Light Bulb Circuits

Pre-Lab: Thomas Edison and Physics with PhET

A Bit of History

In this lab you will spend quite a bit of time working with little incandescent light bulbs that probably don't seem especially impressive. But consider this: the telegraph, telephone, photograph, and steam engine were all ubiquitous before Thomas Edison introduced the first commercially viable incandescent lighting system. It is worth taking a brief look at the steps that led to Edison's great innovation.

Up until the year 1800, the study of electricity was limited almost entirely to electrostatics. Large static charges could be produced with relative ease, but extremely limited usefulness. Imagine shuffling across a carpet in your socks. That wouldn't have been too far from the state of the art. The charges produced could be stored in devices called Leyden jars, which were the forerunners of capacitors, a device that we will study in the second part of this lab. But, once again, there were no practical uses for this stored charge.

But in the first year of the nineteenth century (or last of the eighteenth?), Italian physicist Alessandro Volta invented the first battery. This was a monumental achievement, as it was the first time in the history of man that a steady electrical current could be produced. Less than a decade after the battery was introduced, English scientist Sir Humphrey Davy used an absolutely huge one to power the first ever arc light. In this light, two charcoal rods were placed nearly end-to-end, separated by only a few centimeters of air. When the rods were each connected to a terminal of the battery, the tremendous potential difference caused a very bright, continuous electrical discharge across the gap. Davy also demonstrated the incandescence of a platinum wire, showing that it became so hot when carrying a large current that it actually glowed. Sir Humphrey was not interested in developing either lighting technique any further (he was too busy discovering most of the alkaline earth metals). It was up to others to improve upon his demonstrations and make electric lights commercially viable.

Many decades later, following the invention of the first practical electrical generators (c. 1870), there were real successes in the development of the arc light. A few streets in Paris and New York were lit using many arc lights connected one after the other. In addition, some theatres and high-end retailers employed the arc light indoors. But although the arc light did not emit fumes like a gas lantern, it was still less than ideal. For one, they were so tremendously bright that one could not comfortably look in the direction of an arc light. Further, they were fairly unreliable and required dangerously high voltages. (Arc lights have come a long way since then: fluorescent bulbs are highly evolved descendants.)

After viewing an exhibition of arc lights in 1878, Thomas Edison was sure that the electric light was the way of the future. However, he believed that the incandescent light could be made to provide a more useful illumination than the arc light. When Edison began his work on the electric light, incandescent bulbs already existed, but they were nowhere near practical. Edison and his team made significant improvements to filaments, vacuum pumps, electrical generators, and electrical wiring, among other things. Four years and lots of money later, Edison proved that his faith in incandescence was well-placed when he gave electric light to a large section of Lower Manhattan (this required him to build and install all the necessary generators and wiring!). Do the little bulbs seem more impressive now?

(Most of the history in this lab comes from *Age of Edison* by Ernest Freeberg and *Empire of Light* by Jill Jonnes. There's more good stuff in there!)

Simulated Circuits

Before coming to lab and working with some real circuits, here's a chance to spend some time with simulated circuits. This will introduce you to the use of voltmeters and ammeters within a circuit, which is a vital skill this semester. Further, this Pre-Lab will give you a very brief introduction to Kirchhoff's Rules, which will form the backbone of any circuit analysis course you take in the future.

Using Voltmeters and Ammeters

Begin by reading about multimeters on the Reference page of the lab website. The Reference page can be accessed from the home page of the lab website.

Do This: Find the PhET DC Circuit applet on the Pre-Lab Links on the course website to download the virtual lab software from the University of Colorado Boulder. The applet, along with a file called *CircuitsPreLab_Kirchhoff,* will be contained in a zip file called *CircuitPreLabFiles.zip* that you may have to unzip or extract. In Olin library, this requires right-clicking the folder and selecting "Extract All" from the drop-down menu.

Do This: Open the applet.

Do This: In the "Grab Bag" located near the top right corner, there is pencil lead. Click on the pencil. It will move to the main screen. Begin by connecting a battery to the pencil lead using a couple of wires. (Please do not change the voltage of the battery.) If you do this correctly, you should see the electrons moving within the circuit.

Do This: Now add an ammeter to the circuit so that you can measure the current through the pencil. Note that correctly adding an ammeter to a circuit requires breaking the circuit. To disconnect a wire from an object, either right-click or control-click the junction. When you get the electrons flowing again, you can move on.

Do This: Now add a voltmeter to the circuit so that you can measure the voltage across the pencil. Note that adding voltmeters to a circuit is easy. You almost never need to break a circuit in order to add a voltmeter. When you get a plausible reading on the voltmeter, you can move on.

PL1. What is the magnitude of the current through the pencil lead?

PL2. What is the magnitude of the voltage across the pencil lead?

PL3. What is the resistance of the pencil lead?

Kirchhoff's Rules, Briefly

Begin by reading Appendix A on Kirchhoff's Rules.

Do This: In this part of the Pre-Lab you will be analyzing a circuit that has already been created. In the top-right corner of the PhET applet there is a button labeled *Load*. Click the *Load* button and open the *CircuitsPreLab_Kirchhoff* file. Make sure you load this file after it has been extracted from the zipped folder that you downloaded. If you try to load the version of the file that is still in the zipped folder, the simulation will likely freeze up.

Read This: Upon successful loading, you should see a circuit with a battery, a switch, three resistors, and three ammeters. The switch is open so nothing should be happening.

Do This: Close the switch using the mouse. You should see electrons (blue circles) within the wires start moving. They are moving opposite the direction of the current.

PL4. Explain how the current readings support Kirchhoff's Junction Rule. (This is also sometimes known as Kirchhoff's Current Rule. And the word *Law* is sometimes used in place of *Rule*. See Appendix A for more information on Kirchhoff's Rules.)

Do This: Use the voltmeter to measure the voltage across each resistor.

PL5. Explain how the voltages that you just measured are consistent with Kirchhoff's Loop Rule for the bottom loop (i.e. the loop that contains all three resistors).

PL6. Explain how the voltages that you just measured are consistent with Kirchhoff's Loop Rule for the outside loop (i.e. the loop that contains the battery and the two resistors on the bottom).

End of Pre-Lab

Part I: Just Light Bulbs

The Story

There's an interesting part of the Edison tale that was left out of the Bit of History. When arc lights were used to light a street, they tended to be connected to each other in *series*. When Edison began exhibiting his incandescent bulbs to investors and the interested public, he connected the lights in *parallel*, an alternative to series connections.

Why was Edison so concerned about how his lights were connected?

It's up to you to do some detective work so that you can solve this historical mystery as completely as possible. In Part I, you will explore several ways in which you can connect light bulbs to a power supply. After you've discovered how the geometry of the connection affects the operation of the bulbs, you'll explain Edison's dilemma.

Equipment

- Three light bulbs in holders
- Four white connectors (used to connect light bulbs to each other)
- Test leads (one red, one black, one green)
- DC power supply

1A. Bulbs in Series

Two light bulbs are connected in series if a charge flowing through the first bulb must also flow through the second bulb. Here you will characterize a series connection of bulbs and explain your observations.

Read This: The power supply is easy to use if you know a few simple things. There are two knobs. The top knob adjusts the voltage of the supply. This is the knob that you will turn as you are doing the experiment. The bottom knob is a current limiter. You don't need to adjust the bottom knob during lab. Just make sure that it is turned all the way up (clockwise) and leave it there. The other thing to know is that the blue terminal on the supply is referred to as the *black* terminal throughout this manual since black is usually used to denote the negative terminal.

Figure 1: How to use the power supply during lab. Check that the bottom knob is turned all the way up and leave it there.

Do This: Before connecting anything to your power supply, please take a moment to inspect the three bulb holders. Each bulb holder has two red terminals and two black terminals. Flip a bulb holder over so that you can inspect the underside. Notice that the two red terminals are connected to each other by a wire. That means that the two red terminals function identically. Current can flow from one red terminal to the other red terminal without going through the bulb. Similarly, the two black terminals are connected by a wire. The reason that there are two terminals of each color is to allow you to construct more attractive circuits.

Do This: Examine a single bulb connected to the supply. Begin with the supply voltage turned all the way down (top knob turned all the way counterclockwise). Connect the bulb to the supply using the red and black leads and switch it on. Slowly raise the voltage. Do not raise the voltage past 6.0 V or you risk damaging the bulb.

Checkpoint 1.1: Discuss how the brightness of the bulb changes as you raise the voltage on the supply.

Read This: In the rest of Part I, we will be talking about the brightness of bulbs. You will be asked to discuss relative brightness and absolute brightness. When discussing ***relative*** brightness, consider how a bulb compares to other bulbs within the same circuit. When discussing ***absolute*** brightness, you will be answering the question, "How does the brightness of a bulb compare to the brightness of a single bulb connected to a power supply that is set at 5.0 V." This single bulb with 5.0 V across it could be called our standard candle.

Do This: Set the power supply to 5.0 V and take note of the brightness of the bulb (our standard candle). Then remove the red and black leads from the power supply. Get a second bulb and connect it in series with the first. That is, construct the circuit depicted in Figure 2. In this lab, ***use the short white connectors to connect light bulbs to each other***.

Read This: As you make predictions in this lab, you will be discussing the voltage or voltage drop ***across*** light bulbs as well as the current flowing ***through*** light bulbs. It is important to pay attention to your prepositions! And remember that voltage doesn't flow. It is the current that flows.

Checkpoint 1.2: Before powering up the circuit, *predict* both the relative brightness and the absolute brightness of the two bulbs. (By *absolute* we mean compare it to a single bulb connected to the power supply at 5.0 V.)

Do This: Plug the red and black leads into the power supply. Make sure the voltage reads 5 V.

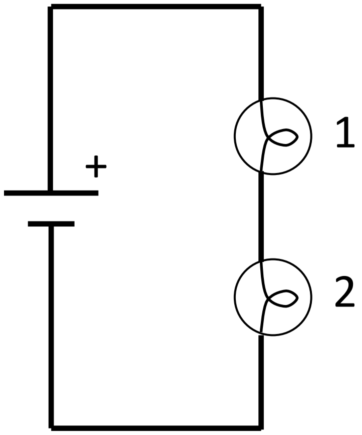

Figure 2: Two bulbs in series.

Checkpoint 1.3: Were your predictions correct? If not, discuss where your reasoning failed.

Checkpoint 1.4: *Predict* what will happen if you unscrew Bulb 1 and remove it from the holder.

Do This: Unscrew Bulb 1 and remove it from the holder.

Checkpoint 1.5: Were your predictions correct? If not, discuss where your reasoning failed.

Do This: Screw Bulb 1 back into the holder.

Checkpoint 1.6: *Predict* what will happen if you unscrew Bulb 2 and remove it from the holder.

Do This: Unscrew Bulb 2 and remove it from the holder.

Checkpoint 1.7: Were your predictions correct? If not, discuss where your reasoning failed.

Do This: Screw Bulb 2 back into the holder.

Checkpoint 1.8: *Predict* what will happen to the brightness of each bulb if you connect one end of your green lead to the red terminal of Bulb 2 and the other end of the green lead to the black terminal of Bulb 2.

Do This: Connect the green lead as described in Checkpoint 1.8.

Checkpoint 1.9: Were your predictions correct? If not, discuss where your reasoning failed.

Read This: We say that the green wire has created a *short circuit* around Bulb 2.

Do This: Disconnect the green lead.

Checkpoint 1.10: *Predict* what will happen if you connect a third bulb in series.

Do This: Add a third bulb in series.

Checkpoint 1.11: Were your predictions correct? If not, discuss where your reasoning failed.

1B. Bulbs in Parallel

A set of bulbs are connected in parallel if a given charge carrier flowing through the set flows though only one of its elements and the voltage drop across each element is the same for the entire set. Here you will characterize bulbs connected in parallel and explain your observations.

Checkpoint 1.12: Using the basic symbols for electric circuits drawing, draw the circuit diagram for two bulbs connected in parallel connected to a battery. Suggestion: circuitlab.com is a great program to help you draw electric circuit diagrams. You do not have to create an account for it. Just refresh everytime you want to draw a new diagram.

Do This: Label the bulb that is closer to the battery *Bulb 1*. Label the bulb that is farther from the battery *Bulb 2*.

Checkpoint 1.13: *Predict* the relative and absolute brightness of the bulbs in the circuit you just drew. (By *absolute* we mean compare it to a single bulb connected to the power supply at 5.0 V.)

Do This: Build the circuit you drew in Checkpoint 1.12 and power it up. (Check that the power supply is still at 5.0 V.)

Checkpoint 1.14: Were your predictions correct? If not, discuss where your reasoning failed.

Checkpoint 1.15: *Predict* what will happen if you unscrew Bulb 1 and remove it from the holder.

Do This: Unscrew Bulb 1 and remove it from the holder.

Checkpoint 1.16: Were your predictions correct? If not, discuss where your reasoning failed.

Do This: Screw Bulb 1 back into its holder.

Checkpoint 1.17: *Predict* what will happen if you add a third bulb in parallel.

Do This: Add a third bulb in parallel.

Checkpoint 1.18: Were your predictions correct? If not, discuss where your reasoning failed.

Checkpoint 1.19: Do you suspect the headlights of a car are connected in series or in parallel? Discuss.

1C. The Three-Bulb Circuit

Many circuits will have certain sets of elements that are connected in series while other sets of elements are connected in parallel. In Section 1C, you'll look at another way that three bulbs can be connected to a power supply.

Checkpoint 1.20: Look at Figure 3. Draw the corresponding circuit diagram. Be sure to label the bulbs in your diagram using the same numbers that are used in the figure.

Checkpoint 1.21: *Predict* the relative and absolute brightness of the bulbs.

Do This: Build the circuit and set the supply voltage to 5.0 V. Your circuit may look different from the photo. There's more than one way to construct the same circuit.

Checkpoint 1.22: Were your predictions correct? If not, explain where your reasoning failed.

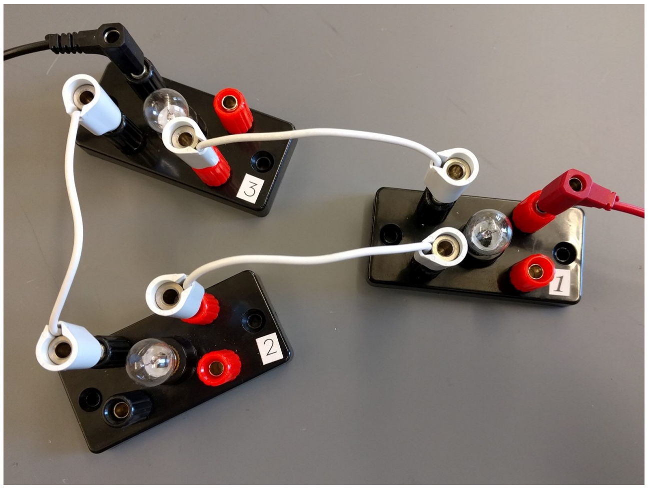

Figure 3: Three-bulb circuit for Section 1C.

Checkpoint 1.23: *Predict* what will happen if you unscrew Bulb 1 and remove it from the holder.

Do This: Unscrew Bulb 1 and remove it from the holder.

Checkpoint 1.24: Were your predictions correct? If not, explain where your reasoning failed.

Do This: Screw Bulb 1 back into its holder.

Checkpoint 1.25: *Predict* what will happen if you unscrew Bulb 2 and remove it from the holder.

Do This: Unscrew Bulb 2 and remove it from the holder.

Checkpoint 1.26: Were your predictions correct? If not, explain where your reasoning failed.

Do This: Screw Bulb 2 back into its holder.

Checkpoint 1.27: *Predict* what will happen if you unscrew Bulb 3 and remove it from the holder.

Do This: Unscrew Bulb 3 and remove it from the holder.

Checkpoint 1.28: Were your predictions correct? If not, explain where your reasoning failed.

Do This: Screw Bulb 3 back into its holder.

1D. The Edison Mystery Solved

It's time to see how good of a scientific detective you are.

S1

Synthesis Question 1 (15 points): As mentioned in the story, Thomas Edison would hold exhibitions of his latest bulbs for investors. These gatherings would take place at night at his Menlo Park laboratory, lit only by his electric bulbs. Explain why Thomas Edison was right to be concerned with the details of how his light bulbs were connected during his exhibitions. There should be **at least two advantages** that one type of connections would have had over the other. Your advantages must be supported by your observations made while you went through the checkpoints. Include the circuit diagrams.

1E. Analyzing the Three-Bulb Circuit with Kirchhoff and Ohm

We'll stay on this circuit for a moment, as we can still learn some interesting things from it. We'll figure out why exactly the circuit looks like it does, as well as investigating the way some famous circuit laws actually work in real life!

Read This: You'll be using your multimeters to get a closer look at the circuit. Familiarize yourself with using a multimeter to measure voltage and current with the "Using Multimeters" page in the Reference section of the Lab Website.

Do This: Set up your multimeters to measure the total current and voltage for the entire circuit. Check that your results agree with the values given on the power supply readouts. **If your current goes above 1 A, turn off the power supply immediately and ask your LAI for help reconfiguring your circuit.**

Checkpoint 1.29: Record your overall current and voltage data in a table. Create space to record the current and voltage of each bulb as well.

Read This: The reading for the *current* should have three digits after the decimal point and the uncertainty is 0.001 A. The reading for the *voltage* should have two digits after the decimal point and the uncertainty is 0.01 V.

Checkpoint 1.30: Add the circuit symbols for the Ammeter and Voltmeter to your diagram from Checkpoint 1.20 in the proper places to measure current and voltage simultaneously for Bulb 1.

Checkpoint 1.31: Set up your multimeters to measure current and voltage for Bulb 1. Record your data in your table.

Do This: Repeat the previous two checkpoints for Bulbs 2 and 3 respectively. Ask your LAI if you're having trouble, as some of those measurements can be tricky!

1F: Learning the Laws

Now that we have our data, let's use it to learn some useful things about circuits. We're concerned with two patterns in particular: Kirchhoff's circuit rules (the loop and junction rules) and Ohm's Law.

Checkpoint 1.32: Explain Kirchhoff's Loop Rule and Junction Rule in your own words (two sentences each or fewer). Reference Appendix A and your work in the prelab.

Checkpoint 1.33: Does your data satisfy the relationships that Kirchoff's rules predict? How do you know? If not, why not?

Read This: Ohm's Law in its simplest form simply says that the **voltage drop** across a circuit element divided by the **current** through that same element gives us the **resistance** of that circuit element. This is true by definition, as resistance is defined to be the ratio of voltage to current. A more interesting question is to ask if that resistance is a fundamental property of the circuit element, or if it can change depending on external conditions. A circuit element that has constant resistance (V/I = constant) is called an **ohmic** conductor. One that has a changing resistance is a **non-ohmic** conductor. This means that if we plot Voltage against Current for a given circuit element, we should get a straight line for an **ohmic** conductor but not for a **non-ohmic** conductor. (See Figure 4.)

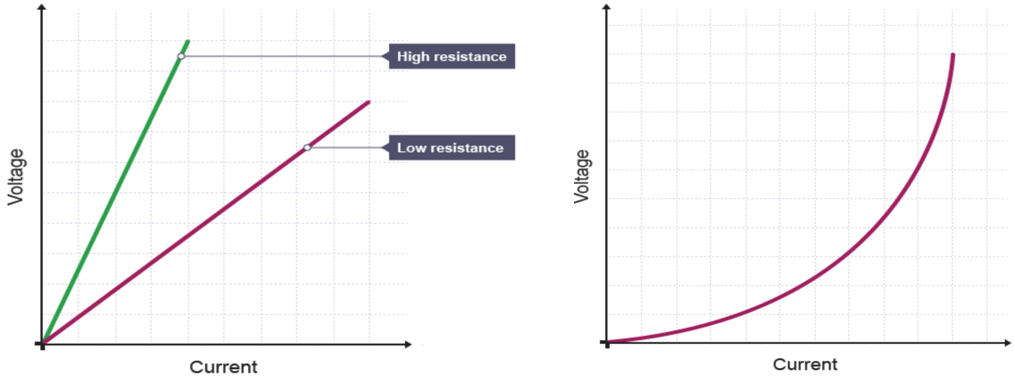

Figure 4: Voltage vs Current graphs for ohmic (left) and non-ohmic (right) conductors

Do This: Set up your multimeters to measure the voltage and current for the *entire circuit* again. Do an experiment to test whether or not the three-bulb circuit (and therefore the lightbulbs within) are ohmic conductors.

Checkpoint 1.34: Create a table for Voltage and Current of the **entire circuit** (not the individual bulbs) and populated using a range of supply voltages from 1 V to 8 V. Create a plot of Voltage vs Current in Logger Pro to evaluate your data.

S2

Synthesis Question 2 (30 Points): Do Kirchhoff's Laws apply to this circuit? Are the bulbs ohmic or non-ohmic? Use the definitions of these laws and own data to make an argument to support your response. (Hint: what should the slope of your plot be? Do the slopes of your first and last three points agree?) A good answer must include:

- A clear description of how the bulbs are connected
- A clear diagram of the circuit with labeled junctions (including the ammeter and voltmeter positions used to measure I and V for the entire circuit)
- Data organized in a data table (including the uncertainty for each measurement)
- Clear math calculations needed.
- Clear graph of Current vs Voltage for the entire circuit
- Analysis of the data and graphs to prove the laws
- Conclusion whether the laws apply to the circuit

Part II: Christmas Lights

Edison's light shows weren't too different from modern-day Christmas light displays. As such, you can use the skills you developed as you analyzed Edison's dilemma to do a little reverse engineering of Christmas lights.

Equipment

- **Strand of 100 lights**
- **Tiny screwdriver used to remove bulbs (inside pill bottle)**
- **Red-tipped bulb (inside pill bottle)**

Equipment Note

STOP

Do This: In the following experiments you will be removing bulbs from a strand of Christmas lights. If you do this incorrectly, you can break the lights. To avoid damaging the lights, go to the In-Lab Links page and watch the video that demonstrates the proper and improper ways to remove the lights. The proper method uses the little screwdriver that can be found in the pillbox inside the box of Christmas lights.

2. The Christmas Light Circuit

Do This: After watching the video, plug your strand of lights into the power strip on top of the lab table. If your strand does not light up, please notify your LAI so that you can get a new strand of lights. If your lights work, continue on.

S3

Synthesis Question 3 (20 points): Now that you're an expert on the basics of wiring light bulbs, figure out how your strand of Christmas lights is wired by removing bulbs and noting the results. (Please remove the bulbs using the method shown in the online video.) Detail your procedure and your observations. Then draw a circuit diagram for the strand of lights, making sure to explain how you came to your conclusion. (You don't need to draw all 100 bulbs. Just make sure it's clear how they're wired.)

3. The Red-Tipped Bulb

Many strands of Christmas lights will include a special red-tipped bulb that will allow us to explore some bonus physics.

Do This: Replace any bulbs that you have removed from the strand of lights.

Checkpoint 3.1: What happens to the temperature of a wire or a resistor when current flows through it?

CURRENT
Washington University in St. Louis
RESEARCH

Read This: A special class of materials called *superconductors* can carry current without changing temperature because they have zero resistance. Unfortunately, all known superconductors must be at very low temperature and/or very high pressure in order to exhibit superconductivity. A group led by Dr. Schilling in the Wash U physics department has discovered numerous materials that become superconductors at high pressures. Check out the lab website for links to details.

Do This: Remove one of the bulbs and replace it with the red-tipped bulb that can be found in the pill bottle where you found the screwdriver.

Checkpoint 3.2: What do you observe? (If nothing interesting happens, please consult your LAI.)

Do This: When you are done observing the red-tipped bulb, remove it and replace it with a regular bulb. Put the red-tipped bulb back in the pillbox.

Read This: Let's try to understand the physics of the red-tipped bulb. If you were to look closely at the red-tipped bulb while it is not plugged in, you would notice that it looks different from the other bulbs. Inside a normal bulb you can see two conductors connected by a very thin wire called the filament. The red-tipped bulb has an extra component called a bimetallic strip. (See Figure 5.)

Read This: To understand a bimetallic strip, we must know that when metals heat up, they expand. Different metals expand at different rates. Copper expands faster than steel given the same change in temperature. So if you couple a strip of copper to a strip of steel, the resulting bimetallic strip will bend as it changes temperature as shown in Figure 5.

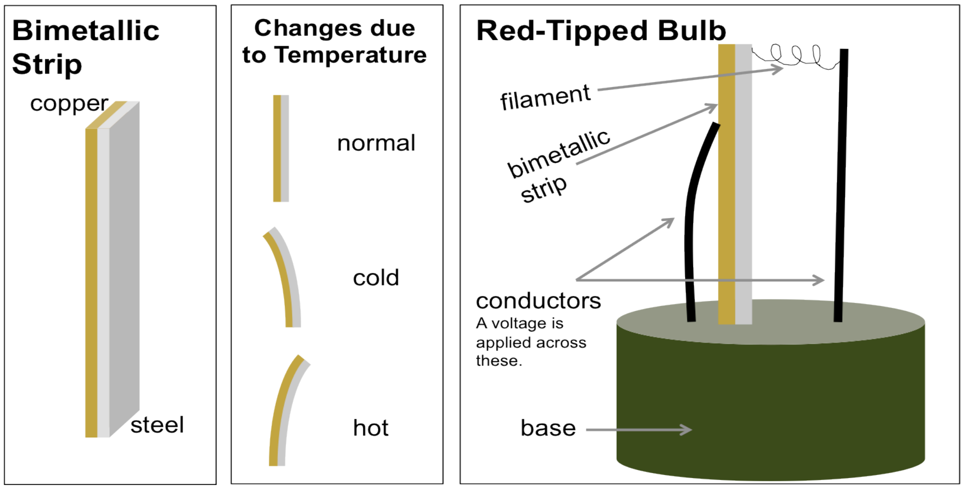

Figure 5: Bimetallic strips and the red-tipped bulb.

S4

Synthesis Question 4 (15 points): Explain the observations that you recorded in Checkpoint 3.2. That is, how does the red-tipped bulb cause the lights to flash?

Read This: Here's a final interesting fact about these particular Christmas lights. It turns out that removing one of these bulbs does not have the same effect as if one of the bulbs burns out. These are special bulbs that are equipped with an *antifuse* that completes the circuit if the filament happens to break. (A *fuse* acts in the opposite way. It is designed to break a circuit under certain conditions.) However, most light bulbs do not contain an antifuse, and current will *not* flow through most bulbs with a broken filament.

Part III: Light Bulbs and Capacitors

The Story

Leyden jars, the ancestors of the modern capacitor, were able to store charge, and in that charge, energy. The energy wasn't all that practical (although Benjamin Franklin is said to have used a Leyden jar to kill a turkey for a dinner party at one point). In the days that Thomas Edison was trying to wow investors, capacitors like the ones you will use today didn't exist. Were they available, however, there is little doubt that he would have employed them to make his light shows even more impressive. But how?

Equipment

- Two light bulbs in holders with connectors
- One 1-F capacitor
- DC power supply
- Test leads (one red, one black)

Equipment Notes

The particular capacitors that you will use in Part III have a capacitance of 1 farad, which is an absolutely tremendous capacitance. But this high capacitance comes with two drawbacks.

STOP

Drawback 1: The maximum voltage that the capacitor can handle is 5.5 volts. Just to be safe, do not put more than 5 volts across the capacitor at any time.

Drawback 2: The capacitor is polarized. ***The black terminal on the capacitor should always be connected to the black terminal of the power supply using the black test lead***. The capacitor could be irreparably damaged if you are careless about the polarity.

For us, these drawbacks are worth the benefits of large capacitance. We start the foray into the world of capacitance by showing that they can store energy.

4A. Storing Energy in a Capacitor

Do This: Set the voltage on the power supply to 5.0 V.

Do This: Connect the negative terminal of the power supply to the black terminal of the capacitor. Then connect the positive terminal of the power supply to the red terminal of the capacitor. The capacitor is now charging. (You should see a digital readout of the current on the power supply. If that meter reads zero, alert your LAI.) Let the capacitor charge for about 20 seconds.

Do This: Remove the leads from the power supply and connect the capacitor to one of your light bulbs.

Checkpoint 4.1: What happens? What does this say about a capacitor’s ability to store energy?

Do This: Discharge your capacitor by connecting its two terminals with a test lead for 10 seconds. **Remember to discharge your capacitor like this after each experiment in which you use it.**

Read This: In the following two experiments you will connect a capacitor and a light bulb to the power supply at the same time. The way these circuits evolve with time should be interesting to observe.

4B. Capacitor and Bulb in Series

When a resistor and a capacitor are connected to a power supply in series, we refer to the setup as an *RC circuit*. In this experiment, a light bulb will act as your resistor.

Checkpoint 4.2: Draw the circuit diagram that shows a light bulb and a capacitor connected in series hooked up to a power supply.

Checkpoint 4.3: If the capacitor begins uncharged, *predict* how the brightness of the bulb will change in time after turning on the supply.

Do This: Set the supply voltage to 5.0 V. Build the circuit you drew in Checkpoint 4.2 and test your prediction.

Checkpoint 4.4: Were you right? If not, discuss where your reasoning failed.

Read This: Here's a nice rule of thumb. DC circuits with resistors and capacitors tend to settle into a steady state if given enough time. Initially, capacitors act like wires (if they begin uncharged). When steady state is reached, a capacitor acts like a gap in the circuit. Sometimes the details of how steady state is reached are complicated; however, predicting the initial and final behavior of the circuit is often manageable, even in a complicated circuit.

Checkpoint 4.5: *Predict* what will happen if you disconnect the red and black leads from the power supply.

Do This: Disconnect the leads from the power supply and observe.

Checkpoint 4.6: Evaluate the prediction you made in Checkpoint 4.5. Were you right? If not, discuss where your reasoning failed.

Checkpoint 4.7: *Predict* what will happen if you connect the free ends of the red and black test leads (that is, the ends that were connected to the power supply).

Do This: Connect the free ends of the red and black leads to test your prediction.

Checkpoint 4.8: Evaluate the prediction you made in Checkpoint 4.7. Were you right? If not, discuss where your reasoning failed.

Do This: Discharge your capacitor by connecting its two terminals with a test lead for at least 10 seconds.

4C. Capacitor and Bulb in Parallel

Let's see what happens when a capacitor and a light bulb are connected in parallel.

Checkpoint 4.9: Take a look at the circuit diagram in Figure 6. If the capacitor begins uncharged, *predict* how the brightness of Bulb 2 will change in time after powering up the circuit. (You might want to think back to the most recent "**Read This**".)

Do This: Set the supply to 5.0 V. Build the circuit and test your prediction. Remember that the black terminal of the capacitor should be connected directly to the black terminal of the power supply.

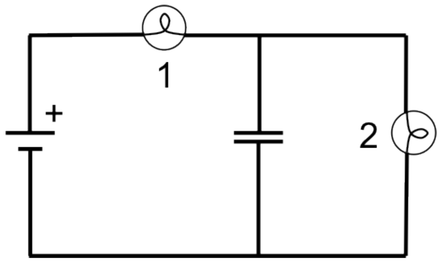

Figure 6: The circuit used in Section 4C.

Checkpoint 4.10: Evaluate the prediction you made in Checkpoint 4.9. Were you right? If not, discuss where your reasoning failed.

Checkpoint 4.11: *Predict* what will happen if you disconnect the leads from the power supply. Make a prediction for both Bulb 1 and Bulb 2.

Do This: Disconnect the leads from the power supply.

Checkpoint 4.12: Evaluate the predictions you made in Checkpoint 4.11. Were you right? If not, discuss where your reasoning failed.

Read This: The circuit you just built demonstrates how one might use a capacitor to protect an electrical device against power outages. Even if the power supply gets unplugged, there is stored energy in the capacitor that can keep things running (for awhile, anyway). This works well for devices that don't require much power.

4D. Improving Edison's Light Shows with Capacitors

S5

Synthesis Question 5 (20 points): How do you think Edison could have improved his light shows if he had these capacitors available to him? Detail **at least two functions** that the capacitors could have had. Your functions must be supported by your observations made while you went through the checkpoints.

Time to Clean Up!

Please clean up your station according to the Cleanup! Slideshow found on the lab website.

Appendix A: Kirchhoff's Rules

In 1845, the Prussian physicist Gustov Kirchhoff wrote down two rules that describe how the current and potential difference changes throughout a circuit. Although we won't do much with these laws, they offer a handy way to understand circuits. They are particularly invaluable for electrical engineers!

Kirchhoff's Junction Rule

The junction rule states that at any circuit junction (in other words, at any point where wires meet in a circuit), the total current that flows into the junction must equal the total current flowing out of the junction. This is really just another way of saying that charge is conserved – you can't add charges or take them away just because some wires meet.

Convention says that charge flowing into a wire junction gets a positive sign and charge flowing out of a wire junction gets a negative sign. That means that for any junction, Kirchhoff's Junction Rule can be written as $\sum I = 0$.

For example, in Figure 7, the current flowing into Junction 1 splits into the two currents flowing out of Junction 1. Kirchhoff's Junction Rule tells us that $I_A = I_B + I_C$.

Kirchhoff's Loop Rule

The loop rule states that the potential difference across each circuit element in a closed loop must add up to zero. Figure 8 provides a simple example. The battery has a potential difference between its terminals, called its EMF. The potential difference across Resistor 1 plus the potential difference across Resistor 2 will always equal the battery's EMF. For any closed loop, Kirchhoff's Loop Rule can be written as $\sum V = 0$. This is particularly helpful when investigating complicated circuits since the Loop Rule applies to each of the closed loops. Figure 9 shows the three closed loops present in Figure 7's circuit.

The loop rule is really just another way of saying that energy is conserved. Energy can't be created or destroyed, but it can change forms. In Figure 8, the battery converts chemical energy into electrical potential energy, then each resistor converts part of this electrical potential energy into thermal energy. After the current has flowed through both resistors, all of the electrical potential energy created by the battery has been converted into other forms, leaving the net change in voltage (the energy per unit charge) as zero.

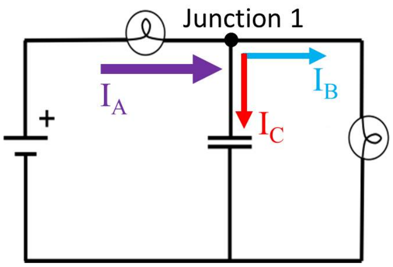

Figure 7: Current at a wire junction

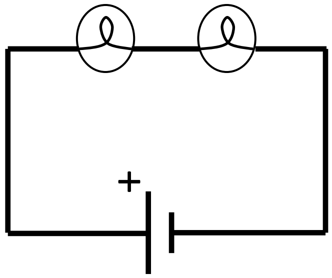

Figure 8: A closed loop

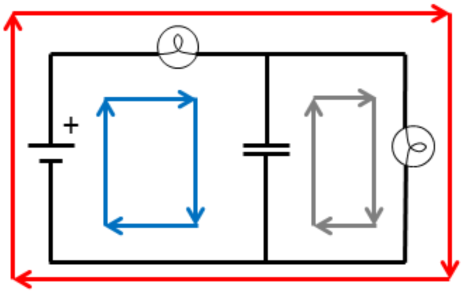

Figure 9: The same circuit as Figure 8. There are three closed loops to analyze: the outer loop; the left loop; the right loop.