Determining Planck's Constant Using Light Emitting Diodes (LEDs)

PS253 – Physics Laboratory for Engineers
Department of Physical Sciences
Embry-Riddle Aeronautical University, Daytona Beach, Florida
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Introduction

In this experiment, a test using 6 different color LEDs provides an estimate of one of the fundamental constants of modern physics- *h*, Planck's constant. Max Planck devised a mathematical model that accurately predicts the type and quantity of energy emitted by all objects as a result of the object's temperature, i.e. due to the random thermal vibrations of its constituent particles. It took years of work to develop this equation. It works well, but for the model to work Planck had to invent one very strange condition:

> Atoms cannot give up (absorb) arbitrary amounts of energy to (from) the environment. There is a minimum energy that can be transferred at any moment; the smallest amount that a vibrating system can give up (absorb) is equal to some base constant value multiplied by the system's frequency of vibration. All larger energies that can be exchanged must be twice the minimum, then three times and so on in integer multiples of this base constant. The energy changes occur in discrete, quantized steps of fixed size and there is no way to get an atom to exchange amounts of energy between the discrete values.

This ultimately means that all things in nature change in 'jumps'- not smoothly. Consider what this means in a familiar example, the definition of acceleration. It is based upon infinitesimally small changes in velocity divided by infinitesimally small changes in time, and smoothly approaches a constant ratio. Planck's model contradicts the basic premise in the definition. Under Planck's model the velocity changes in short bursts and in a particular instant between bursts the acceleration is zero. However, the familiar definition of acceleration works well as an approximation since the amount of energy causing the 'jumps' of velocity change is very small compared to amounts that can be noticed in the everyday experiences of people and the large objects we deal with. We are bombarded by too many billions upon billions of tiny step changes in a very short span of time (in human terms) to be able to sense the individual jumps and pauses.

Planck didn't think that his model and the artificially introduced constant *h* were great insights at first; he regarded it as a convenient way to construct a theory for making useful predictions and believed it to be purely a formality and not how the universe really works. On the contrary, it completely changed our picture of all the processes in the universe. It turns out that all physical phenomenon, mass, position, and even time, can be defined by a universal quantized unit. This was the birth of quantum theory and won Max Planck the Nobel Prize in Physics in 1918.

Energy Transfer and Light Emission in LEDs

Consider the LEDs used in this experiment and the "colors" of light they emit (one is infrared- a color invisible to humans). The photon energy E_γ for each color can be computed:

$$E_\gamma = h\nu \quad h = 6.626 \times 10^{-34} Js\dagger \tag{1}$$

where ν is the frequency of the photon. These colors are due to photons of light emitted by electrons jumping down from one energy level in the LED to a lower energy level. Relate this to Planck's model by considering that the electron is the vibrating component that emits the photon. Recall the Bohr model of the hydrogen atom: for an electron to jump from one energy level to another requires a very precise amount of energy, a tiny deviation from the required amount will not work.

The energy levels of electrons indicate how tightly they are attached to an atom. The levels are measured in units of electron-volts [eV], where *1 eV = 1.60217662 × 10*$^{-19}$ *Joules*.‡ The energies are always negative because they are defined as the amount of energy needed to free the electron from the atom. For example, an electron in a level at -4 eV can be removed by a 4 volt battery if the battery leads were suitably placed in the vicinity of the electron (a silly but hopefully illuminating example), or if a 4 eV photon is absorbed by the electron.

In an LED things are a little more interesting. The electric fields of neighboring atoms overlap due to the close packing of the atoms in a solid. Slight variations in the electric field result in slightly varying forces holding the electron to the atom. These slight variations in force on the electrons in solids allow them to exist in small bands of energy rather than the well-defined levels available to them in gases. If a photon is fired at a region where atoms are clustered together, as in a solid, its energy has many more combinations available to match.

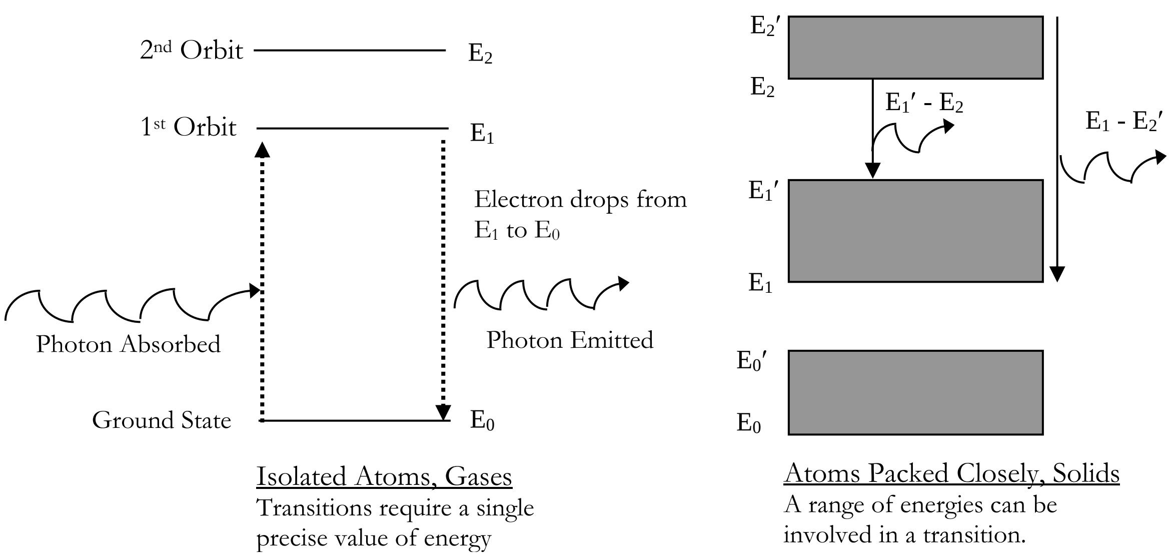

Figure 1: Light emission(absorption) and changes in electron energy within gases and solids. In both cases a photon must be created(destroyed) whenever an electron decreases(increases) in energy.

† A more precise value is available at http://physics.nist.gov/cuu/Constants/index.html
‡ Available from the NIST Reference on Constants, Units, and Uncertainty.

Referring to Figure 1, observe that the energy levels for the gas atoms are represented as lines, while the atoms in the solid have wide ranges of energies, separated by gaps. The wide energy ranges shown in the diagram conjure the term 'bands' and this model is known as the *Band Theory of Solids*. Jumps from one band to another can occur from any point within the band to any other point in another band. The minimum energy needed to induce an electron to jump from one band to the next higher band is equal to the energy gap between the bands.

In this experiment, voltage is a quantity we can easily control. If we apply a voltage across an LED we are placing all the electrons within it in an electric potential. With the proper voltage supplied an electron can gain the right amount of energy to jump up a level within its atom. After increasing in energy the electron will, at some later time, spontaneously and randomly emit a photon as it seeks to return to the lowest available energy state. The minimum voltage needed to induce this jump is taken as approximately equal to the energy of the photons of the predominant color emitted by a given LED.

In a semiconductor such as an LED, the photons of interest are emitted from the transition between the two highest energy levels of its atoms: the conduction band and the valence band. The minimum energy required to raise electrons into the higher conduction band from the valence band can be detected by slowly increasing the voltage applied to the LED until electrons begin to flow through it. The flow of electrons provides the evidence that the applied voltage has raised them into the conduction energy band. We will most accurately determine the voltage when charges begin to flow by finding the y-intercept of a graph of voltage and current measurements made with an ordinary digital millimeter (DMM). Assuming that the light produced by the LED results from the complete conversion of the electrical potential energy from the applied voltage, then we know the energy of the photons of light by knowing the applied voltage needed to emit them and start a current to flow.

$$W_{e^-} = qV_{LED} = eV_{LED} = h\nu = E_\gamma$$

$$eV_{LED} = h\nu \qquad (2)$$

The energy of the photons E_γ is equal to the work done on the electron W_{e^-} by the supplied voltage V_{LED} across the LED, where ν is the frequency of light emitted from the LED.

LED Current Limits and Careful Handling in This Experiment

In the procedures carried out in this experiment **start at 0mA and increase the power gradually to <u>no more than</u> 18mA in every trial for each LED.**

!Warning! At no time should the current reach or surpass 20mA. Above 20mA the LEDs are likely to start degrading quickly and burn out. Also if the current is left running at >20mA for more than 30 seconds the load resistor will start to produce fumes.

Always return the power supply back to 0.0V and 0.0mA when finishing a trial to ensure the components are not damaged accidentally over time.

If your group burns out an LED(s) each person will have 3 points deducted per each damaged LED from their report assignment grade.

The apparatus used in this experiment, see Figure 2, consists of six LEDs and a resistor mounted on a circuit board. A critical parameter to monitor closely is the current flowing through the circuit. Each LED can tolerate a maximum current of ~18mA before breaking down due to excessive heating. Another critical safety feature is that the diode must always have a higher resistance connected in series to absorb most of the potential (voltage) at higher currents. The inline ~100Ω resistor serves this purpose. To begin the test for each LED, the power supply voltage must always be turned to zero and gradually increased to stay below the maximum current safe limit.

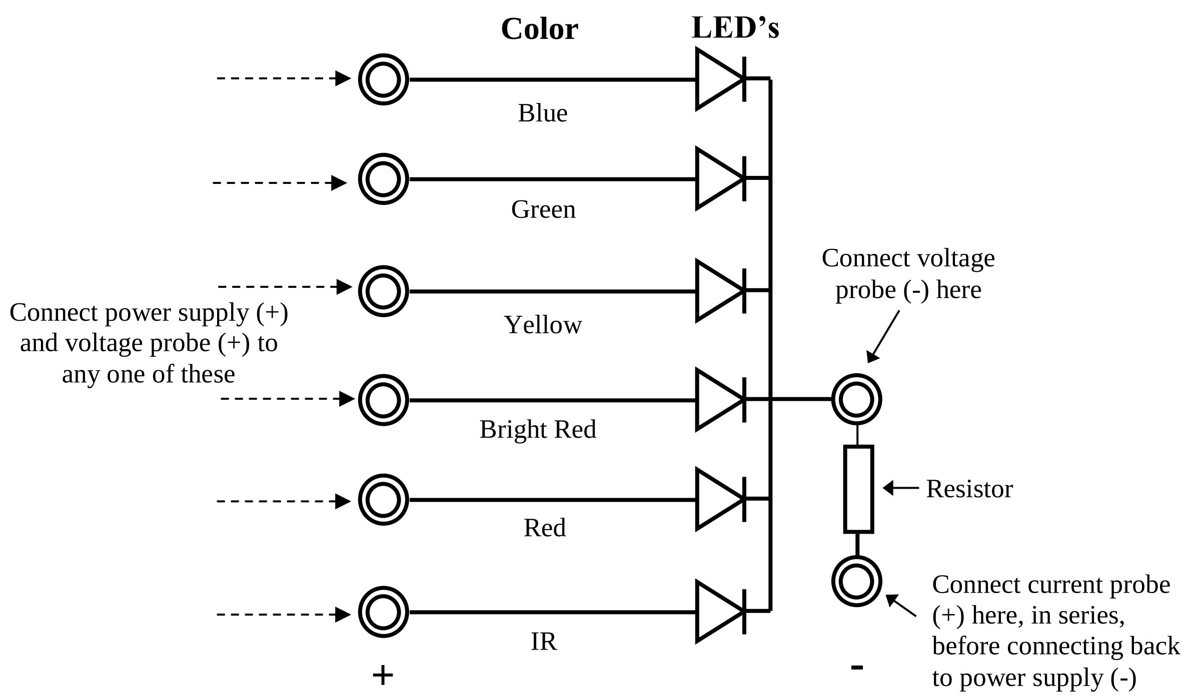

Figure 2: Layout of the LED circuit board. Only one LED is ever connected to power at one time, and a resistor is mounted to always be in series with any given LED at any time. Note the LEDs are listed by their color of emission, but each board will have specific wavelengths [nm] indicated.

Reverse Voltage Warning

!Warning! Do not connect the power supply to the board backwards. Positive (+) current flow should always be in the forward direction across the LED. It should flow in the direction of the LED arrow symbol.

If the voltage is turned on and increased with the polarity reversed, negative (black) and positive (red) reversed, then the LED will very likely be ruined by overheating. In general diodes will only allow current to flow in one direction across them- from their positive anode to their negative cathode. Connecting LEDs to a current source backwards, called *reverse biased*, quickly degrades the semiconductor starting at extremely low currents.

Procedure

1. With the power supply switched off, turn the voltage control on the power supply to the lowest position. Adjust the current limit control knob to be about ½ turn above zero.

2. Now construct the circuit as shown in Figure 3 using the blue LED (roughly 430nm) and connect the power supply to the circuit. Both the ammeter and voltmeter will be sensors connected to the Pasco box and operated through *Capstone*.

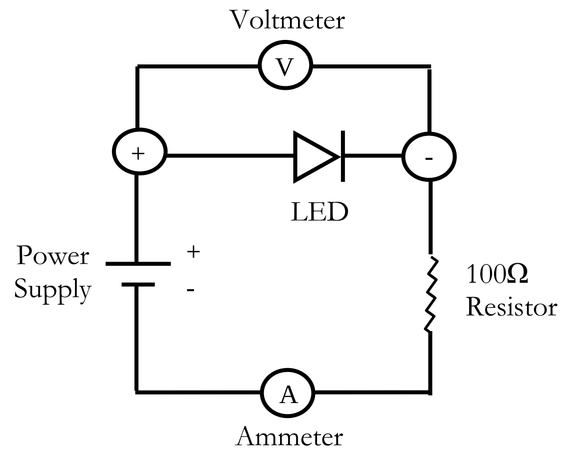

Figure 3: Circuit diagram for measuring voltage and current across a single LED at a time on the LED board.

3. Make sure the Current Probe, ammeter, is connected to **CH B** on the Pasco box and that the direction of current flow across it matches the graphic printed on its top surface. Make sure the Voltage Probe, voltmeter, is connected to **CH A**.

4. Using the PC that is attached to the Pasco interface by USB, download the *Capstone* file from *Canvas* for this experiment named *Plancks_Constant.cap*. Open the downloaded file in *Capstone* and make sure the Pasco control box is turned ON.

5. The software should be setup with the sensors already added to the proper channels and with settings already set to work best for this experiment. There is also a pre-scaled graph window for live viewing of data collection. You will fully edit and format this graph for saving as your *Raw Data* for the lab before you leave class.

Calibrate the Current Sensor 'Ammeter'

6. The final piece of setup must be done individually by the experimenter. In the left-side *Tools Palette* click the *Calibration* tab. 

   a. At the top of the new window choose *Current Sensor* to calibrate, then click *Next*.

   b. Choose *One Standard (1 point offset)* then click *Next*.

   c. You should now see a live sensor reading from the current sensor along with a field for *Standard Value* = 0.0. Ideally the sensor should be reading zero current, but it likely has some very small mA offset that we need to eliminate.

   If the *Current Value* field is not giving live readings click the *Record* button.

   d. With the power supply switch turned OFF, but all electrical connections made, click *Set Current Value to Standard Value*. This adjusts the zero point for your specific current probe in your specific circuit.

   e. Review the new versus old current sensor calibration and live readings. If the new *Live Value* is nearly zero click *Finish* and close the *Calibration* tab. If not, redo or seek help from your instructor.

The Pasco Current Probe actually reads a voltage across an internal 1.0Ω±0.5% thermally stable resistor and the software uses the calibration to convert this into a displayed current in Amps or mA. Note that you can readily see from the calibration that we are assuming the resistor is exactly 1.0Ω since a sensor reading of 1.0V across a 1.0Ω resistor would give 1.0A.

READ STEPS 7 AND 8 COMPLETELY BEFORE PROCEEDING.

7. With the power supply voltage control turned all the way down, and the current limit control knob about ½ turn above zero, turn the power supply switch to ON. In *Capstone* click the *Record* button to begin collecting data, and slowly increase the applied voltage.

   !Warning! At no time should the current reach or surpass 20mA.

   While increasing the applied voltage, watch the live data collection in the *Capstone* graph as it plots Voltage vs Current. Be aware that once the LED lights up current will begin increasing very rapidly, and you should stop increasing voltage when current reaches 17-18mA.

8. When you have covered the current range (0-18mA) for the blue LED turn the voltage on the power supply back down to zero, and then click *Stop* in *Capstone* to finish collecting data for the blue LED run, and turn the power supply switch to OFF.

9. In the *Tools Palette* menu of *Capstone*, open the *Data Summary* tab, right-click the *Run 1* line under the *Voltage Sensor, CH A* listing. Rename this to your exact wavelength for the blue LED (Example: ###nm) and set the plotted data to be blue in color (right-click, *color picker*). It should update the graph display.

10. Repeat Steps 7-9 for the remaining LEDs and pick unique plot colors for each run.

The 950nm LED

This LED is a special case; we cannot see infrared emissions but many cell phone cameras can. At each pixel, color CCD cameras have 3 light detectors behind different color filters that produce each pixel in the image. There is a red sensor with a filter that passes ~620 nm light, a green filter that passes ~540nm light, and a blue filter that passes ~480nm light. The three filters may use wave interference to filter the light, so they also pass light with wavelengths that are 2, 3 etc. times the visible wavelength that they transmit. Since our infrared LED is at ~950nm, about twice the blue wavelength, the LED should appear to be blue in the camera display. As a side project a student can obtain some IR LEDs with longer wavelength and test those with a cell phone camera. For example, an 1100nm LED should appear green in the camera, however the camera detector sensitivity drops very fast at about 1100 nm so even if the filter passes the light it may not be visible in the image.

The experimental portion of this lab should proceed very quickly leaving you a good deal of class time left. You should work to complete most if not all the analysis before leaving lab.

Analysis

On your *Capstone* graphs you will notice each LED turned on at a different voltage, but they all seemed to follow the same trend. As voltage initially increased, current barely increases at all resulting in a nearly vertical line. Then as the voltage nears the level necessary to cross the band gap energy for that specific wavelength LED current begins to finally increase. This doesn't happen sharply and results in a bend or "knee" in the V vs I curve that is characteristic of all LEDs. See Figure 4 for an example of this in the Forward region.

This characteristic "knee" response of LEDs is a small problem for our analysis because we must find the minimum voltage needed to just barely start emission of photons. We know this must be a non-zero voltage since the photons emitted must have some energy that they receive from the electrons excited by our potential. So we cannot follow the curve directly back to zero current as it would give us zero voltage as well. Instead we must fit a linear trendline to the data *above* the point where the LED has turned on and project this back to a point where current would barely start flowing to obtain a minimum voltage (i.e. a minimum energy for photo-emission).

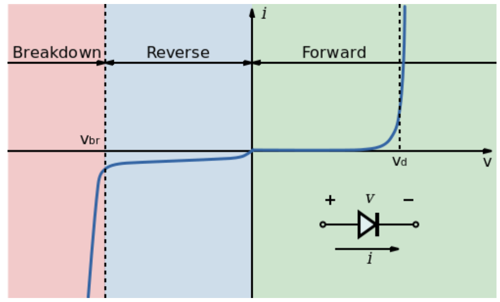

Figure 4: Characteristic LED "knee" response. Note the axes are flipped with respect to our plotted results. [Wikimedia Commons]

1. In the *Capstone* graph window menu, select the  *Data* icon and using the drop down list check to display all LED runs. There should only be one good run for each LED. Your 6 runs should now display in the graph and a Legend should appear. Move this Legend to a region where it does not block any data.

2. Using the graph Legend, select the blue LED run to interact with it. This should make the data points for that run **bold**. Then select the  *Range* icon to bring up a highlight selection box in the graph. Click-and-drag the box around and resize it to select blue LED run data to highlight it. Only select data in the roughly linear region above the "knee"; including data > 3mA and < 18mA would be appropriate.

3. Once all this data is selected above the "knee" for the blue LED run, select the  *Curve Fit* icon and select *Linear* from the drop down list. This will create a linear fit on the graph to only the blue LED data you selected. It also displays a box with the linear fit parameters including the y-intercept (minimum photo-emission voltage), uncertainty in the y-intercept, and an R^2 value.

   The y-intercept of this fit line is what you will use as V_{LED} for the blue LED.

4. Repeat Steps 1-3 for each LED's run fitting a line to each dataset. Carefully arrange the fit equation boxes so it is clear which data they go with and that they do not overlap anything else in the graph window. Make sure you have recorded the specific wavelength for each of your LEDs as the name of each run in the graph Legend, and that you know and will remember which fit line goes to which wavelength LED.

5. When finished formatting your *Capstone* graph, open the application *Snipping Tool* (you can do a Windows Search). Take a screen capture of your graph and save it as an image file for your report. <u>You MUST include this image in your lab report, it essentially contains all of your *Raw Data*.</u>

The remainder of the Analysis should be completed in MS Excel or a similar program.

6. Calculate the energy for each LEDs characteristic photon emission based on your values obtained for V_{LED}.

$$E = qV_{LED} = V_{LED} \times 1.60217646 \times 10^{-19} Coulombs \qquad (3)$$

7. Calculate the frequency of the photons emitted by each LED based on the wavelengths given on your LED board.

$$\nu = c/\lambda \qquad (4)$$

where $c = 2.99792458 \times 10^{8}\ m/s$.§

8. Prepare a summary table with 6 rows and 5 columns labeled: LED Color, V_{LED} ± uncertainty [V], Wavelength [nm], Frequency [Hz], and Photon Energy ± uncertainty [Joules]. This table should appear in your lab report.

9. Construct a plot of minimum photon energy, determined in Step 6, versus the frequency of LED emission, determined in Step 7, including each of your six LEDs.

By Max Planck's theory $E = h\nu$ for a photon of frequency ν. A plot of the photon energy at minimum voltage for each LED versus ν should have a slope equal to h, Planck's Constant.

10. On your plot, fit a linear trendline and include the equation of the fit in the plot area. Make sure the equation displays a proper number of sig figs (Hint: A single whole number value for slope is insufficient). If using MS Excel, you can select and format the displayed equation to increase the displayed decimal precision. Make sure the tick marks scaling the y-axis and x-axis are readable and span an appropriate range with an appropriate tick mark scaling.

    Include error bars for each data point's energy, since you calculated these earlier for each individual LED.

    Additionally, use a *Regression* technique to find the uncertainty of the slope of this line so that you have an experimental value for Planck's Constant as your final result along with a given uncertainty to state in your report.

    Base your experimental h sig figs off of your measurement precisions- at worst you should have no less than 2 significant digits in the slope value.

11. Compute the % difference between the reference value of h and the result found in your experiment from the slope of the E vs ν plot. Round the reference value sig figs to fit the sig figs of your experimental value- NOT the other way around!

Further Questions and Discussion for Your Report

- Do you feel you could *precisely* determine a value for Planck's Constant with the given procedure and materials?
- From your results did you *accurately* determine Planck's Constant with respect to the modern accepted value?

§ Available from the NIST Reference on Constants, Units, and Uncertainty.

- Is your value for h greater than or less than the reference value? Looking back at your data and especially the E vs ν plot, might there be one LED in particular that could be throwing off your experimental value much more than any other LED. For example: If you removed it from consideration in your linear fit would your results improve dramatically? Remember you should always be hesitant to exclude data as outliers; if you do so be prepared to back it up with really sound reasoning, or at least present both options to your reader side by side.
- Can you imagine any changes in method or assumptions that would improve the experiment as it is currently presented? Consider what you believe to be major sources of uncertainty(error) and how you might further minimize them.
- LEDs tend to emit only a small band of continuous wavelengths around a peak emission wavelength, especially when compared to broadband emission sources like incandescent or fluorescent lights. However, you can research that all LEDs certainly emit in at least a small range of wavelengths, some emit a much broader range than others. Could this have affected your results?

Planck's Constant Guidelines

- Include signed raw data sheet, or raw data with your report (The DataStudio plot or equivalent)
- One column abstract, two column for everything else
- Correct units and sig-figs on all numbers
- Cite any item taken from the lab module
- Cite any work taken from anywhere else
- **Abstract:** Very briefly describe the experiment, state goals, summarize results including experimental values, expected values, and percent differences or standard errors, state degree of success
- **Background:** Why doing experiment, state goals, give background and historical info explain any deviations from procedure
- **Theory & Methods:** State and explain equations for V_{LED}, for Work, and relationship between E and ν, how frequency was determined. State any assumed constants including their values and sources. State assumptions or limits of theories applied. Relevant physics for LED emission of light, how energy is transferred from voltage source to electrons to photons.
- Overview of the general process of how data was taken. Anything important to point out or clarify about the procedure and equipment's setup/operation *including* sensors. Particular attention to calibrations (if any). Diagrams or photos of setup could help here.
- **Results:** Experimental value for h with uncertainty, reference value with source, % difference. Summary table for 6 LEDs. Plot of E vs. ν (where ν is horizontal axis). Discuss at least two sources of error, and respond to the "Further questions" section.
- **References:** Proper format as seen in Good Lab Report and Example Reports
- **Calculations:** *One complete example of all equations used, should show steps needed to get from*

data to final result(s).

- **Plot Data/Raw Data:** for E vs ν plot, this can be included in the Summary Table in Results. Graph(s) of the V vs I output and linear fits for each of 6 LEDs.

These are just guidelines. You may need to add more items as these are just some of the things expected.