Chapter 2

Electrical Devices

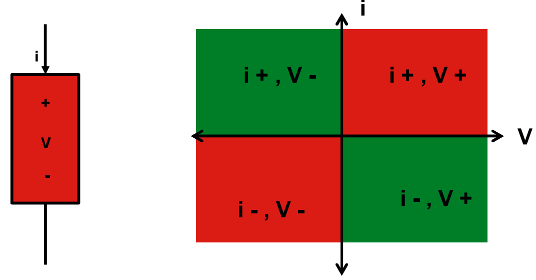


Figure 2.1: The reference directions and axis for measuring the iV relationship of an electronic device. The voltage across the device is plotted horizontally, and the current through the device is plotted vertically. Notice that the voltage and current can be positive or negative. Using the std reference direction, which set positive current to be current flowing into the + terminal and out of the - terminal, the quadrant indicates whether the device absorbs energy (red) or provides energy (green).

The previous chapter introduced the core ideas behind what makes something electrical. Electrical circuits are connections of electrical devices, and electrical devices are things that allow charge to flow through them, where the charge is driven by voltage differences, and we measure the flow of charge as a current. In this chapter we will more formally define what we mean when we talk about an electrical device, and will introduce our first four electrical devices: voltage and current sources, resistors and diodes.

An electrical circuit consists of a number of connected electrical devices. We know that in this circuit both KCL (the sum of the currents into each node is zero sum of the currents flowing into each device is zero), and KVL (the sum of voltages across the devices that form any loop is zero. While these rules provide constraints on the voltages and currents in the system, they are not enough to allow one to solve for these values. To find these values we need additional constraints, and these come from the characteristics of the electrical devices: electrical devices relate device voltage to device current.

In fact the way you characterize any electrical device is by how the device current depends on the voltage across the device (or conversely how the voltage depends on the current). This relationship is most easily visualized as a plot of the device current vs. the voltage across the device, and so we will use this plot to help us understand the device operation. Figure 2.1 shows a generic device with reference direction defined for voltage and current. In this chapter we will use the standard convention for reference directions, which defines positive current as current flowing into the lead of the device that is labeled positive.[1]

We have divided this i-V space into four quadrants depends on the sign of the voltage and current through the device. If we think back to how we measure power, iV, we can see that the quadrant that we operate in determines whether the power is positive (shown in red), or negative (shown in green). When the power is positive, the current is flowing into the higher voltage terminal[2] and flowing out of the lower voltage terminal. Since the charge carriers are losing energy, the device must be absorbing this energy. Conversely, if the iV is negative (the green regions) current is flowing into the lower voltage terminal and out of the higher voltage terminal, so the device is supplying energy to the circuit (it is giving the charge carriers more energy). Since physics says that energy must be conserved, unless a device has a source of energy, it must operate only in the red regions.

Many different electrical devices have similar shapes, so we group them together into a class. The rest of the chapter will discuss a few of the important device classes.

2.1 Voltage Source

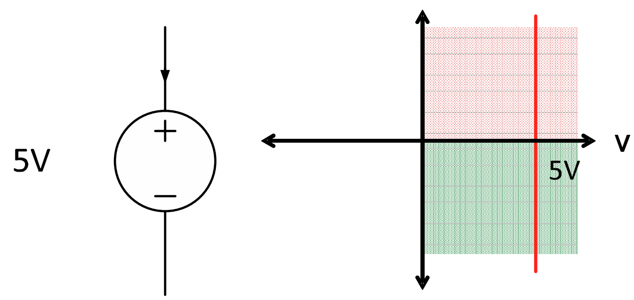


Figure 2.2: A voltage source. On the left is the symbol used for a voltage source, and one the right is the iV curve of the device. Since the voltage across a voltage source is constant, the resulting curve is a vertical line — it can support any current needed to maintain the voltage across the device.

We have already been introduced to a couple of types of devices in the first chapter. We described a battery as a device that tries to keep the voltage across it constant. The device class with this type of characteristic is called a *voltage source*. The voltage across an ideal voltage source is always constant, and equal the "voltage" of the voltage source. Since a voltage source only sets the voltage across it, it will support any current that the other devices in the circuit need to maintain its

[1] Note that these are only the reference directions, and the resulting voltage or current might be negative, which simply means that the terminal you labeled as positive is really at a lower voltage than the terminal you labeled as negative (negative voltage), or the current is flowing the opposite direction as your reference arrow (negative current).

[2] Either positive current is flowing into the positive terminal, or current is flowing out of the lower voltage terminal, which means that current must be flowing into the higher voltage terminal to maintain charge neutrality in the device

voltage. This gives the iV curve shown in Figure 2.2. The red line in this figure is the set of voltage - current points that the device supports. The line in vertical, since the voltage is always fixed independent of the current that the device supplies.

Notice that the output of a voltage source exists in both a red and green region. This is because it can either absorb or supply energy. If the voltage is positive, when current flows into the positive terminal the carriers will leave the negative terminal with less energy so the voltage source absorbs energy from the circuit. However when the current flows out of the positive terminal, the voltage source is supplying energy to the circuit.

These dual roles happen in the real world as well. Consider a rechargeable battery. When you use the battery to power your circuit, current flows from the positive terminal of the battery through your circuit (perhaps to the light in your flashlight) back into the negative battery terminal. During this operation the battery is converting chemical energy into electrical energy which is then consumed by the circuit. But when you charge this battery you take another source of energy (the wall socket) and flow current from the charger into the positive terminal of the battery. The battery absorbs this energy and stores it as chemical energy so it can be used again when it is needed.

2.2 Resistor

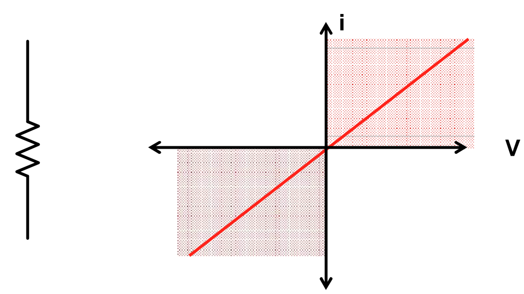
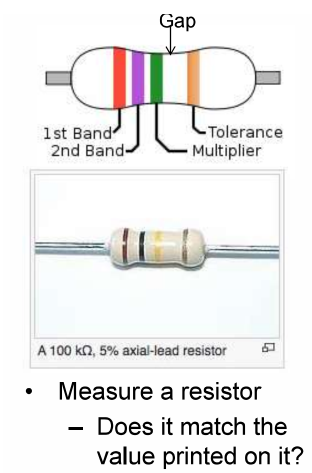


Figure 2.3: A resistor. On the left is the symbol used for a resistor, and one the right is the iV curve of the device. In a resistor the voltage is proportional to the current, so the iV curve is a diagonal line. The slope of the line is one over the resistance. Note that resistors only absorb energy, which makes sense, since they don't contain any energy sources.

One of the most common devices that we will work with are *resistors*. A resistor is another two terminal device, but in a resistor the voltage across the device is proportional to the current running through it. In fact the proportionality constant is called the resistance of the resistor, and it is measured in ohms, Ω.

$$V = i \cdot R$$

Figure 2.4: Resistors come in many different shapes and sizes. The resistors on the lower right are surface mount resistors.



Color	First Digit	Second Digit	Third Digit 1% Resistors	Multiplier	Tolerance
Black	0	0	0	1	
Brown	1	1	1	10	±1%
Red	2	2	2	100	±2%
Orange	3	3	3	1000 (=1k)	
Yellow	4	4	4	10k	
Green	5	5	5	100k	
Blue	6	6	6	1000k (=1M)	
Violet	7	7	7	10M	
Gray	8	8	8	100M	
White	9	9	9	1000M (=1G)	
Gold				0.1	±5%
Silver				0.01	±10%

Figure 2.5: Resistor color code. On many resistors the three numbers are represented by colors and not be numerals, which makes reading resistors even more fun.

The iV curve of a resistor is shown in Figure 2.3. The slope of the line is 1/R of the resistor. Resistance is used to model the fact that all material,[3] even material like metal that conducts charge very well, still causes the moving charge to lose some energy as they flow through the material. The

[3]Well except for superconductors which are a macro scale manifestation of a quantum phenomenon. These materials, which only exist at cold temperatures, have truly no resistance so seem magical if you are use to normal conductors with loss. They have interesting properties, like current can flow in a loop forever without any voltage driving them. Since currents cause magnetic fields, superconducting circulating currents are used in MRI machines to make large magnetic fields, and the can even levitate objects.

useful range of resistance we use in our circuits is quite large. Some circuits will use resistors larger than $10\,\mathrm{M\Omega}$, which is nearly a horizontal line near zero, to model the small amount of current that flows through a device which doesn't take much current (like a good voltage meter). Other circuits might need resistors less than a $10\,\mathrm{m\Omega}$ which is a nearly vertical line, to measure the resistance of a thick wire carrying a large current (like battery jumper cables). The difference of resistance between these two cases is 10^9.

Figure 2.4 shows a picture of different types of resistors. The smaller resistors can handle less power before they burn up (literally). The resistors on the lower right don't have leads and mount to the surface of a circuit board. They are much smaller than the other resistors that are shown. All resistors mark their resistance on them, but the marking is a little cryptic. Each resistor generally has 3 or 4 numbers on them. For example one resistor in the picture says 391. The first two numbers are put together, in this case to form 39, and this number is then multiplied by 10 raised the power of the third number (which was done to cover a wide resistance range). So 391 represents a resistor of $390\,\Omega$. The 270 resistor represents $27\,\Omega$.

To make reading resistor values even more challenging, on most resistors with leads the value of the three digits are encoded by a color, as shown in Figure 2.5. This would not be so bad, but sometimes the colors are hard to figure out. Violet, Green and Grey sometimes don't look much different. When in doubt, you should pull out your trusty DMM and measure the resistance.

One final note about resistors. Just because the resistor says it is $10\,\mathrm{k\Omega}$ doesn't mean that the resistance of the device will be exactly $10\,\mathrm{k\Omega}$. Most of the resistors in the lab are 5% resistors, which means that their value is within 5% of the value specified. This means the resistance be between $9.5\,\mathrm{k\Omega}$ and $10.5\,\mathrm{k\Omega}$.

While all real wires have some resistance, that resistance is generally pretty small, and in most situations we can ignore it. If the resistance of the wire is important, then it must be explicitly added in the circuit diagram that we draw. Wires in our circuit diagrams are always perfect conductors with no voltage drop, so the voltage of all points on the wire in a circuit diagram is exactly the same.

2.3 Battery

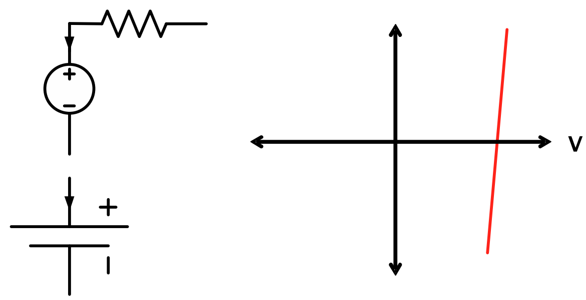


Figure 2.6: A battery. On the bottom left is the circuit symbol for a battery, and on the right is a more accurate iV plot of a battery. While the line is pretty vertical, there is some slope to it. We can model this real battery by combining a perfect voltage source with a resistor. The output voltage of this combination is going to be equal to the sum of the voltage drop across the voltage source and the resistor. When current is flowing out of the voltage source, it will flow into the resistor, so the charge will leave with less energy (voltage) then they started with, so the voltage across the combination decreases as the current becomes more negative (the current reference direction is into the positive terminal).

We previously mentioned that a battery could be represented as a voltage source. This is basically correct. However if you measured the output voltage of a battery as you increased the current you pulled out of it, you would notice that is would not be a vertical line. As the current you pulled out of the battery increased, the voltage across the battery would decrease as shown in Figure 2.6. The slope of this line depends on the type of battery you have. A 9 V battery has a large change in voltage with current, where your 12 V car battery can supply 100 A with only a small change in voltage. What ever the voltage drop, we can model change in voltage with current by combining our voltage source and resistor models, which is shown in the top right of Figure 2.6. The resistance of the car battery might be less than 10 mΩ, where a 9 V battery might have a series resistance of 100 Ω.

2.4 Current Source

Another primitive class of device is called a *current source*. This device is the dual of a voltage source. It doesn't care what voltage it has across it; it only cares about the current going through it. An ideal current source will support any voltage necessary to maintain its current. The symbol for a current source and its iV curve is shown in Figure 2.7

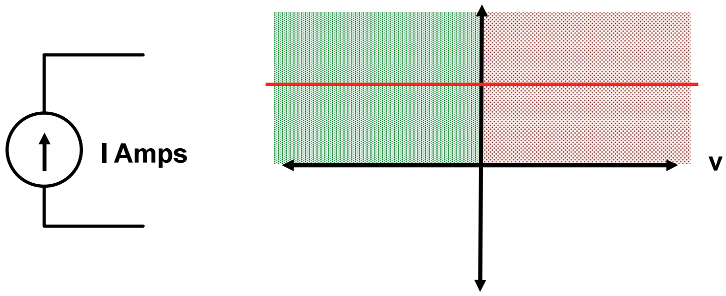
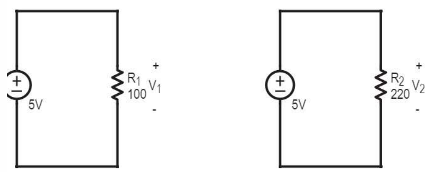


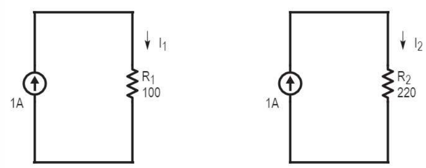
Figure 2.7: A current source. On the left is the circuit symbol for a current source, and on the right is its iV curve. Since this device keeps its current constant independent of its voltage, its curve is a horizontal line. Like a voltage source, this means that a current source can either supply or absorb energy from the circuit.

While there are nice components that you can buy like batteries that are a good approximation of a voltage source, there are not any components that look like just a current source (except for lab supplies that can be set to be either a voltage or current source). But as we will see next, they can be used in combination with other device models to model real world effects.

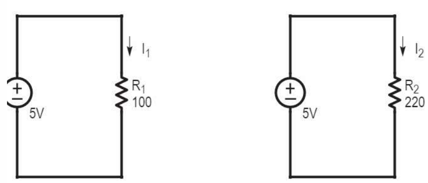
Problem 2.1 : Voltage sources
Find V_1 and V_2.



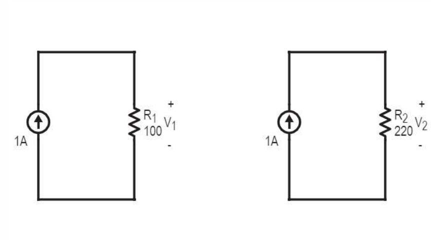
Problem 2.2 : Current sources
Find I_1 and I_2.



Problem 2.3 : Simple applications of Ohm's law
Find I_1 and I_2.



Find V_1 and V_2.

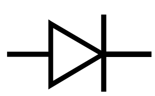


2.5 Diodes

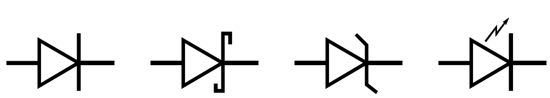
Another electrical device that we often use is a diode. They are one of the main components in solar chargers. A diode is like a one-way valve for current, not unlike a plumbing check-valve which allows water to only flow in one direction. Like resistors, diodes don't contain any power sources, so its iV curve can only exist in the "red" regions of the iV curve. They are differnt than a diode because their behavior in the two quadrants they operate in are very different. When there is a positive voltage across the diode, positive current flows, but when the voltage reverses, no negative current flows. This combination means current can flow only in one direction. This behavior is very useful in circuits where the voltages change over time, and we'll explore this in more detail later. However, it turns out that diodes are even more useful: LEDs and solar panels are also kinds of diodes. They take advantage of quantum physics and the interaction between photons and electrons to convert electrical energy into light or vice-versa.

2.5.1 Ideal diode model

A diode is represented in a schematic with the symbol below. The arrow points in the direction that current can flow. Usually, the diode package will have an alternate-colored band (often silver or white on a black package) indicating the negative end (current output) of the diode. Since current can only flow one way in a diode, we always label the voltage and current across it the same way. The positive end of the diode (sometimes called its anode) is on the side where current can flow into the device (the triangle side), and the negative end of the diode (sometimes called the cathode) is where the current can flow out of the device (the side with the line).

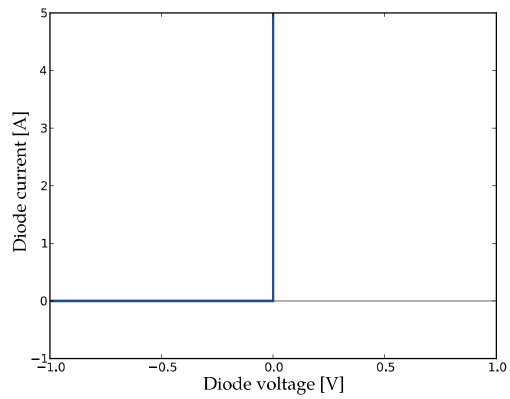


It turns out that there are several types of diodes with special characteristics, and these have slightly different schematic symbols. We won't discuss them in more detail here, but be aware that you might see these symbols, and that they represent special-purpose diodes.

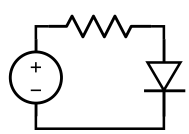


The simplest way to mathematically model a diode in a circuit it to split its behavior into two states: "on" and "off". When the diode is on, it acts like a short circuit: there is zero voltage across the terminals, and current flows through. When the diode is off, it acts like an open circuit: zero current flows, and there is a negative voltage across the terminals. This is called the "ideal" model of a diode because it describes theoretically perfect diode behavior. Needless to say, real diodes are not ideal, but this model is still useful.

Graphically, we can represent an ideal diode with the i-V curve below:



Notice that in this model, the i-V curve lies exclusively on the i and V axes, with current always ≥ 0, and voltage always ≤ 0. The fact that current is ≥ 0 should make sense; this just says that the current can only flow one way, which is what makes the device a diode. The fact that voltage is always ≤ 0 is a little more subtle. To understand what is happening, imagine what happens with the circuit below.



If the voltage is negative, the diode is in the off state, and no current flows. Regardless of how many negative charges there are above the diode, none of them can flow across, and the voltage remains negative.[4] If the voltage across the diode were positive, current would just flow through the diode, bringing the potential difference back to zero. Regardless of how much current flows, there will be no potential difference across the diode, because the current flows straight through it.

To solve a circuit containing ideal diodes:

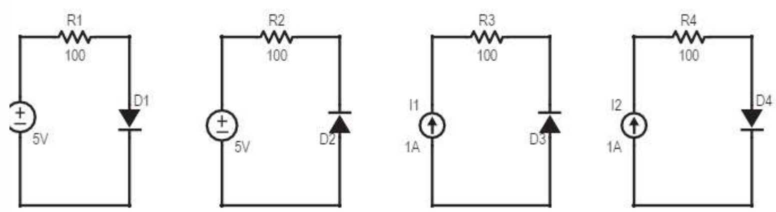
- Assume that current through the diode is zero (i.e., that the diode is off, and acts like an open circuit). Find the voltage across the diode under this assumption.
- If the diode voltage is negative, then the diode is in fact off, and our analysis holds.

[4] In a real diode, there is some voltage beyond which the diode can't block the charges, and current begins to flow in the reverse direction. This is known as "reverse breakdown".

- If the diode voltage is positive, then the assumption was incorrect, and the diode is on. The diode voltage can't actually be positive, so re-solve the circuit assuming that the diode is on and replace it with a wire (which is a zero voltage voltage source) and solve the circuit again. This time you should find positive current flowing through the wire you added.

The next chapter describes the general method of solving for voltages and current in circuits, and will have some example circuits with diodes.

Problem 2.4 : Ideal diodes
Assume that all diodes in the following circuits are ideal. Determine which of the diodes are on.



2.5.2 Actual diode I-V equation

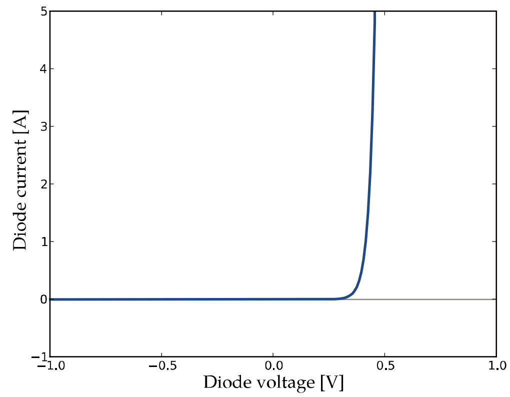
The ideal diode model introduces us to the most important characteristic of a diode — it only allows current to flow in one direction. Unfortunately it is not a very accurate model of the actual While the ideal model is convenient, it's not physically accurate. A more correct model based on the underlying physics is given by the equation

$$I = I_S \left(e^{V_D/V_T} - 1 \right)$$

where I is the current through the diode, I_S is a scale factor, V_D is the voltage across the diode, and V_T is a constant which is approximately 26 mV at room temperature.

Plotting this gives the curve below:[5]

[5] Of course, this is still an approximation which assumes that the underlying physical behavior is ideal. Real diodes have resistance in series with the "ideal" diode, so the current can't exponentially increase forever, and all doides will "breakdown" and conduct when the reverse voltage is negative enough. But for this class we will ignore these effects

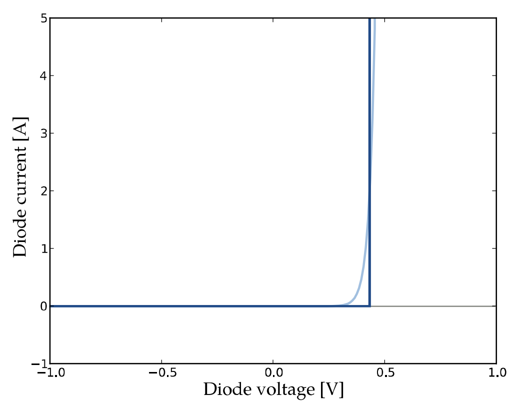


Dealing with the diode's exponential i - V relationship is painful unless you are working with a computer program which can model these devices. Such programs exist, and we will introduce them on later in these notes. It would be nice to have a model that is more accurate than the idea diode model, but simpler than the exponential model. The *idealized diode* model provides a compromise between the ideal model and the physical model.

2.5.3 Idealized model

Like the ideal model, the idealized model assumes that the diode can be either on (conducting current) or off (blocking current). But unlike the ideal model, it assumes that when the diode is on, there is still some constant voltage drop across the diode.

Graphically, the I-V curve looks like the following:



Note that this is quite close to the ideal model.

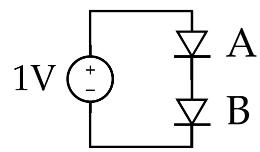
The voltage at which the diode turns on is known as the *forward voltage*. We can solve a circuit with idealized diodes in much the same was as we would for ideal diodes:

- Assume the diode is off,

- If the voltage is less than the forward voltage (including negative), then the diode is off, and our assumption was correct.
- If the voltage is greater than the forward voltage, then the diode is on, and the voltage across the diode is equal to the forward voltage. Solve the circuit as if the diode was a constant voltage source matching the forward voltage.

When we have multiple diodes together, it's important to consider the circuit as a whole, using KVL and KCL.

Question: In the circuit below, which diodes are on? Use the idealized model, and assume a forward voltage of 0.7 V.



If we consider only diode A, we might assume that the diode is on because the 1 V source is greater than the diode's threshold voltage. Then we go to diode B, and observe that the voltage across it is

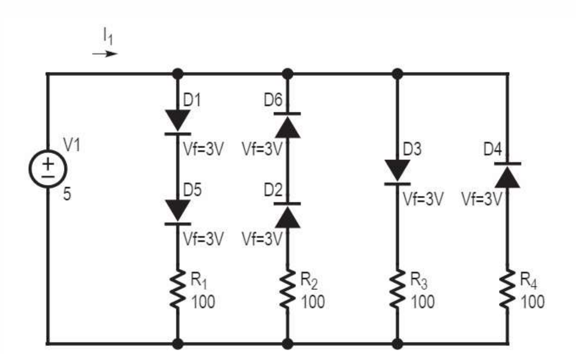
$$1\,\mathrm{V} - 0.7\,\mathrm{V} = 0.3\,\mathrm{V}$$

This is less than its threshold voltage, so it must be off.

However, this can't possibly happen. If the first diode is on, current is flowing through it, and that current has to flow through the second diode. But that implies that the second diode will also be on. Conversely, if the second diode is off, the first one must also be off. This is in fact what happens. If the supply voltage is not sufficient to turn on both diodes, they will both be off.

Problem 2.5 : **Non-ideal diodes**

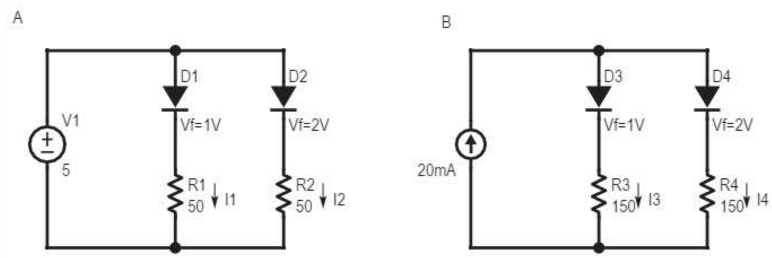
Again, the diodes in the following circuit have forward voltages as labelled. Determine which diodes are turned on, and what the current I_1 is.



Problem 2.6 : **Non-ideal diodes**

The diodes in the following circuit have a forward voltage as labelled. ($V_f = 2V$ indicates a forward voltage of 2V). Determine which diodes are turned on, and what the current I_2, I_2, I_3

and I_4 are. *Hint: Try to follow the steps in the text, especially for circuit B, which is a slight extension problem.*



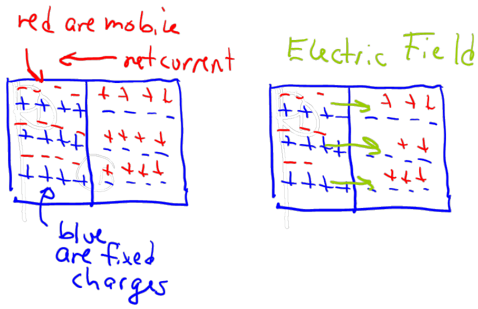
2.6 LEDs and Solar Cells

One of the most interesting and useful properties of diodes is their ability to convert light power into electrical power, and convert electrical power into light. Not all diodes have this ability. Diodes that convert light to electrical power are typically called solar cells, or photo-diodes, and diodes that convert electrical energy into light are called light-emitting-diodes, or LEDs for short. Understanding the full mechanism which enable this behavior requires learning more about solid-state physics and semiconductor devices. While these are fascinating subjects, they are a little advanced for this class. So the next two sections provides a high-level explanation of the physics behind diodes and light to give you a little feeling for why light can interact with diodes. If you are interested in this subject, please talk with one of the instructors of the class.

2.6.1 The physics behind diodes

A diode is formed when you connect the right two types of material together. Both materials conduct charge, and of course charge neutral, but on one side the mobile charge is positive, and the negative charge is fixed, while on the other side the negative charge is mobile and the positive charge is fixed.[6] Since the mobile charge is mobile it moves around. Now when there is not a voltage applied to it, it moves in a random directions (you can think of the charges jiggling around some moving left and some right), so there is no net charge motion, and no current flow. When the two sides are put together some interesting stuff happens. Lets assume that the mobile + charges are on the right and the mobile - charges are on the left as shown in the figure below.

[6] There are a lot of restrictions here about the types of material and how they are connected together. Generally both sides of the diode are the same material, a semiconductor, that is made conductive by adding a small amount of other material into it which is called doping. One side is doped to make the mobile carriers positive, and one side is doped to make the mobile charges negative



At the boundary between the mobile + and - charges, when the mobile charge begin to move, some mobile + charges move left, but there are no mobile + on the left to move right. Instead the mobile - charges on the left move right. This gives rise to a net current to the left! This is called the diffusion current, since it is the result of the random thermal motion of charged particles. Like perfume in air, random motion will tend to spread out, or diffuse, any material with a concentration gradient. This is true whether the particles are charged or not. However when the particles have charge some other interesting stuff happens. When mobile + and - charge meet, they neutralize each other[7] and disappear. When charged particles diffuse they create a secondary effect. Since some of the mobile positive charge near the border are moving left and disappearing, the fixed negative charge in this region is no longer matched by mobile positive charge; similarly the fixed positive charge on the left side of the boundary is also exposed. This means around this boundary we have now have a net negative charge on the right, and a net positive charge on the left. Remembering back to the first chapter, this charge separation in the middle of our diode causes an electrical field to form, and this field will apply a force on the mobile charges.

Question: What is the direction of the electric field? Which way does it push the mobile carriers?

The electric field points to the right, as shown in the figure above. This exerts a force to the left on the negative charge, and a force to the right on positive charge. Notice that this force is opposite the direction that the charges were going as a result of diffusion. As diffusion continues, the field gets larger until this field is large enough to stop the diffusion current caused by the concentration gradient. One way to think of this situation is to consider the total current to be the sum of the diffusion current and the current caused by the electric field, which is called the drift current. In this view the diffusion current causes the electric field to grow, which increases the drift current, until the drift current is equal and opposite to the diffusion current.

Question: Since there is a voltage difference inside the device, can we measure it with our voltmeter?

The electric field in the device does create a voltage difference between the mobile positive carrier and mobile negative carrier materials. At first it seems like we should be able to measure it. Unfortunately these types of "voltage" differences happen whenever you connect different materials together. So while there is a voltage difference in the middle of the diode, there also is a voltage difference between the end of the diode material and the wire that connects to it. So if the leads of the diode are the same material, you won't be able to measure any voltage difference between the leads, even if there is a voltage difference inside the material.

Question: What happens if we apply an external voltage to the diode?

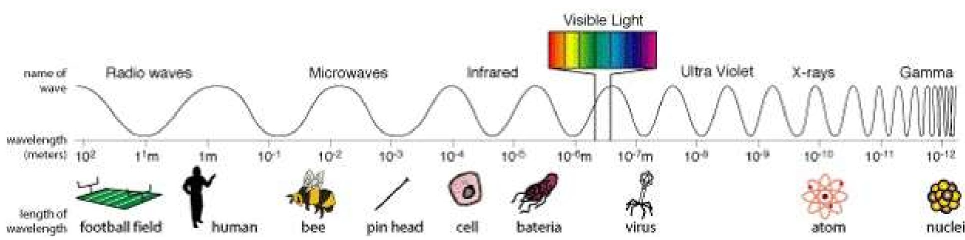
[7] Another more complicated process that we will talk about again later in this section

When we apply an external voltage, we either make the voltage difference inside the diode larger, which increasing the internal field, or smaller, which decreases the field. When the field gets larger no current can flow, since now the field pushes positive charges to the right, and negative charge to the left. But there are no mobile positive carriers on the left to move right, or mobile negative charge on the right to move left. However, when we apply a positive voltage to the side that has mobile positive charge, we decrease the internal voltage. This decreases the drift current, so there is a net diffusion current, and current will flow through the device. Since the diffusion current is very large (there is a very large concentration gradient in a diode) as you increase the voltage the diffusion current becomes very large.

If you want to know more about how this works, you should take a class like EE 116.

2.6.2 The physics behind light

Light is all around us, we use it every day, but when you dig into the physics behind light, things get a little strange (it is quantum stuff again). Let's start with the not strange stuff. Light is a traveling electromagnetic wave that can travel through the air/space like radio, TV, or cell phone signals. These types of signals are characterized by the frequency of signal, which also sets the length of a wave that is traveling in space. Since these waves all travel at the speed of light, $3 \cdot 10^8$m/s short wavelengths require very high frequencies. You cell phone runs between 1-5GHz, and has a wavelength that is a few tenths of a meter. Light runs at 100s of THz, and has a wavelength that is less than 1 µm. The figure shown below shows the wavelength of different types of electromagnetic waves.



What makes light strange is that while light is a wave, it is also a particle call a photon. This duality is part of quantum mechanics, and has been validated in many experiments. We know that photons exist, since when we measure very dim light, we record the arrival of individual photons. The photon nature of light is interesting since this means that light is quantized into photons, and the energy that a photon carries is precisely set by the frequency of the light it is transmitting.

$$E = \frac{hc}{\lambda}$$

where h is Planks constant, $6.6 \cdot 10^{-}19$ J, and c is the speed of light, $3 \cdot 10^8$m/s.

Since we are interested in the exchange of energy between a photon and a charge particle, either electron or its positive counterpart, we can measure this energy in electron voltage (eV). This is the energy needed to raise the potential energy of an electron by 1V. In these units, hc = 1.24 eV · µm.

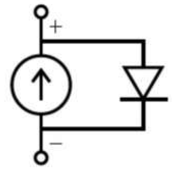


Figure 2.8: A picture of a solar cell on the left, and the circuit model of the solar cell on the right. When light hits the solar cell it generates a current which is represented by the current source. The value of the current is proportional to the photon flux, which is proportional to the light intensity.

2.6.3 LEDs

When we forward bias a diode, mobile + and - charge move across the junction between the two materials, and then combine with a charge of the opposite type. Since there was an internal voltage built up across this junction, when the positive carrier makes it across the junction, it has more energy than the mobile negative charges. It generally loses this energy by converting it to heat, but in some materials it loses this energy by emitting a photon. These materials are used to make LEDs. When this happens the color of the photon is related to the energy that the particle loses, which is related to the internal voltage in the diode, which is related to the forward voltage of the diode.

Question: What voltage drop do we need to release a photon of visible light?

Visible light is roughly in the range of 400 to 750 nm, with red at about 700 nm Use Planck's constant, etc. Red: 2Vish

Question: How do we get white light out of an LED?

We use a blue LED with a yellow phosphor. Some of the blue light is absorbed by the phosphor and released as yellow light. To human eyes, the mixture appears white. If you look at white LEDs, you'll usually see some kind of yellow spot where the diode itself it. Since a white LED is really a blue LED in disguise, the forward voltage for a white LED is also about 3V.

We've seen that current flowing through an LED releases photons, so we might ask: is it possible to generate current by shining light on an LED? In other words, if an electron can fall across a bandgap and release a photon, can an incoming photon push an electron up across the bandgap?

The crazy answer is yes, this does in fact work. In fact, this is the principle that makes solar panels work.

2.6.4 Solar Cells - Capturing Light

A solar cell is a diode that is made generally from silicon, which has a forward drop of around 0.7 V. If a photon with enough energy is absorbed into the solar cell, it can create a mobile + and - charge pair. Normally if this happens on the side with many mobile - charges, the + charge will just combine with another - charge and nothing happens. But if the light is absorbed close the the junction between the two materials, there will be an electric field, and the two carriers will be pushed in different directions, and the mobile + will move the side with more mobile + charges,

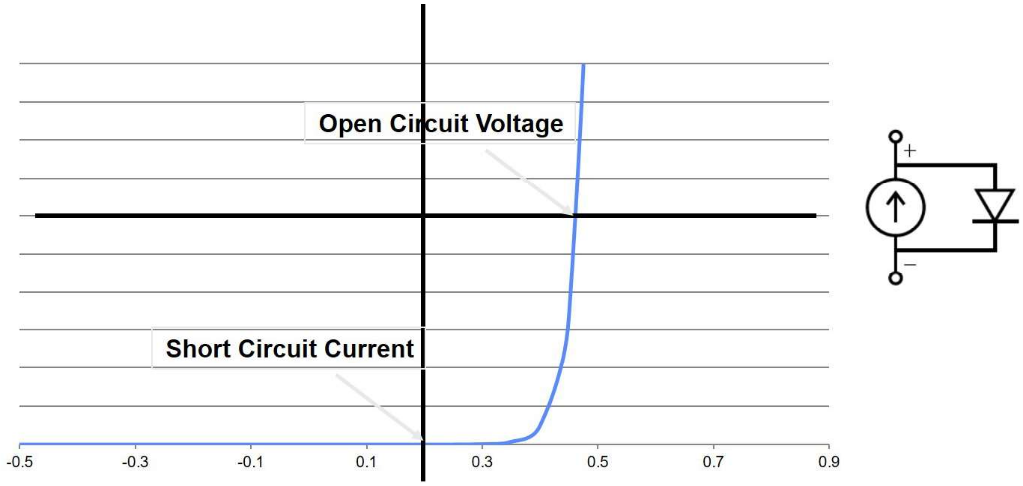


Figure 2.9: The iV curve of a solar cell when light is shining on it. Notice that this is just the iV curve for a diode shifted down by the value of the current source: we just added a constant current to the diode current.

and the mobile - will be pushed to the side that has mobile - charges. This means that each photon that strikes the solar cell near the junction generates a current between the positive and negative leads, and can be represented by a current source, as shown in Figure 2.8. Solar cells are made with the junction close to the surface, so that most of the light get absorbed close to the junction and can generate current.

This means if you take a solar cell out in the light and connect your current meter between its two leads, you will directly measure this photon current. The current meter will keep the diode voltage below its turn on voltage (with is around 0.7 V, so not current will flow through the diode, and the current flows through the meter.

Question: What happens if nothing is connected to the solar cell leads?

If you put a solar cell in the light, photons will turn on the current source. Remember a current source will create any voltage needed to maintain its current. This current will start increasing the voltage across its terminals and as it does the solar cell diode will start to turn on. Eventually the voltage will exceed the forward voltage of the diode, and all the photon generated current will flow back though the diode. Essentially the photo current will forward bias your solar cell diode, and you can see this effect by measuring the voltage across the solar cell.

The iV characteristics of this device can be found by adding together the current from the current source and the current from the diode and is shown in Figure 2.9. The only tricky part is that the current source flows out of the positive terminal and into the negative terminal, which means from the conventional labeling for the diode this is a negative current. This added current means that this device can operate in three different quadrants, and one of them can supply power to the circuit. In the lower right quadrant the solar cell is providing power to the circuit.

This iV plot makes it very simple to see the current we will measure when we short out the solar cell with our current meter (the short circuit current), and what voltage will appear if we don't allow any current to flow out of the device (the open circuit voltage). The open circuit voltage is

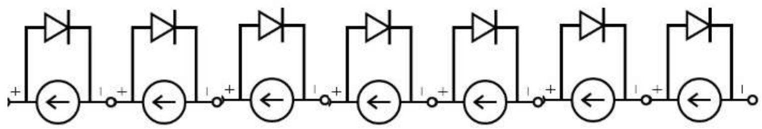


Figure 2.10: How a solar cell can generate a higher voltage by stacking many cells in series.

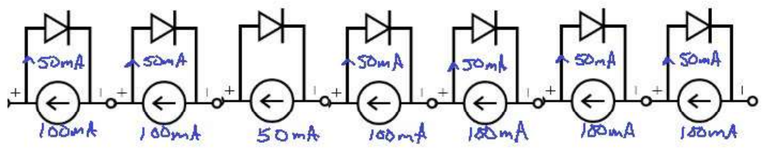


Figure 2.11: This figure shows the current path when one of the solar cells in a stack is partially blocked.

the point where the net current from the device is zero, and the short circuit current is the point on the curve where the voltage across the device is zero. While these points are easy to measure, neither of those points allow you to extract much power from the solar cell. Since power is iV, the power you extract in both of these situations is about zero. One has roughly zero voltage, and one has zero current.

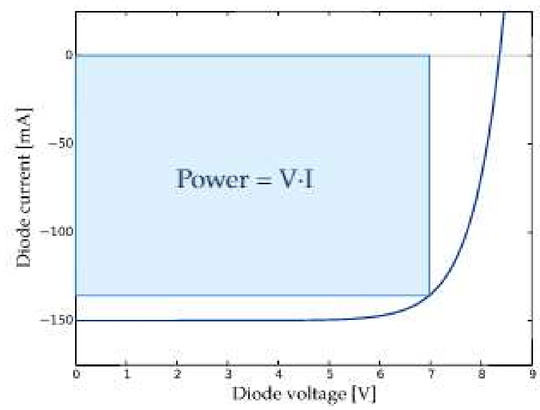
If we use our idealized model for the silicon diode, that is the current through it is zero until the forward voltage is V_F, then the open circuit voltage would be V_F, and if I moved just a hair below that voltage, I would still be able to extract all of the available current. In this case the max power I could get from the solar cell is $I_{SC} \cdot V_{OC}$. While this is a guaranteed not to exceed power number, the maximum power you can get from a solar cell is only slightly smaller than this number.

While a large solar cell can generate a lot of current, the max voltage is limited by the forward voltage of the diode, which for silicon is around 0.6V. Since our battery is 3.7 - 4V, it will never generate enough voltage to charge the battery. There are a couple of solutions for this problem. Most solar cells increase the output voltage by putting a number of solar cells in series, as is shown in Figure 2.10.This approach works and is how most solar panels are made, but still has a major weakness: the only path for the photo-current is through the series connected current sources.

Question: What happens if 6 of the current sources in Figure 2.10 generate 100 mA but one of the cell is partially blocked and only generates 50 mA?

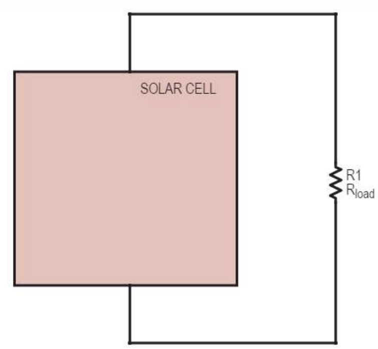
In this circuit the diode only conduct current from left to right, while the current source are producing current that flows from right to left. The only path for this current is through the next current source, so if one of the current sources in the string is only 50 mA, the total current from the entire string will only be 50 mA. When the 100 mA current reaches this device, half of the current will flow through the weak current source, and the other half will flow to the right, through the diode that is in parallel with the current source as shown in Figure 2.11.

Problem 2.7
We will solve some problems related to a solar cell which has the specifications as shown in the graph below. It provides power of 1W at an output voltage of 7V.



1.) How much current does the solar cell provide when its output voltage is 7V?

2.) Consider the solar cell connected to a load resistor as shown below.



What value of R_{load} will draw the maximum power from the solar cell?

3.) For this question we will again consider the same circuit of a solar cell connected to a load resistor. You do not know what the value of the resistor is. The voltage across the resistor is 3V. **What is the current flowing through the resistor? Knowing this, what must be the value of the resistor?**

2.7 Solutions to practice problems

Solution 2.1:
V_1=5V, V_2=5V

Solution 2.2:
I_1=1A, I_2=1A

Solution 2.3:
I_1=50mA, I_2=22.7mA
V_1=100V, V_2=220V

Solution 2.4:
Ideal diodes
D1 and D4 are on, while D2 and D3 are off. It would be a helpful exercise to check the current through the diode for the case of it being on, and then being off, to convince yourself that for the diode to be on, the current through it must be positive.

Non-ideal diodes
Solution 2.5:
Only D3 is turned on. The current through I_1 is simply $I_1 = \frac{V}{R} = \frac{5-3}{100} = 20mA$.

Solution 2.6:
Non-ideal diodes

For circuit A:
Diodes D1 and D2 are both turned on.
$I_1 = \frac{5V-1V}{50} = 80mA$
$I_2 = \frac{5V-2V}{50} = 60mA$.
The voltage source provides a fixed voltage which is always greater than their forward voltage, and provides however much current the circuit requires. Hence, both diodes are always turned on.

For circuit B:
This circuit is more complex than it initially appears. It is important to understand here that the current source can have ***any*** *voltage across it. By making different assumptions about which diodes are on, the voltage across the current source will change. Therefore, for this kind of circuit, we first make a "guess" of which diodes are on, then check our assumptions. Essentially, this is a chance for you to practice applying steps described above to solving more complex diode circuits*

To solve this particular circuit, the steps we take are as follows:
1. Assume D4 on. (Arbitrary choice - you can always choose another option, but preferably one easier to solve)
2. Solve the circuit with this assumption: The voltage across the current source is: $V_I = 2V + 20mA \times 150 = 2V + 3V = 5V$ However, if this is the case, then D3 must also be on.
Hence our assumption is incorrect. D3 is also on.
3. Solve the circuit with this assumption:
- Let's call the voltage across the current source V_{tot}.
- Voltage across $R_3 = V_{R3} = V_{tot} - 1V$
- Voltage across $R_4 = V_{R4} = V_{tot} - 2V$
- By Kirchoff's current law: $20mA = \frac{V_{R3}}{R3} + \frac{V_{R4}}{R4} = \frac{V_{tot}-1V}{R3} + \frac{V_{tot}-2V}{R4}$
- Solving the above equation, we find that $V_{tot} = 3V$. This is enough voltage to turn both the diodes on so this assumption is correct.
4. Thus:
$I_3 = \frac{2}{150} = 13.3mA$
$I_4 = \frac{1}{150} = 6.6mA$

Solution 2.7:
1.) Output power is 1W at 7V, so:

$$I_{out} = \frac{P}{V} = \frac{1}{7} = 142mA$$

2.) Maximum power is drawn when $V = 7V$ and $I = 142mA$. The only resistor value for which that is true is $R = \frac{V}{I} = \frac{7}{142mA} = 49.3\Omega$.

3.) You can simply read of the specifications graph. At an output voltage of 3V, the solar cell delivers 150mA of current. Hence the current flowing through the resistor is 150mA. The resistor value must then be 20Ω.