General Physics Lab 11

Planck's Constant

Objectives:

- To observe the spectra from a variety of light sources
- To measure Planck's constant using Light Emitting Diodes

Equipment:

- Handheld Spectroscope
- Multimeter with Probes
- Breadboard
- Jumper Wire Kit
- 2 Alligator Clip Wires
- 9V Battery
- 9V Battery Connector
- 470 Ω Resistor
- 1 kΩ Potentiometer
- 4 Colored LEDs (red, yellow, green, blue) in clear housing
- Variety of Light Sources
- Black Electrical Tape
- Black Paper (can reuse conductive paper)
- Smartphone Camera (or other camera)

Physical Principles:

LEDs and Planck's Constant

A hole is an empty, unoccupied electronic state in a positively-charged ion or crystal lattice. Holes (the absence of an electron) can behave just like particles of positive charge. When an electron meets a hole, the electron combines with and neutralizes it, filling the hole and emitting a photon of energy equal to the recombination (or removal) energy (see Fig. 1).

The depth of the negative potential energy well (hole) is characterized by a voltage, V_0, such that

$$PE_{hole} = -e|V_0| \ . \tag{1}$$

The energy of the emitted photon is given by the Planck relation,

$$E_{photon} = hf = \frac{hc}{\lambda}, \tag{2}$$

where f is the frequency, λ is the wavelength, c is the speed of light, and h is Planck's constant.

During recombination, the energy of the emitted photon is equal to the energy lost by the electron as it fell into the hole, such that,

$$hf = e|V_0| \,. \tag{3}$$

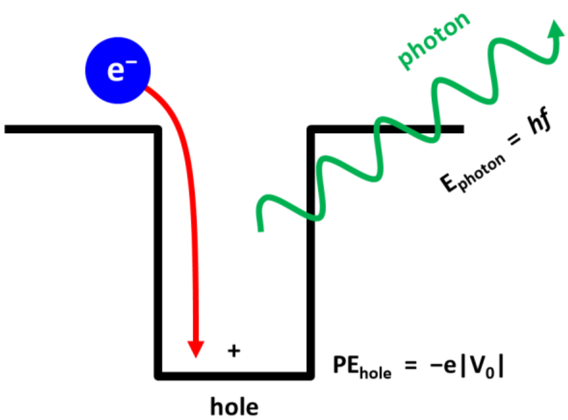

Fig. 1: An electron combines with a hole, falls into a potential energy well, and emits a photon with energy, E_{photon} = hf.

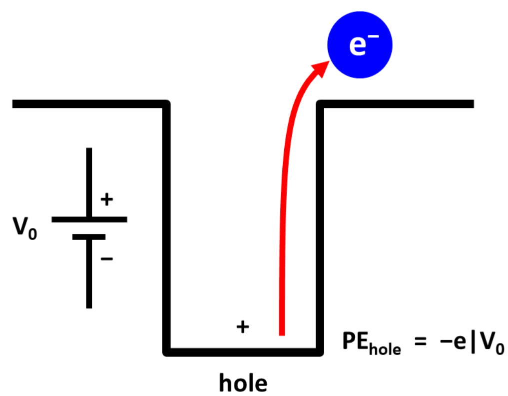

Fig. 2: An applied voltage, V_0, can remove an electron from a neutral atom, creating both a hole and a free electron.

Conversely, the application of a voltage, V_0, to a neutral atom in a solid can supply electrons with enough energy to escape the hole and become conducting electrons (see Fig. 2).

In an LED, no electrons can flow until a voltage, equal to or exceeding V_0, is applied to the semiconducting material. Applying a voltage greater than V_0 creates electron/hole pairs, allowing current (electrons) to flow and emitting photons of light (via the recombination process). The color (wavelength) of light depends on the removal voltage, V_0, for the specific materials in the LED.

To put it simply, if you apply a high enough voltage ($V > V_0$), current will flow through the LED, producing light.

Rather than obeying Ohm's Law for resistors, a graph of current vs. applied voltage for an LED appears as in Fig. 3. For applied voltages below V_0, very little current can flow. Above, V_0, the current grows rapidly and the LED light turns on.

Different semiconductor materials have different electron removal energies, $e|V_0|$, which can be measured as the turn-on voltage, V_0.

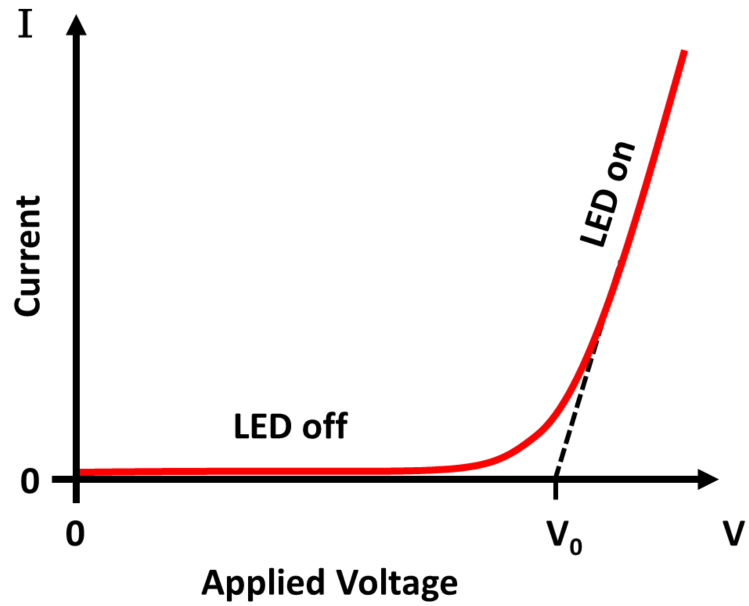

Fig. 3: Current vs. Applied Voltage for an LED – Current only flows for $V > V_0$, i.e., voltages large enough to remove electrons from holes in the semiconducting material.

In the historic Photoelectric Effect experiment, photons of light eject electrons from a metal. The kinetic energy of the ejected electrons is measured by the application of a stopping potential, V_s. Einstein used conservation of energy to write the equation

$$hf = eV_S + W \, , \tag{4}$$

or, photon energy = kinetic energy + work function.

Your experiment today examines the reverse process. An electron falls into a potential well of depth, $e|V_0|$, and the frequency of the emitted photons is measured. Eq. (3), then gives the value of Planck's constant, h. There should also be a non-zero offset (y-intercept) in Eq. (3), but we are not going to analyze that in this experiment.

Procedure:

Prepare Spectroscope

1. Your handheld spectroscope has a few openings that are key to its operation (see Fig. 4).
   a. On the end of the short edge of the wedge-shaped case, find the diffraction-grating **eyepiece** that splits light into component colors.
   b. Locate the vertical **slit** near one end of the longest edge of the wedge-shaped case.
   c. Find the long, horizontal opening across the front edge of the wedge that illuminates a transparent, printed **wavelength scale**. The numbers printed on the scale (4, 5, 6, 7) represent the wavelengths in hundreds of nanometers (400 nm, 500 nm, 600 nm, 700 nm). Each mark on the scale stands for 10 nm.

Fig. 4: Handheld spectroscope with eyepiece, vertical slit, and wavelength scale.

2. Hold your handheld spectroscope up to a light source, looking into the eyepiece to check that plenty of light is coming through the slit. Then look for a rainbow of colors spread along the wavelength scale.
3. Use electrical tape to narrow the slit of the spectroscope down to 0.5 mm of width (or less) to increase its wavelength resolution. Also, shorten the length of the slit to about 2 mm. See Fig. 5.

   Note: narrowing the slit also has the deleterious effect of limiting the intensity of the light – so a trade-off is necessary. You may have to adjust the tape after looking through it to fine-tune the spectroscope resolution and brightness.

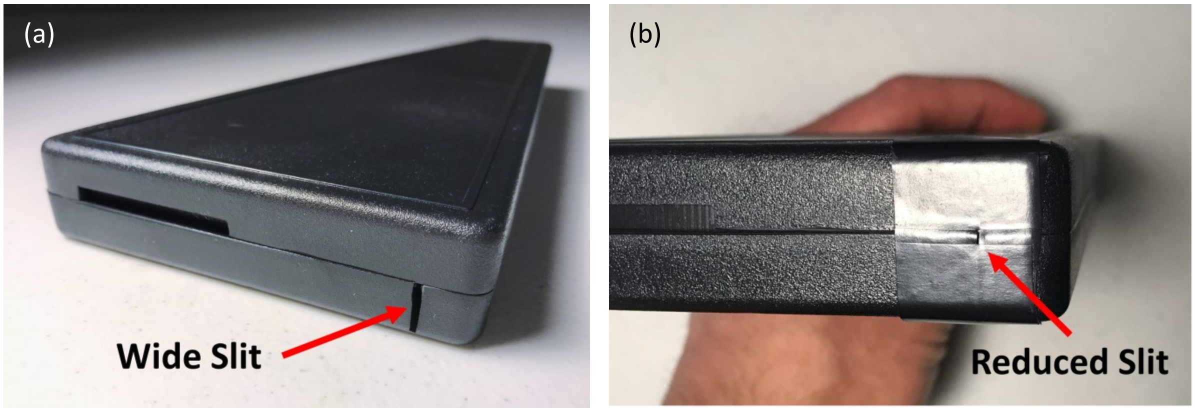

Fig. 5: Handheld spectroscope – (a) Before the application of electrical tape. (b) After the slit has been narrowed and shortened with electrical tape.

4. Aim the spectroscope at various light sources around your home and describe the spectrum of each. We have included a few pictures taken through the spectroscope for comparison (see Fig. 6).

   WARNING: Do NOT look at a laser or directly at the sun as it could damage your eye!

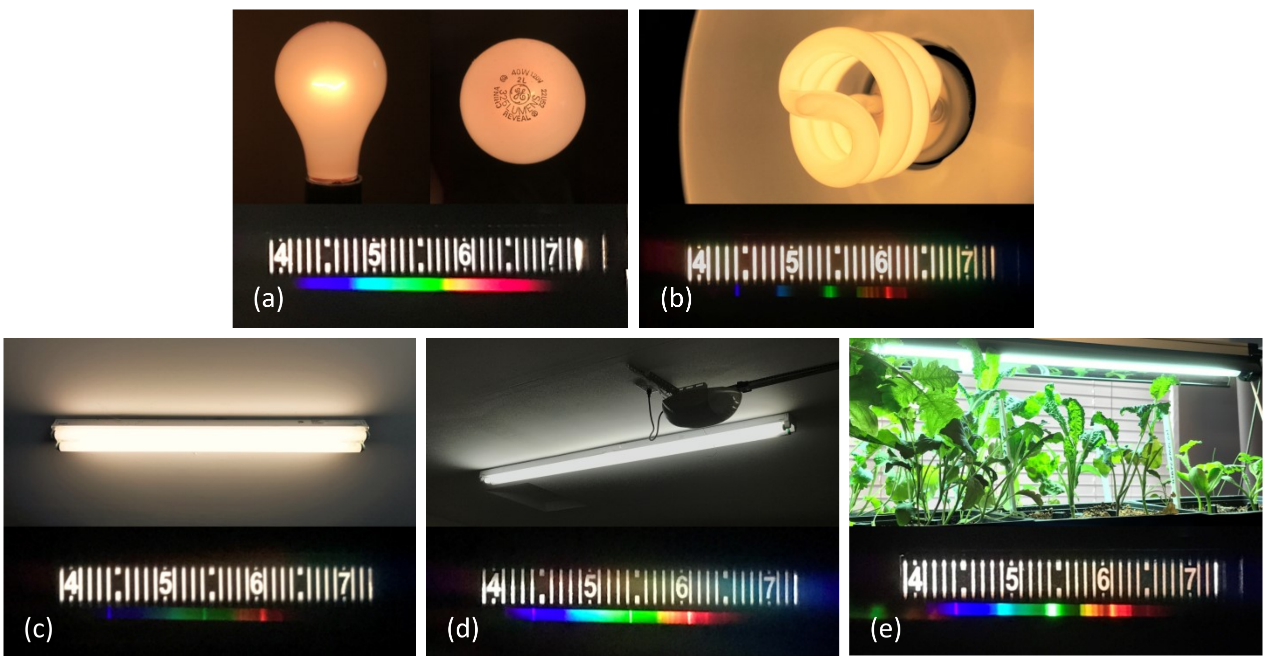

Fig. 6: Spectra of various household light sources.

(a) Incandescent light bulb emits all colors of radiation like a black-body radiator.
(b) CFL shows some broadened mercury emission lines.
(c) Warm fluorescent bulb shows emission lines of mercury with emphasis on red line.
(d) Cool fluorescent bulb shows strongly the blue wavelength.
(e) Full spectrum grow light emphasizes the blue and red light absorbed by chlorophyll.

Build the Circuit

1. Turn the multimeter dial to measure DC voltage (V ⎓), set it to the 20V range, and insert the probes in the appropriate ports (black in COM, red in V). Note that while most voltage measurements in this experiment would work on the 2000 mV range, the values jump around too much at this precision.
2. Build the LED circuit shown in Fig. 7. This is the same circuit as you used previously in Lab 0 and in the Inverse-Square Law experiment.
3. When placing the potentiometer in the circuit, make sure that each of the three pins are in separate rows. In this diagram (Fig. 7b), the breadboard is turned on its side with the rows (5 holes) running vertical.
4. The potentiometer (adjustable resistor) is used to adjust the voltage supplied to the LED.
5. Locate the 470 Ω resistor from your lab kit.

   You can tell the resistor's nominal value from the 4 or 5-band color code printed on the resistor. To interpret this code, look up a resistor color code table or use an online calculator such as this one: https://resistorcolorcodecalc.com/.

6. The 470 Ω resistor is included to prevent too much current from flowing through the LED and burning it out.
7. For the LED in the circuit, you will use the 4 colored LEDs (red, yellow, green, blue) instead of the white LED from the Inverse-Square Law experiment. During the experiment, you will swap out the different LEDs, making measurements on each. It doesn't matter which one you start with, so just choose one for now.
8. Test the LEDs in the circuit to check their color. Make sure you use the colored LEDs and not the white LEDs. All the LEDs are transparent so it will be impossible to distinguish them without testing.
9. Note that LEDs allow current to flow in only one direction (like a turnstile at a sporting event). The LED must be oriented as shown with the positive lead (long lead) in the more positive position (connected to the resistor) and the negative lead (short lead) in the more negative position (connected to the negative source wire). See Fig. 7a & b.
10. When you connect the multimeter across the LED, do not connect it directly to the LED. Later, you will need to surround the LED with a paper tube, making it impossible to connect alligator clips directly to the LED. Instead, connect the red multimeter probe to the resistor lead (same row of 5 holes as the positive LED lead) and connect the black multimeter probe to an extra jumper wire (same row of 5 holes as the negative LED lead). See Fig. 7b & c.
11. Test the circuit to make sure it works. When you twist the potentiometer knob, the LED should turn on and then shine brighter as you twist it farther. Notice that the LED does not shine for low voltages, turns on at some voltage, V_0, and then shines brighter for higher voltages as in Fig. 3.

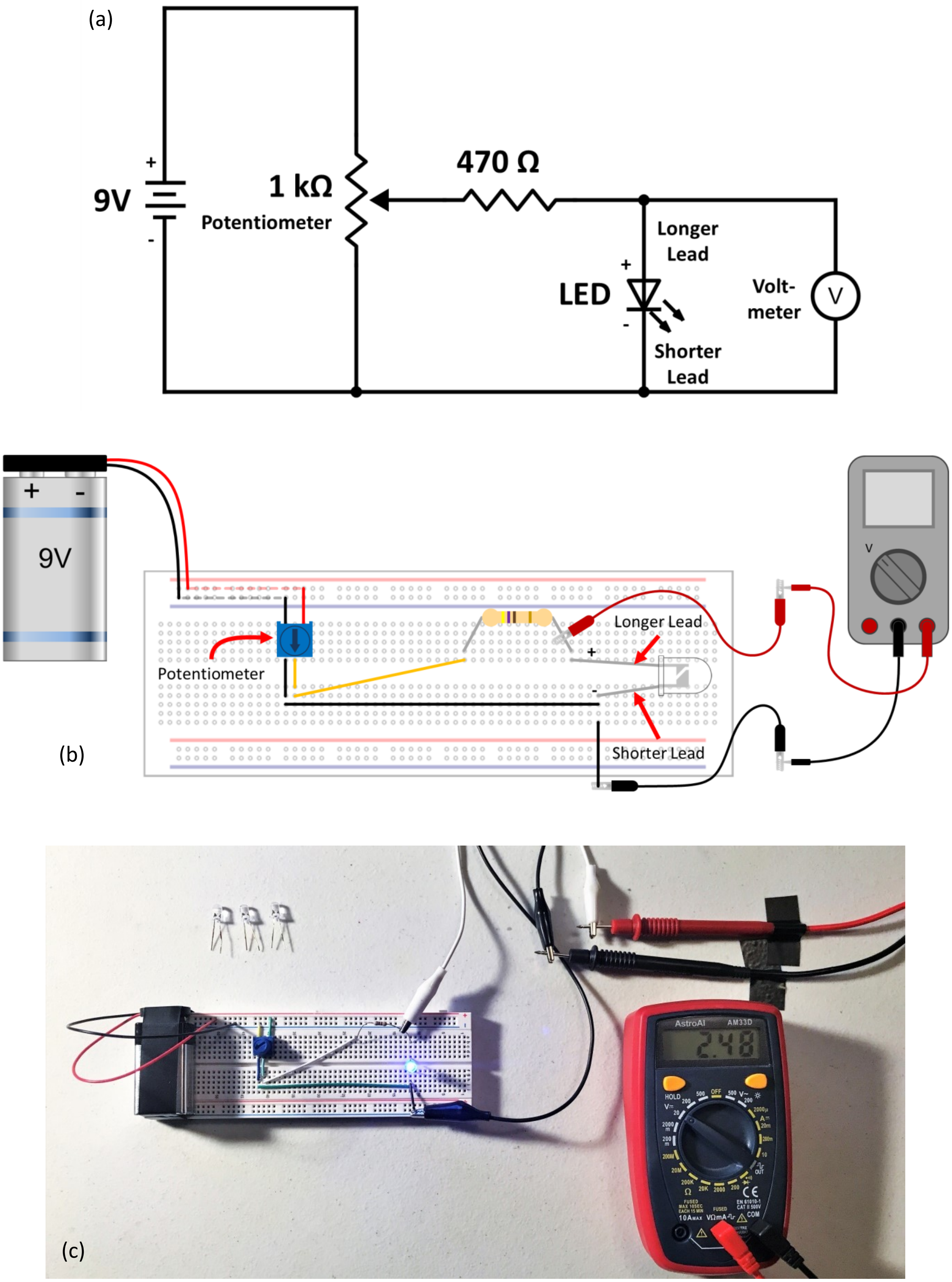

Fig. 7: Adjustable LED Circuit for measuring h – (a) Circuit Diagram, (b) Breadboard Wiring Diagram, (c) Assembled circuit with three additional LEDs to swap in later.

In order to accurately measure the turn-on voltage, V_0, for each LED, we need to reduce the ambient light around the LED.

12. Cut off two short strips of black electrical tape (about 4 cm long). Remove the LED from the circuit and place the tape over the spot where the LED was. It should make a square about 4 cm on each side.
13. Poke the LED leads through the tape into the breadboard and double check that it went into the correct holes (see Fig. 8a). If it did not, peel up the tape with the LED, line up the leads, and insert the LED again. Then press the tape back down. If the tape is too tough for the leads to poke through, use something like a paperclip or a pin.
14. Roll a piece of black paper and tape it into a tube to place around the LED to darken the background light further (see Fig. 8b & c). You can use your own paper for this or some of the conductive paper from the earlier labs. If you use conductive paper, make sure the black side of the paper is on the inside of the roll.

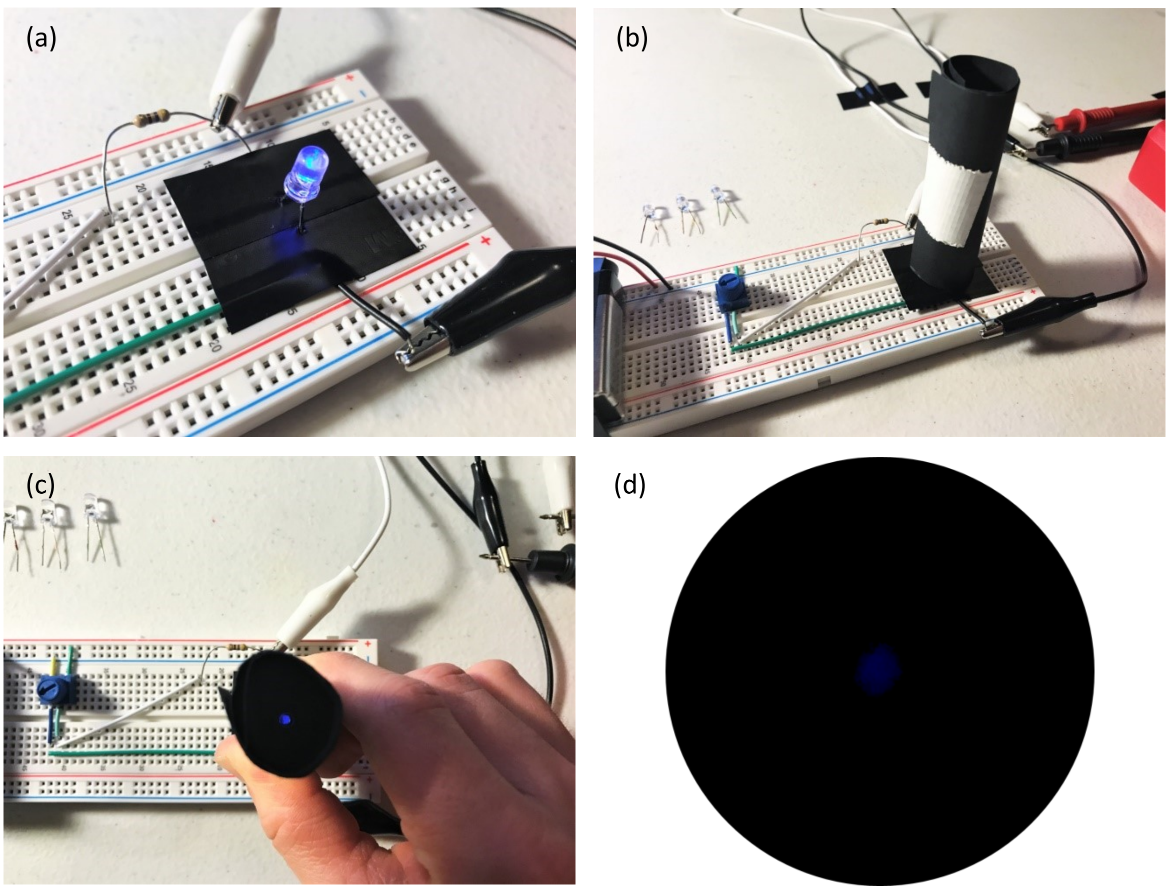

Fig. 8: (a) Black electrical tape placed beneath the LED helps remove ambient light from below. (b, c) A rolled piece of black paper acts as a viewing tube that blocks ambient light from the LED. (d) This picture shows what the LED in the tube should look like when it first begins to glow (notice the faint blue spot in the center).

Measure Turn-On Voltage

For this part, it may be helpful to turn off the room lights and close the blinds (reduce the ambient light).

1. Turn the LED voltage all the way down so that the LED light is off.
2. Make sure the LED is pointed straight up and is not at an angle or you won't see it as brightly.
3. Press the black paper tube down onto the tape, center the tube around the LED, and press your eye up against the top of the tube so that all you can see from that eye is black.
4. Slowly adjust the potentiometer up until the LED glows very dimly (see Fig. 8d).
5. Be careful to avoid making the LED too bright or your eye will adjust to the brightness and make it difficult to see the dim light afterwards.
6. Turn the brightness down slowly and stop right when the light disappears. Keep your fingers on the potentiometer knob and hit the HOLD button on your multimeter to capture the value. Then let go of the potentiometer.

   Hint: We found that the voltage would change when we let go of the potentiometer because of the slight torque being applied by our fingers, which disappears when you let go. To avoid this, keep your fingers on the knob, watch the light, hit the hold button on the multimeter, and then let go of the potentiometer. The voltage, V_0, is then saved and you can write it down without it changing.

7. Record the color of the LED and the turn-on voltage, V_0.
8. Repeat this process for the other three LEDs, each time recording their color and unique turn-on voltage, V_0.

IMPORTANT: When you finish using the multimeter, turn it off to save the battery. The simpler inexpensive multimeters often do not shut off automatically.

Measure Wavelength

Now you need to measure the wavelength of light emitted by each LED. This can be done with the room lights on, making it easier to read the wavelength scale. Also, you may remove the black tape from under the LED as this is no longer needed.

1. It may be easiest to read the spectroscope in a hands-free manner, so bend the LED 90° to aim horizontally toward the spectroscope (see Fig. 9).

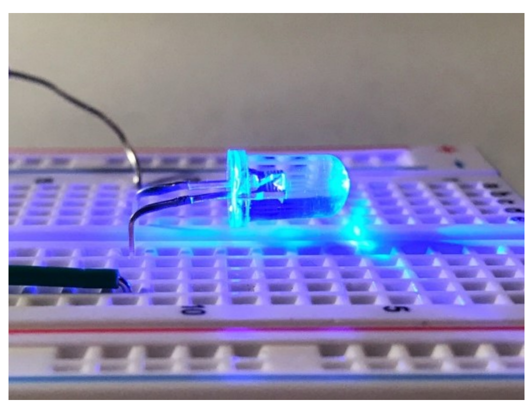

Fig. 9: LED bent to shine horizontally for easy viewing through the spectroscope.

2. Turn up the voltage to the LED until it shines brightly.
3. Place the spectroscope on the table and aim it at the LED.
4. Prop up the spectroscope and/or breadboard so that the LED shines directly into the slit on the spectroscope. You can use thin books, stacks of paper, or other objects to adjust the height appropriately. Fig. 10 shows one way to do this, using only items from the lab kit. The breadboard is sitting on the jumper wire box and the spectroscope is on top of the CD and the electrical tape roll.

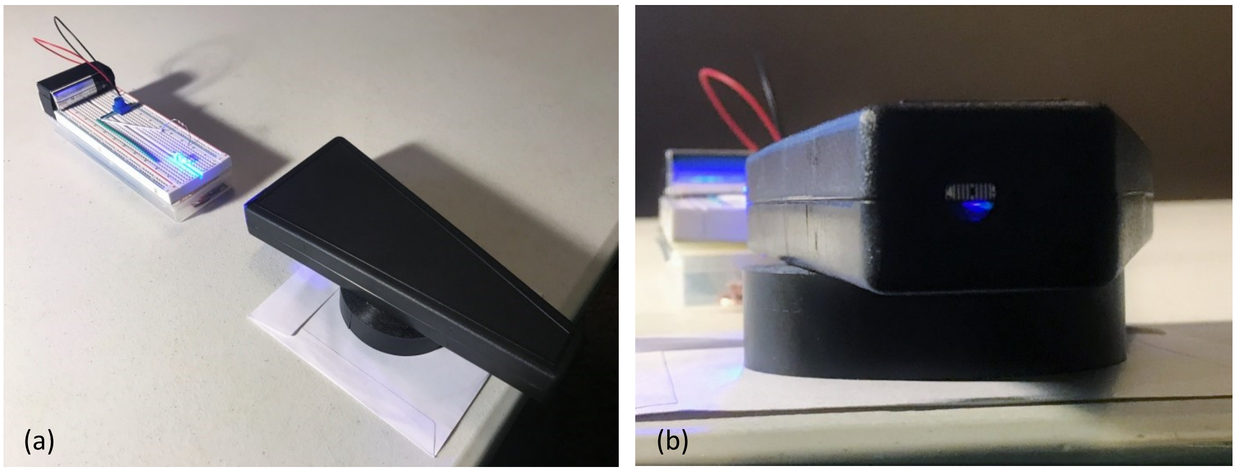

Fig. 10: Spectroscope slit lined up with the LED. Various lab kit items are used to adjust the heights so that the LED shines directly through the spectroscope slit.

5. If you have difficulty seeing the wavelength scale, try using white paper to reflect light onto the scale or shine a flashlight indirectly onto the scale to illuminate it from the backside.
6. Look into the spectroscope and make sure the LED is shining directly into the slit. Then turn down the LED brightness with the potentiometer to narrow the distribution of wavelengths (reduce the width of the smear of light).
7. Estimate the wavelength value at the center of the distribution (see Fig. 11).
   See if you can estimate the central wavelength to the nearest 5 nm (each division on the scale is 10 nm).
8. Record this central wavelength, λ, with the corresponding turn-on voltage and color for each LED.

   Tip: It may be easier to accurately read the values if you have the spectroscope set up completely hands free, take a picture through the eyepiece, and then look at the picture to find the central value. You will need to take pictures for the next step anyway.

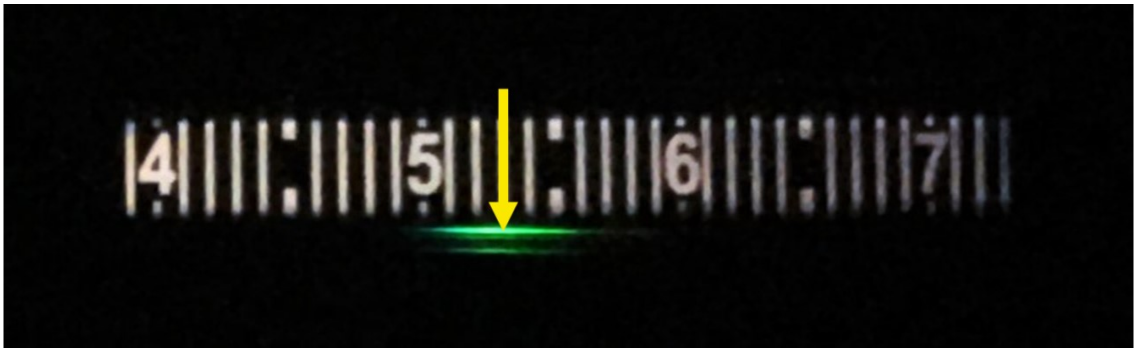

Fig. 11: Image of spectrum produced by a green LED with central wavelength indicated.

9. Do your best to focus your camera through the spectroscope viewfinder to capture images of each spectra for inclusion in your eJournal. It's ok if the wavelength scale is small in the picture. Just make sure you can see it completely and crop in on it after you take the picture. That is how the above example (Fig. 11) was captured.

IMPORTANT: When you finish the experiment, be sure to disconnect the battery from the LED circuit. Even if you turned off the LED using the potentiometer, the potentiometer is still consuming power from the battery.

Analysis:

According to Eq. (3), there should be a linear relationship between photon frequency, f, and the transition energy of an electron-hole recombination, eV_0.

1. Convert the measured wavelengths into frequencies (units of Hz = 1/s), using Eq. (5). If you recorded the wavelengths in nanometers, convert to meters before calculating the frequency.

$$f = \frac{c}{\lambda} \qquad (5)$$

2. Plot V_0 (y-axis) vs. f (x-axis), perform a linear fit, and record the slope.

Eq. (3) suggests the slope of your graph should be Planck's constant divided by the charge of an electron, h/e.

3. Multiply your slope by the charge of an electron (e = 1.602×10^{-19} C), to obtain your measured value of Planck's constant, h_{meas}.
4. Use a percent error to compare h_{meas} to Planck's constant, h = 6.626×10^{-34} J·s.

$$\%Error = \frac{|h - h_{meas}|}{h} \times 100\%$$