Engineering Mini Holiday Lights

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The small light bulbs we are using for our activities were cut from strings of mini holiday lights. The strings contained 100 light bulbs arranged in two sets of series circuits (50 lights in each series circuit). This paper will explore the reasons why the bulbs were designed to operate in series circuits.

If your parents own strings of incandescent mini holiday lights, they might tell you they have had trouble with them after a few years of use. If a light bulb burns out or is no longer tight in its socket, all of the lights in the circuit may not glow when plugged in. It can be frustrating to find the bad bulb and replace it to repair the light string. You might ask why the lights were designed to operate in a series circuit due to this problem. In this paper I will try to explain why the lights were designed in series circuits. The explanation will include some math that might be difficult to understand. But if you look carefully at the math, you will discover that it is really nothing more than adding, subtracting, multiplying and dividing.

Series and Parallel circuits

After you have completed lesson one on series and parallel circuits, you should have some understanding of the way electricity behaves in these circuits. Let us review the two circuit types and cover some important points that will help you understand the rest of this paper.

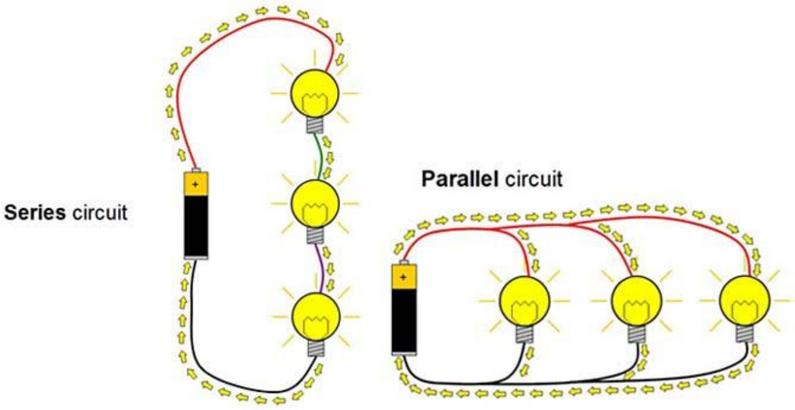

Figure 1 series and parallel circuits

In a series circuit the current flows through one bulb, then the next and then the next. What if we remove one light bulb from the circuit? Then the circuit becomes open and none of the bulbs will have current flowing through them. The situation for a parallel circuit is different. You will notice that the current is divided into separate paths for each bulb. If we have three identical bulbs in parallel, they each receive one third of the current flow from the battery. Each electron in the current flow can go through only one of the three bulbs. In the parallel circuit, if we disconnect one light bulb, there still are two closed paths for current flow through the remaining two bulbs. In a parallel circuit, if one light bulb burns out, the remaining ones continue to operate because they still have a closed circuit for current to flow through the bulb. That is an important difference between series and parallel circuits.

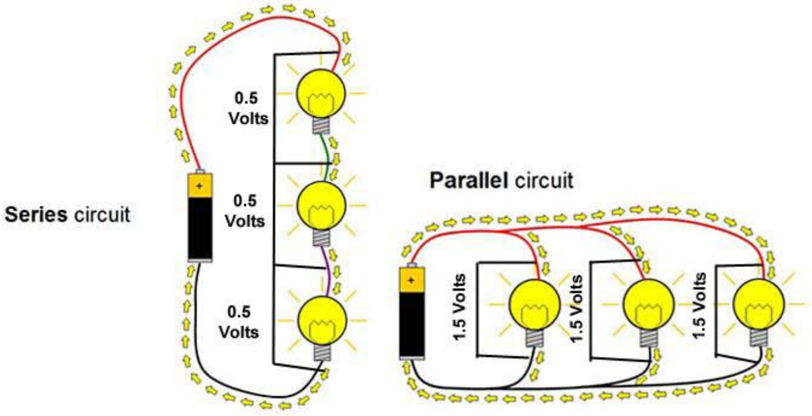

Figure 2 voltage drops in series and parallel circuits

When we make measurements of voltage and current in series and parallel circuits we discover some significant differences. In Figure 2 we see that both circuits are connected to a single cell battery (which supplies 1.5 volts). In the parallel circuit the voltage across each bulb is 1.5 volts. Each bulb is subjected to the full voltage of the battery. The series circuit is much different. Part of the voltage is consumed by each bulb. If the bulbs are identical in their electrical properties, then we need to divide the total voltage by the number of bulbs to find the voltage drop that each bulb experiences. For the circuit in Figure 2 we divide the total voltage by 3 bulbs (1.5 volts/3 bulbs = 0.5 volts per bulb) to find that each bulb in the series circuit has a voltage drop of 0.5 volts. The bulbs in the series circuit experience only one third of the voltage of the light bulbs in the parallel circuit. You probably noticed in your experiments that when you connected the three light bulbs in the series circuit to 1.5 volts, they were not nearly as bright as the bulbs in the parallel circuit. In fact, 0.5 volts may not have been enough for the lights to glow at all.

To summarize then, in the series circuit the **voltage** is divided between the bulbs and in the parallel circuit it is the **current** that is divided between the bulbs. In the series circuit the current is the same for each bulb and for the parallel circuit the voltage drop is the same for each bulb.

What if we placed 50 light bulbs in series, as in our example of a string of mini holiday lights? If we applied only 1.5 volts to 50 light bulbs in series, each bulb would have a voltage drop of only 0.03 volts (1.5 volts/50 lights = 0.03 volts per bulb). That would not be near enough voltage to make the light bulbs glow. What if we applied 120 volts, the amount of voltage that should be applied to the string of mini holiday lights? Then the voltage drop of each bulb would be 2.4 volts (120 volts/50 lights = 2.4 volts per bulb). The 2.4 volts is enough to make the mini light bulbs glow. In fact, the mini light bulbs are engineered to operate properly with a 2.4 volt drop.

Resistance in Conductors

We use wires to transmit electricity. In most circuits the wires contribute very little resistance to current flow and we can ignore that small amount of resistance. However, if the diameter of the wire is especially small or the wire is unusually long, then we may need to account for the resistance of the wire. As we *double the length of a wire, the resistance of the wire doubles*. As we *reduce the diameter of a wire by half, the resistance of the wire increases by a factor of four*. I think it is easier to understand the relationship of wire length to resistance. It just seems to make "common sense" that a wire would have twice the resistance if we double the length. But what about the factor for wire diameter? Why does the resistance increase by a factor of four if we reduce the diameter by a factor of two?

If we cut a wire and look at the end it looks like a circle. Let us make this explanation a bit easier to understand by imagining the wire is square in cross section. When we cut it and look at the end it looks like a square.

The area of a square is calculated by multiplying the length of one side by the length of a second side. Suppose our wire measures 2 inches on a side (it is a very big wire). Then the area of the cross section of the wire would be 4 square inches (2 inches x 2 inches = 4 square inches).

Now imagine that each square inch of the wire could carry one amp of current (actually it could carry much more, but we will just imagine here). If one square inch of the wire cross section could carry one amp of current without getting too hot, then how much current could the entire cross section of the wire carry? It could carry four amps because it has four square inches of cross section.

Suppose we compare the two-inch wire with a wire that is half the diameter (please forgive me for using the word diameter improperly, which should only be used with circles – remember we are imagining that circular wire is square). The smaller wire would be one inch on a side. The one-inch wire would have one square inch of area (1 inch x 1 inch = 1 square inch). It could carry only one amp. There is our answer. The wire that is two inches on a side can carry 4 amps and a wire half that diameter (one inch) can only carry one fourth of 4 amps or one amp.

Perhaps this concept is easier to appreciate if you can see the size of the wire cross sections. Figure 3 is a drawing of four wires with one square inch of cross section each (on the left) and another wire with four square inches of cross section (on the right). White lines drawn over the larger cross section should help you realize that it has the same area as four one-inch square wires. Can you see that the larger cross section can carry four times more current?

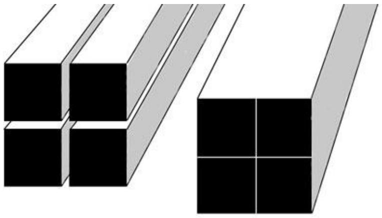

Figure 3 wires with square cross sections

Engineering the Incandescent Light Bulb

We should now consider the design of an incandescent light bulb. Figure 4 is a photo of a 120 volt, 100 watt incandescent light bulb. Inside the bulb there is a filament made from tungsten wire. When the electric current passes through the filament it gets very hot and produces light. The resistance of the filament is determined by its length and diameter. If we want to design a bulb that consumes a certain amount of electrical power, then we must design the filament with the proper length and diameter.

Figure 4 120 volt, 100 watt bulb

The glass bulb surrounding the internal parts functions to protect the fragile filament. The diameter of the filament wire is quite small, on the order of one to a few thousandths of an inch in diameter. It would be very easy to break the wire by just grabing and pulling on it. The filament cannot be heated in an atmosphere containing oxygen because that will result in a chemical reaction that will consume the wire. In just a matter of about one second the wire will be consumed to the point that it will break.

When light bulbs were first manufactured commercially in the 1880s, the bulbs were evacuated with a vaccum pump to remove nearly all the air and then sealed. Therefore, there was almost no oxygen inside the bulb, which protected the filament from oxidation. In air, a heated tungsten filament undergoes the following oxidative chemical reaction:

$$2W + 3O_2 \rightarrow 2WO_3$$

Well, unless you have had chemistry in high school, you may have no idea how to understand the reaction I have given above. So let us go over that. The chemical symbol for tungsten is W, oxygen is O, and the trioxide of tungsten is WO_3. In air, oxygen exists as a molecule comprised of two atoms of oxygen (that is why we write it as O_2). On the left side of the reaction we have two atoms of W, which is tungsten, and 3 molecules of O_2 (which is 6 atoms of oxygen). When we apply a great amount of heat, a reaction occurs (represented by the arrow). The tungsten atoms combine with the oxygen atoms to form a trioxide of tungsten. This oxide is a white powder, not a metal. The reaction results in consumption of the metal wire. That is why we must remove oxygen from the region of the hot filament to insure that it will not be immediately consumed during operation.

While the absence of air protects the filament, it was soon appreciated that an evacuated bulb was not the best design. Under a high vacuum, the heated filament **sublimates** at a moderately fast rate. Sublimation is a process similar to evaporation. In evaporation, matter in the liquid state is converted to the gaseous state. You know that if you put a pan of water out on a hot day it will evaporate into the air. Sublimation is a change from the solid state (like a metal wire) to the gaseous state. Even metal will sublimate if heated to high enough temperatures. And the rate of sublimation is increased under low gas pressures (*i.e.*, a vacuum). If you look at a light bulb that has operated for many hours, you should notice that the glass bulb is partially darkened. That dark material is the tungsten metal that sublimated off the tungsten wire and deposited itself on the inside surface of the glass bulb. Figure 5 shows microscopic views of a new filament (top) and a used filmaent (bottom). The new filament is wrapped around a central wire, to form the coils, and then the central wire is removed. The bottom photo shows the crystal structure of the tungsten which is revealed after some of the tungsten is eroded from the filament due to sublimation.

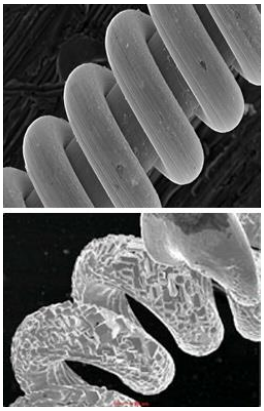

Figure 5 new filament coil top, used filament coil bottom

In order to reduce the rate of sublimation of tungsten filaments, light bulb manufacturers made a change to the manufacturing process. The bulbs were filled with an inert gas such as argon or nitrogen (or a mixture). Inert gases donot react with the filament when it is hot. Modern incandescent bulbs are usually filled with an inert gas. This change in design resulted in slower rates of filament sublimation, which allowed operation at higher temperatures.

Figure 6 – left -evacuated bulb, right - filled with inert gas

Now the engineers were confronted with another problem. When the bulbs were filled with an inert gas, the gas allowed more heat transfer away from the hot wire by a process called convection. You can see this effect in Figure 6. The faster transfer of heat resulted in a lower temperature of the filament, and lower light output. The lower temperature filament is not as bright as the higher temperature filament.

Engineers discovered that if they coiled the filament, they could dramatically reduce the rate of heat loss, restoring the filament to a higher operating temperature. In fact, for high wattage bulbs, the usual design is a double-coiled filament (see Figure 9). This design is even better in slowing down the heat loss from the filament.

The first sucessful light bulbs were manufactured with carbon filaments. These filaments could withstand very high temperatures but sublimated too fast, resulting in a farily short filament life. During the early years of the twentieth century, it was discovered that certain metals could be used for filaments and these did not sublimate as fast as carbon. Tungsten was found to be the best metal for the purpose. Tungsten has a higher melting point then any other elemental metal. It melts at 6,192°F (3,695°K). The high melting point allows the filament to operate at a relatively high temperature, which yields more light.

Engineering the Mini Holiday Light String

When an electrical engineer designs a circuit, it is necessary to consider the properties of the components of the circuit. With enough effort and if cost is not an object, almost anything is possible. But the engineer rarely has that luxury. There are constraints that must be considered. First of all, people will be willing to pay only a limited amount for a string of holiday lights. The lights must be manufactured in a way that keeps the cost low. A nice string of lights may need to have many bulbs, say 100. But each bulb should use a limited amount of electrical power. Otherwise, your parents will not be happy when they get their electric bill at the end of the month.

Suppose you are an electrical engineer and you work for a company that makes holiday lights. It is your job to design a string of holiday lights. The company has already made some decisions regarding the properties of the lights. They want a string that contains 100 light bulbs. Furthermore, the string of lights should consume 40 watts of power. It is your job to design the light bulb and the wiring circuit.

You know that companies in the past have manufactured their light strings using series circuits and you also know that people don't like bulbs in series because of the problems we have already discussed. Your first thought is that it would be a good idea to design a string with lights in a parallel circuit. That way, if one bulb burns out, all the others will continue to glow when the string is plugged in. It will also be easy to find the bad bulb because it will be the only one that won't be glowing.

Your first task is to design a light bulb to use for your new light string. You know that if the lights are connected in parallel, each bulb will experience a voltage drop of 120 volts, which is the standard house voltage. You also need to keep the power consumption of the string of lights to 40 watts. Since there will be 100 light bulbs in the string, each bulb needs to consume 0.40 watts (40 watts/100 bulbs). Already you realize that there may be a problem with your idea. You are not sure you can design a light bulb that will run on 120 volts and consume only 0.40 watts. But you continue to work, trying to come up with a design.

You will need to design the filament for the light bulb. Since you are a light bulb engineer, you already know that the filament needs to run at a temperature of about 3,800°F (2,400°K). You consult a handbook of physics to get some information. You are looking in particular for a property of tungsten called **resistivity**. The value for resistivity of tungsten will help you calculate the dimensions of the filament wire.

You look in the handbook and find that the resistivity of tungsten is 7.0×10^{-7} Ωm at a temperature of 2,400°K. Well, that may be complicated to understand, but let us try. First of all, what is the number 7.0×10^{-7} ? When engineers and scientists do math, they often use powers of ten to represent numbers. For example, the number 100 can be written as 1×10^{2}. The number 7.0×10^{-7} is the same as 0.00000070. Now what about the Ωm part? The symbol Omega (Ω) is resistance in ohms. The letter m is meters, a unit of length in the metric system (one meter is about 3 feet). The two (Ωm) are together because resistivity is a measure of resistance in ohms as it relates to the dimensions of the wire in meters. This may be confusing at this point, but hopefully will become clear later as you study the mathematics that follow.

Remember that each of our mini light bulbs must consume 0.40 watts of electricity and that they will have a voltage drop of 120 volts if placed in a parallel circuit. Also recall the formula for electrical power:

$$\text{Watts} = \text{Volts} \times \text{Amps}$$

We need to know how much current will flow through each light bulb. We know the watts and volts, so we can use the formula above to calculate the amps.

$$0.40 \text{ watts} = 120 \text{ volts} \times \text{amps}$$

Rearranging the equation we have:

$$\text{Amps} = 0.40 \text{ watts}/120 \text{ volts} = 0.0033 \text{ amps}$$

Now we are really starting to worry about our bulb design. With 120 volts applied to the bulb filament, it must have enough resistance to keep the current flow at a very low level, 0.0033 amps. We know that the filament will have to be very long in order to have enough resistance. But how much resistance will be needed? We can use Ohm's Law to calculate the resistance:

Resistance = Volts/Amps

Resistance = 120 volts/0.0033 amps = 36,000 ohms

Wow! The bulb filament will have to have 36,000 ohms of resistance for a current of 0.0033 amps at an applied voltage of 120 volts. That is going to be a problem. How long must the filament be to provide 36,000 ohms resistance? Well, this is where we use the resistivity to calculate the length of the filament. Here is the formula:

Length = (Area x Resistance) / Resistivity

The area is the cross section area of the filament wire. The tungsten filament wire for our mini light bulbs has a diameter of 25 micrometers (µm). I happen to know this because I made measurements with my microscope. So let us use that diameter in our design. A micrometer is one millionth of a meter. Our resistivity value for tungsten is in meters. Therefore we need to convert 25 µm to meters:

25 µm/1,000,000 = 0.000025 meters

To calculate the cross section area of the wire we need to use the formula for the area of a circle (the radius is half the diameter):

Area = radius x radius x π

Area = 0.0000125 meters x 0.0000125 meters x 3.14

Area = 4.9×10^{-10} m^2 (or 0.00000000049 square meters)

In case you have not learned this yet, the value for Pi (symbol π) is approximately 3.14. It is a special number we can use when calculating things having to do with circles.

Now we know the cross section area of the filament wire (0.00000000049 square meters) and the required resistance of the filament (36,000 ohms). That is all we need to calculate the length of the filament using this formula:

Length = (Area x Resistance) / Resistivity

Length = (0.00000000049 m^2 x 36,000 Ω)/ 0.00000070 Ωm

Length = 0.000018 Ωm^2/0.00000070 Ωm = 26 m

The filament must be 26 meters long! If we convert that to the English system it is equivalent to 85 feet. How are we going to fit 85 feet of filament wire into a small mini light bulb? It is not possible. We have just discovered why mini light bulbs cannot be wired using a parallel circuit. It was a good idea, but it is just not possible. Therefore, we need to consider the design of the bulb using a series circuit to see if that will work. But first, let us take a look one more time at the last calculation.

$$\text{Length} = 0.000018\ \Omega m^2/0.00000070\ \Omega m = 26\ m$$

Remember I said previously that the symbol group Ωm for resistivity would become clear as you followed the mathematics. It is the calculation above that hopefully will make it clear. Notice that the value in the numerator is 0.000018 Ωm^2. We want to pay attention to the unit Ωm^2 (ohm-meter-squared). Where did that come from? We got that when we multiplied the area of the wire (in square meters or m^2) by the resistance needed in ohms (Ω). Multiplying square meters by ohms gives us the unit Ωm^2. Now notice what we have in the denominator: 0.00000070 Ωm, which is the resistivity. When we divide Ωm^2 by Ωm, then the answer is m, meters. That is the unit of length we need for the calculation:

$$\Omega m^2/\Omega m = m \text{ (or meters)}$$

Well, I am not sure that is as clear as I hoped to make it, but I tried my best.

Let us change our design now to a series circuit. When we connect the light bulbs in series, each bulb drops much less voltage than when connected in parallel. In a series circuit the voltage is divided evenly between the bulbs in the circuit. We have 120 volts total to be divided between 50 light bulbs in series:

$$120 \text{ volts}/50 \text{ bulbs} = 2.4 \text{ volts per bulb}$$

Now we should calculate the amount of current that must flow through a bulb if it is to consume 0.40 watts of power at an applied voltage of 2.4 volts:

$$\text{Power} = \text{Volts} \times \text{Amps}$$

$$0.40 \text{ watts} = 2.4 \text{ volts} \times \text{amps}$$

$$\text{Amps} = 0.40 \text{ watts}/2.4 \text{ volts} = 0.17 \text{ amps}$$

Already we can see that this might work. We need a current of 0.17 amps flowing through the light bulbs at an applied voltage of 2.4 volts. Compare that to the parallel circuit where we needed 0.0033 amps flowing at 120 volts. When placed in series, the light bulbs will be able to carry 50 times more current than when placed in parallel. We will need much less resistance in the filament to allow a current of 0.17 amps, which means that the filament can be much shorter. So now let us calculate out the required resistance:

$$\text{Resistance} = \text{Volts}/\text{Amps}$$

$$\text{Resistance} = 2.4 \text{ volts}/0.17 \text{ amps} = 14 \text{ ohms}$$

Now that we have the required resistance, let us calculate the length of the filament

$$\text{Length} = (\text{Area} \times \text{Resistance}) / \text{Resistivity}$$

$$\text{Length} = (0.00000000049\ \text{m}^2 \times 14\ \Omega)/ 0.00000070\ \Omega\text{m}$$

$$\text{Length} = 0.0000000069\ \Omega\text{m}^2/0.00000070\ \Omega\text{m} = 0.0099\ \text{m}$$

The filament will need to be 0.0099 meters long. Converted to the English system, 0.0099 meters is about 0.39 inches long. We can fit a filament 0.39 inches long into a mini light bulb, especially if we coil the filament as seen in Figure 8. There is a dramatic difference between 0.39 inches and 85 feet!

These calculations reveal why we must use a series circuit for our design of a set of mini holiday lamps. This math may not be easy to understand at first. But if you really have the desire to understand the math, take a close look at what I have done. It is nothing more than addition, subtraction, multiplication and division. These calculations are the same ones an engineer would use to find the required dimensions of a bulb filament.

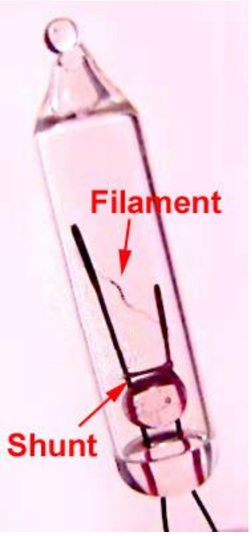

Figure 7 mini light bulb

Is there a way to improve the series circuit so that we don't have problems when a light bulb burns out? As it turns out there is a way! By adding a shunt to the bulb design, it is possible to maintain a string of lit bulbs even when a bulb burns out. The clever design uses a wrapping of wire around the base of the filament electrodes (see Figure 7). Normally this wire has more resistance than the filament. When the filament breaks, electrical current passes through the shunt to maintain a closed circuit. Light bulbs can still work loose from their sockets and the shunt does not overcome that problem. Therefore, you will need to check for loose bulbs if your lights are not working.

Figure 8 magnified view of mini bulb coiled filament

I wanted to see how my theoretical calculations for a mini bulb filament compared with the actual length of a mini bulb filament. I did this by using a microscope equipped with a special eyepiece that allows the measurement of small things. I found that the diameter of the filament coil was 161 micrometers (µm) and as already mentioned, the wire diameter was 25 µm. To make the calculation in the proper way, we must calculate the diameter of the coil from the center of the wire thickness. That is done simply by subtracting the diameter of the wire from the diameter of the coil (161 µm – 25 µm = 136 µm). The circumference of the wire coil is calculated by multiplying its diameter by π (136 µm x 3.14 = 427 µm). Therefore, each turn of the filament coil is 427 micrometers long. Now all we need to do is count the number of turns in the filament coil, which I found to be 27 turns. To find the total length of the wire in the coil we just multiply the number of turns by the length of each turn (427 µm x 27 = 12,000 µm). A micrometer is one millionth of a meter, so if we divide by one million, we get a length of 0.012 meters. The filament coil contains 0.012 meters of tungsten wire. That is a little longer than my theoretical calculation of 0.0099 meters long.

I started to wonder if there is a reason why the actual filament was slightly longer than the length calculated by theory. I decided to look at the filament under the microscope while applying 2.5 volts. I found that the coils on the ends of the filament were not glowing! I estimated that about three turns of the filament coil were not glowing. To make a proper calculation we must then account for only those turns of the filament that do glow when voltage is applied. There are 24 turns of the coil that glow:

427 µm x 24 = 10,000 µm or 0.010 meters

Therefore, the operating portion of the mini bulb filament was measured to be 0.010 meters long. Compare that to the calculated length by theory, which was 0.0099 meters long. The theoretical value is only 0.0001 meter short of the actual measurement. That is, it is only 1% short. Within the error limits of my methods, the two values should be considered the same. This demonstrates that the theoretical calculation can be trusted to give us the proper value for filament length.

Hot and Cold Filaments

In a future lesson you will work with resistors and will measure the resistance of resistors with a meter. I did not have you measure resistance of the filaments in your light bulbs because the resistance of a room temperature filament is much less than a filament at its operating temperature. As a conductor increases in temperature, its resistance increases due to the increased vibrational movements of the atoms in the metal (the hotter something gets, the more strongly its atoms vibrate). It is more difficult for electrons to move through the metal when the metal atoms are vibrating vigorously. That is why the resistance rises with temperature.

Recall that the resistivity of tungsten is 7.0×10^{-7} Ωm at a temperature of 2,400°K. At room temperature, 293°K (68°F), the resistivity of tungsten is much less, 5.6×10^{-8} Ωm (or 0.000000056 Ωm). Recall also that our mini light bulb filament has 14 ohms of resistance at its operating temperature. Let us now calculate the resistance of the filament at room temperature. To make it easier, we first rearrange our formula to this:

Resistance = (Length X Resistivity)/Area

Resistance = (0.014 meters X 0.000000056 Ωm)/ 0.00000000049 m^2

Resistance = 0.00000000078 $\Omega\mathrm{m}^2$/ 0.00000000049 m^2

Resistance = 1.6 Ω

The mini light bulb filament will have 1.6 ohms of resistance when cold and 14 ohms of resistance at its operating temperature. That is a large difference in resistance.

If you are reading carefully you might wonder why I used a length of 0.014 meters for the filament length in the above calculations since the wire length of the coil was calculated to be 0.012 meters.

There is a small length of straight wire on each end of the coil (about 0.001 meter long) which must be included when calculating the cold resistance.

I made some measurements of filament resistance with my meter. It is not possible to directly measure the resistance of the bulb while the filament is at its operating temperature. However, we can measure the voltage drop across the bulb and the current flowing through the bulb. Then we use Ohm's Law to calculate the resistance. I did this for 6 bulbs and averaged the results. I found that the average resistance was 14 ohms.

Measuring the room temperature (cold) resistance of the bulbs is more difficult. The meter applies some voltage to the bulb when it measures resistance. Therefore, a small current flows through the bulb and the bulb filament heats to a slightly higher temperature. That causes the resistance measurement to be too high. To eliminate some of that effect, I measured the resistance of several bulbs in series. I found that the resistance of 9 bulbs in series was 19.5 ohms, or 2.2 ohms per bulb. Therefore, my measurements for a cold filament resistance are slightly higher than the value of 1.6 ohms calculated by theory. I suspect that the difference is due primarily to the limitations of my meter in making an accurate measurement at low resistance values.

The Standard 100 watt light bulb

Now we will do some more calculations. A common size light bulb found in homes is the 100 watt bulb (see Figure 4). The filament wire for this type of bulb typically has a diameter of about 46 µm and a cross section area of 0.0000000017 m^2. The bulb operates at about 2,870°K (a higher temperature than the mini light bulb). The resistivity of tungsten at 2,870°K is 8×10^{-7} Ωm. Let us do some calculations for this type of bulb.

$$100 \text{ watts} = 120 \text{ volts X amps}$$

$$\text{Amps} = 100 \text{ watts}/120 \text{ volts} = 0.83 \text{ amps}$$

Now we use Ohm's Law to calculate the hot resistance of the 100 watt bulb:

$$\text{Resistance} = \text{Volts}/\text{Amps}$$

$$\text{Resistance} = 120 \text{ volts}/0.83 \text{ amps} = 140 \text{ ohms}$$

Then calculate the length of the filament:

$$\text{Length} = (\text{Area x Resistance}) / \text{Resistivity}$$

$$\text{Length} = (0.0000000017 \text{ m}^2 \text{ x } 140\ \Omega)/ 0.0000008\ \Omega\text{m}$$

$$\text{Length} = 0.000000024\ \Omega\text{m}^2/0.0000008\ \Omega\text{m} = 0.3 \text{ m}$$

$$0.3 \text{ m} = 12 \text{ inches}$$

A 100 watt, 120 volt bulb has a filament about 12 inches long. But the diameter of the bulb is much less than 12 inches. To fit the filament inside the bulb, it is coiled. Actually it is double coiled as you can see in Figure 9, a magnified view of the tungsten filament. The mini holiday bulb has a much shorter filament, which only needs to be coiled one time (see Figure 8).

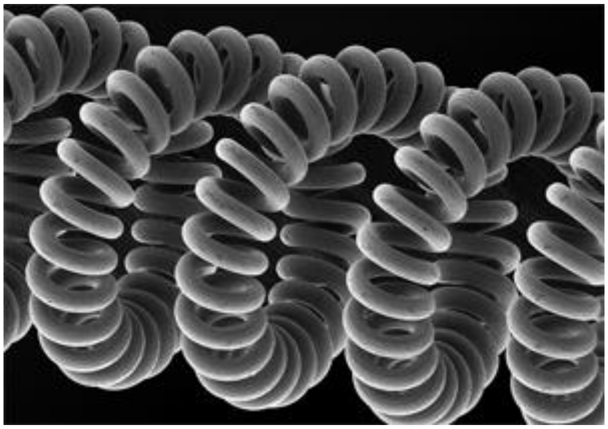

Figure 9 microscopic view of double coiled filament

History and Future of Light Bulbs

The incandescent light bulb has a commercial history that dates back about 130 years, when the first bulbs became available to the public in the 1880s. This was also the start of the electric generation industry, which supplied electricity to run the incandescent bulbs. As technology advanced, other uses were found for electricity, especially for running electric motors. Today we use electricity for many things.

The incandescent light bulb is now considered old technology and is being replaced by more efficient types of lighting. About 90 to 95 percent of the electrical power consumed by an incandescent bulb is lost in the form of heat. Five to ten percent of the energy is used to make light. Other types of lighting, such as fluorescent bulbs and LED bulbs, are much more efficient in producing light. As time goes on we will see fewer incandescent light bulbs being used to light homes and other buildings. They will be replaced by more efficient light sources.

Figure 11 LED bulb

Figure 10 compact fluorescent bulb

Light

Now that we have learned about incandescent light bulbs, it occurred to me that it might be a good idea to cover the topic of light. What is light? I have to admit that it is a mysterious thing, just as electric charge and gravity are mysterious things.

The study of light, as well as electricity, falls under the science of physics. We can say that light and electricity are related to each other because light is produced by electrons. When an electron jumps down from a high energy orbit around the atomic nucleus to a lower energy orbit, a photon of light is emitted. It is the loss of electron energy that creates light energy. It is a law of physics that energy must be conserved. When energy in some form is reduced, an equivalent amount of energy must be increased in another form. When energy is lost from the electron, it is conserved by the creation of energy in the form of a photon of light.

Light detected by the human eye is said to be visible light. Visible light is part of the **electromagnetic spectrum**. The complete spectrum includes radio waves, microwaves, infrared light, visible light, ultraviolet light, x-rays and gamma rays. I am sure you have already heard something about these different parts of the electromagnetic spectrum. The radio in your parents' car receives broadcasts from radio stations by tuning radio waves transmitted through the air. Wireless devices such as cell phones tune radio waves transmitted by cell towers. The microwave oven in your kitchen produces microwaves to heat food. The remote control for your TV uses infrared light to transmit signals to the TV. Visible light is that part of the electromagnetic spectrum that humans can see. If you stay out in the sun too long on a summer day, you will get a sunburn, caused by ultraviolet light. Your dentist uses an x-ray machine to take images of your teeth. The machine emits x-rays.

As hard as it might be to believe, all of these (radio, microwave, light, etc.) are electromagnetic radiation. They are the same thing. The only difference is the wavelength of the electromagnetic radiation. Radio waves have the longest wavelength and gamma rays have the shortest wavelength. Learning about the entire spectrum would take some time. For now we will just concentrate on visible light and infrared light. Those are the parts of the spectrum we will be concerned with when studying light bulbs.

Light (and all electromagnetic radiation) is rather strange in that it has properties of a particle and properties of a wave. That is, it behaves like a particle and also behaves like a wave. The particle of light is called the photon. When you take a picture with your digital camera, the CCD chip (sensor) collects photons in a grid pattern, which will be converted into the pixels of an image. You could think of the CCD as a bunch of tiny cups that collect the photons. The more photons collected in one cup, the brighter that pixel will be in the image.

It would be easier to understand light if it just behaved like a particle. However, when we study light we find that it also behaves like a wave. These two properties may seem to be incompatible, which is part of the mystery of light. In fact, in early studies of light, scientists argued with each other, some believing light to be a wave, others a particle. It was finally realized that it is both!

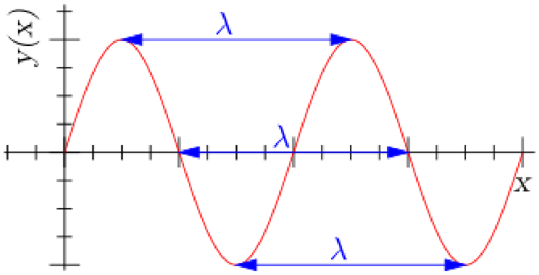

Figure 12 graph of waves

The wave character of light is rather difficult to understand and for our purposes we will not attempt to understand it at a deep level. We can just say that light is a wave. You can't see the waves, but there are methods to measure the waves. In fact, your eyes can be used as an instrument to measure waves of visible light. The measurement we are interested in is the wavelength, the distance from the crest of one wave to the next. Let us take the example of water waves. If you drop a stone in a pool of water, waves radiate away from the location where the stone enters the water. Those waves are actually an up and down movement of the water surface. The crest of the wave is the point where the water is highest. If we measure the distance from one wave crest to the next, that is the wavelength. Figure 12 is a graphic of waves with the wavelength marked. Scientists use the symbol Lambda (λ) for wavelength.

In the case of visible light, the wavelength is very small. We use the unit nanometer (nm) for measuring the wavelength. A nanometer is one billionth of a meter ($1 \text{ nm} = 1 \times 10^{-9} \text{ m}$). There are 1,000,000,000 nanometers in one meter. Visible light ranges from 400 nm to 700 nm in wavelength. One interesting thing about visible light is that the color of the light depends on its wavelength. Red light is in the region of 650 nm and violet is about 400 nm. As wavelength decreases, the color of visible light goes from red to orange to yellow to green to blue to violet (the colors of the rainbow). Therefore, your eyes do measure, in an approximate way, the wavelength of visible light.

What about white light? As it turns out, white light is a mixture of all the colors of the rainbow. You probably know that if white light is passed through a prism, it is separated into all the colors of the rainbow. You can do the reverse experiment as well. If you shine a blue light, a green light, and a red light at the same place on a screen it will seem like magic: the color will be white. If you look closely at your TV screen in an area that is white, you will notice small dots of green, blue and red next to each other. The display screen creates different colors just by mixing those three colors together in various amounts. If all three colors are equally bright, then the color will be white. When I think about white, it seems intuitively to be the absence of color. In reality, white is a mixture of all colors of the rainbow. That does seem strange.

Infrared light cannot be detected by the human eye. It ranges in wavelength from 700 nm to 1,000,000 nm. While we can't see infrared light, we can feel it as heat. Much of the heat you feel from the sun on a warm day is due to infrared light. Much of the light energy produced by an incandescent light bulb is in the form of infrared light. In fact, incandescent bulbs produce much more infrared light than visible light. That is why they are so inefficient. If we could see infrared light, then incandescent bulbs would not be considered inefficient.

The amount and quality of light emitted by an object depends on its temperature. Physicists use the Kelvin system for temperature. There is a low limit to temperature known as absolute zero. Nothing can be colder than absolute zero. Material at absolute zero is at a temperature of zero degrees Kelvin

(0°K). In the United States we also use the Fahrenheit system for temperature measurement. Absolute zero is -459.67°F. Wow, that is pretty cold! Water freezes at 273°K and boils at 373°K. Steel melts at about 1,644°K (2500°F).

Any material above absolute zero in temperature will emit electromagnetic radiation. At cold temperatures the radiation has long wavelengths. As the temperature rises, the radiation includes shorter and shorter wavelengths. At a temperature of about 800°K, we can see a dim glow of red light emitted. Typical incandescent light bulbs run at temperatures between 2800 and 2900°K. Figure 13 is a graph of the wavelengths of radiation emitted by 60, 100 and 150 watt light bulbs. You should notice that the highest point on the curve for each bulb is at a wavelength longer than visible light. You should be able to appreciate from the curves that the majority of electromagnetic energy emitted by incandescent light bulbs is in the region of infrared light. Since humans can't see infrared light, it represents wasted energy, lost in the form of heat.

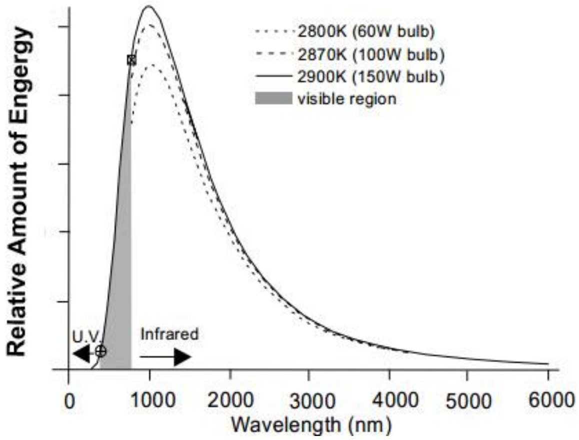

Figure 13 light curves for incandescent bulbs

Wien's displacement law provides a formula for calculating the wavelength of maximum energy output for a black body. A black body is an idealized body that absorbs all electromagnetic radiation that strikes it. The filament of an incandescent light bulb behaves approximately like a black body and we can use Wien's law with fairly accurate results. Here is the law:

Wavelength of maximum light energy = Wien's displacement constant/Temperature

$$\lambda_{max} = b/T$$

$b = 2.9 \times 10^{-3}$ Km (or 0.0029 Km)

Let us calculate the max wavelength for a 60 watt light bulb running at 2800 degrees Kelvin.

$$\lambda_{max} = 2.9 \times 10^{-3} \text{ Km} / 2800°\text{K}$$

$$\lambda_{max} = 0.0029 \text{ Km} / 2800°\text{K} = 1.0 \times 10^{-6} \text{ m (or 0.0000010 meters)}$$

The wavelength of maximum energy emission is 0.0000010 meters. We can convert that to nanometers by multiplying by one billion:

$$(0.0000010 \text{ m})(1{,}000{,}000{,}000 \text{ nm/m}) = 1{,}000 \text{ nm}$$

The wavelength of maximum energy emission for a filament at 2800 degrees Kelvin is 1,000 nanometers. If you look at the curve for the 60 watt bulb in Figure 13, you should see that the top of the curve is at 1,000 nm. Recall that visible light ranges from 400 to 700 nm. Therefore, the wavelength of maximum energy emission for the 60 watt bulb is outside the region of visible light.

Astronomers find Wien's displacement law very useful. As an astronomer, you would like to know how hot stars are. Yet they are much too far away for us to measure with a thermometer. An alternative is to analyze the light from a star. If we can measure λ_{max} of the light from a star, then we can use the law to calculate the temperature of that star.

Figure 14 is a drawing of the energy levels of electrons for the hydrogen atom, the simplest element. Hydrogen contains only one proton in its nucleus (represented by the red dot) and one electron orbiting around the nucleus. The available orbits are represented by blue circles. Normally the electron orbits around the nucleus in the lowest energy orbit, close to the nucleus (n=1). However, the electron can be bumped up to a higher orbit. This can happen for example if the atom is heated. The vibrational energy of a hot material can knock electrons into higher orbits. When the electron jumps down from a higher orbit, it emits a photon of light. The wavelength of that light will depend on the difference in energy between the higher orbit and the lower orbit. The different orbits or energy states of the electron are labeled (n=1, n=2, etc.). There are three series: Lyman, Balmer and Paschen. Let us just take a look at the Balmer series. In this series the electron jumps down from n=6, 5, 4 or 3 to energy level 2. This results in production of photons of wavelengths 410 nm, 434 nm, 486 nm and 656 nm. All of these wavelengths are visible light. If we place a little hydrogen in a vacuum tube and apply high voltage to the tube, the hydrogen will glow with these four specific colors. If we look at the glowing tube with a spectrometer (something like a prism), the light is separated into these four colors.

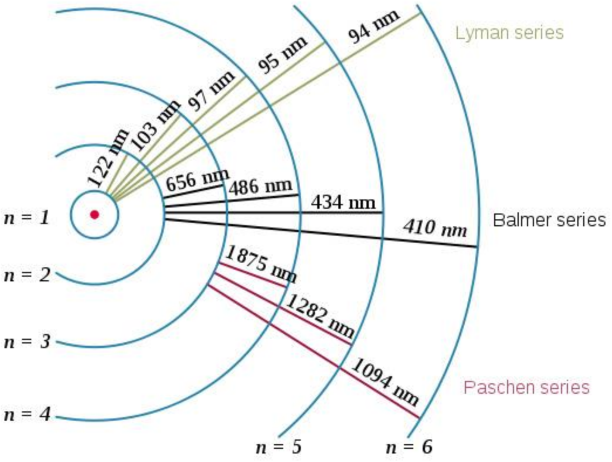

Figure 14 different orbits of the hydrogen atom

When an atom is in the gas form and is not very concentrated (*i.e.,* a relatively high vacuum), then there are a limited number of energy levels for the electron to have. In a solid (like a metal filament) the case is different. The bonds between atoms result in a myriad of electron energy levels. When a solid is heated, it produces the colors of the rainbow. That is, we can find a continuous spectrum of wavelengths.