + R_L} \]
\[ I_1 = 25 \text{ mA} \]

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

\[ V_D = \frac{R_L}{R_1 + R_L} V_S \]
\[ V_D = 3.75 \text{ V} < V_Z = 4.5 \text{ V} \]

so this assumption is OK

**Ex3** What if \( V_S \) is smaller instead of \( R_L \)? \( V_S = 6 \text{ V} \)

Assume conducting in breakdown region

\[ I_1 = \frac{V_S - V_Z}{R_1} \]
\[ I_1 = 6 \text{ mA} \]
\[ I_D = I_1 - I_L \]
\[ I_D = -3 \text{ mA} < 0, \text{ so assumption is WRONG!} \]

Circuit "falls out of regulation"

Assume not conducting

\[ I_L = I_1 = \frac{V_S}{R_1 + R_L} \]
\[ I_1 = 8 \text{ mA} \]

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

\[ V_D = \frac{R_L}{R_1 + R_L} V_S \]
\[ V_D = 4 \text{ V} < V_Z = 4.5 \text{ V} \]

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 D₁ does NOT conduct.
Assume that diode D₂ 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.

\[
\begin{align*}
V_{R2} &= \underline{\phantom{0.7}} \\
V_{R1} &= \underline{\phantom{0.7}} \\
I_{R1} &= \underline{\phantom{0.7}} \\
I_{D2} &= \underline{\phantom{0.7}} 
\end{align*}
\]

Solution to a)

\[
\begin{align*}
V_{R2} &= V_2 - 0.7 \cdot V \\
V_{R1} &= V_1 - V_{R2} \\
I_{R1} &= \frac{V_{R1}}{R_1} \\
I_{R2} &= \frac{V_{R2}}{R_2} \\
I_{D2} &= I_{R2} - I_{R1}
\end{align*}
\]

b) Based on your numbers above, does it look like the assumption about D₁ was correct? yes no (circle one)
How do you know? (Specifically show a value which is or is not within a correct range.)

\[
\begin{align*}
yes & \quad V_{D1} = V_{R1} = 0.5 \cdot V < 0.7V \\
nonumber \\
\end{align*}
\]

c) Based on your numbers above, does it look like the assumption about D₂ was correct? yes no (circle one)
How do you know?

\[
\begin{align*}
no & \quad I_{D2} = -5 \cdot mA < 0
\end{align*}
\]

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

\[
\begin{align*}
V_{R2} & \quad V_{R1} & \quad I_{R1} & \quad I_{D2}
\end{align*}
\]
(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.

\[
\begin{align*}
V_{R1} &= \underline{\quad} \\
I_{R1} &= \underline{\quad} \\
I_{R3} &= \underline{\quad} \\
I_{D1} &= \underline{\quad} \\
V_{R2} &= \underline{\quad}
\end{align*}
\]

Solution:

\[
\begin{align*}
V_{R1} &= 0.7 \text{ V} \\
I_{R1} &= \frac{V_{R1}}{R_1} \\
I_{R3} &= \frac{V_{\text{in}} - 0.7 \text{ V}}{R_2 + R_3} \\
I_{D1} &= I_{R3} - I_{R1} \\
I_{R2} &= I_{R3} \quad (\text{circle one}) \\
V_{R2} &= I_{R2} R_2 = 0.46 \text{ V}
\end{align*}
\]

b) Was the assumption about $D_1$ correct? 
\(\text{yes}\) \(\text{no}\)
How do you know? (Specifically show a value which is or is not within a correct range.)
\[\text{yes} \quad I_{R2} = 4.6 \text{ mA} > 0\]

c) Was the assumption about $D_2$ correct? 
\(\text{yes}\) \(\text{no}\)
How do you know?
\[\text{yes} \quad V_{D2} = V_{R2} = 0.46 \text{ V} < 0.7 \text{ V}\]

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

\[
\begin{align*}
V_{R1} & \quad I_{R1} & \quad I_{R3} & \quad I_{D2} & \quad V_{R2} \\
(\text{circle any number of answers})
\end{align*}
\]

Circle none in this case
A voltage waveform (dotted line) is applied to the circuit shown. Accurately draw the output waveform ($v_o$) you expect to see. Label important times and voltage levels.

If diode doesn't conduct:

Positive half

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

Maximum:

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

$$v_o = 6.2\cdot V$$

Negative half

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

Maximum:

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

$$v_o = -4\cdot V$$
A voltage waveform (dotted line) is applied to the circuit shown. Accurately draw the output waveform \( (v_o) \) you expect to see. Label important times and voltage levels.

If diode doesn't conduct:

\[
v_o = \frac{R_2}{R_1 + R_2} v_{in}
\]

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

When: \( v_{in} = \frac{R_1 + R_2}{R_2} \cdot 2 \cdot V \)

\( v_{in} = 5 \cdot V \) at: 5 ms Diode begins to conduct

When diode conducts:

\[v_o = 2 \cdot V\]