A Primer in Quantum Computing
Bonus Lab: Measuring Planck's Constant

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1 Introduction

The scale of quantum mechanical effects is governed by Planck's constant: 'h'. Do you experience quantum effects in your daily life? Outside of a lab setting, probably not. Let's get a measure of h and see if that makes sense.

2 Materials

Everyone doing this experiment should have access to the following materials:

- Spectrophotometer
- Multimeter
- Mini Breadboard
- 2 MΩ Potentiometer (Variable resistor)
- 100 KΩ Resistor
- LEDs
- 9V Battery
- Battery lead adapter

3 Procedure

3.1 Populating the Breadboard

A breadboard is a convenient way to make prototype circuits. These mini breadboards have been made such that rows of holes (to one side of the middle channel) are electrically connected. This is what they look like under the hood:

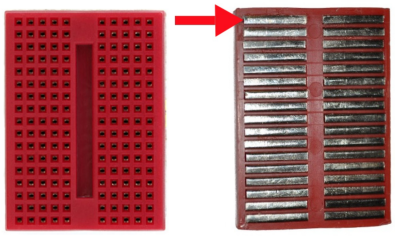

Figure 1: Rows of holes in a breadboard are electrically connected. Image credit: SparkFun

We'll use these electrical connections to make a simple LED-resistor circuit; here we go!

1. Connect the 9V battery to its adapter

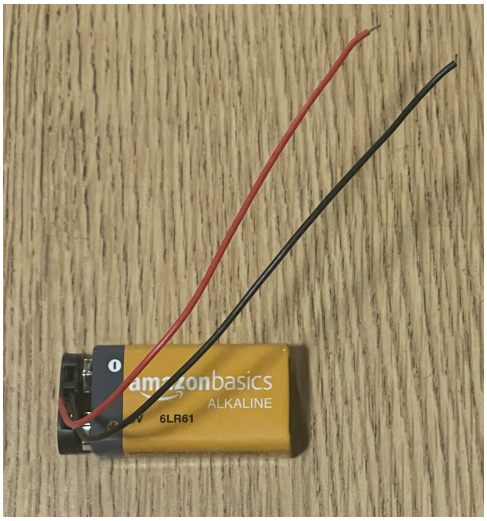

Figure 2: Nothing crazy yet... just a battery and its adapter.

2. Use the following image to properly insert the potentiometer, resistor, and **any color LED** into the breadboard:

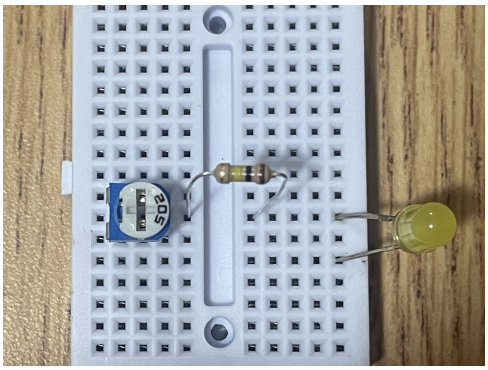

Figure 3: It's a bit hard to make out, but the potentiometer has three pins, and the resistor is connected in the same row as the middle one.

Note that the orientation of the LED is super important! **You want the longer pin to go into the same row as the resistor!**

3. Connect the leads from the battery adapter into the breadboard.

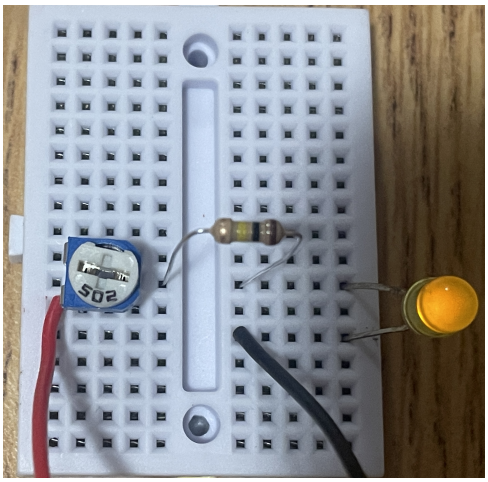

Figure 4: Also a little hard to tell, but the red lead from the battery is connected to the same row as the bottom pin of the potentiometer. Depending on the state of the potentiometer, the LED may shine brightly or very faintly. Turn it and see if you can change the LED's brightness!

At this point the LED should begin to glow (at least faintly). If it doesn't, try turning the potentiometer from one extreme to the other; it should certainly turn on in at least one of these cases.

3.2 Data collection

For each LED...

1. Turn the potentiometer head so that the ***LED shines brightly***. These potentiometers are a bit tough to turn manually while in the breadboard, so you may want to pull them out, turn them, and stick them back in.
2. Cup the LED with your hand such that you block out as much ambient light as possible. Bring the spectrophotometer to your eye and direct it at the LED. Record the wavelength reading in the table below. If the reading is smeared, just take the middle value. Here's an example:

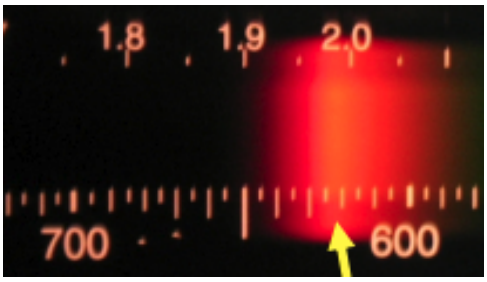

Figure 5: You might take the center value as your estimated wavelength, which is roughly 620 nm. Don't worry too too much about nailing this measurement.

3. Now turn the potentiometer so that LED is ***barely lit***.
4. Measure the voltage across the LED using a multimeter like so:

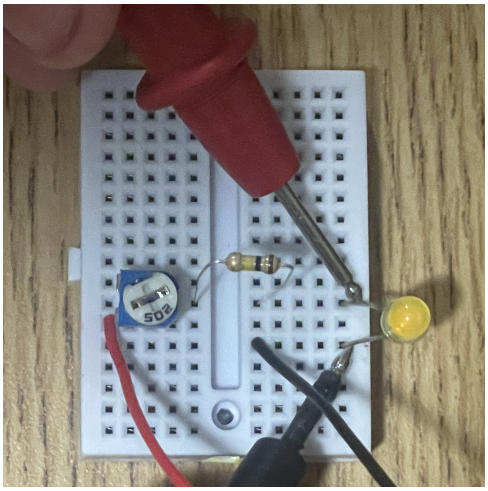

Figure 6: Measure the voltage across the LED by touching one multimeter probe to one LED pin.

Figure 7: Make sure the multimeter is in DC mode, which means the dial is turned to the "V—" setting like in the picture.

> **Note that if you get a negative value, this is because you've switched the positive and negative probes of the multimeter.** This is okay, just record the absolute value in the table below.

5. Repeat for all your LED's!

As you're collecting data, record your voltages (from the multimeter) and your wavelengths (from the spectrophotometer) below (I've filled in an example from when I did this lab myself):

LED	Voltage (V)	Wavelength (nm)	E (J)	f (Hz)	h (j x s)
Blue	2.38 V	475	3.808×10^{-19}	6.316×10^{14}	6.03×10^{-34}

Note that up to this point, you should only have columns for voltage and wavelength filled in (for the available LEDs). The next section talks about how to fill in the rest.

4 Analysis

We will use three quantum mechanical formulas to compute the energy (E) and frequency (f) of the photons (light particles) coming from the LEDs. **For these, feel free to use an online calculator like Desmos to make your life easier.**

1. To compute the energy, take your voltage values for each LED (V) and multiply them by $e = 1.602 \times 10^{-19}$. This will give you an energy in *Joules*, the international standard unit of energy:
$$E = e \times V \tag{1}$$

2. To compute the frequency, plug your wavelength value (λ, in nm) into the following equation:
$$f = \frac{c}{\lambda} \times 10^{-9} \tag{2}$$
where c is the famous speed of light: $c = 3.00 \times 10^8 \frac{\text{m}}{\text{s}}$.

3. Let's put this all together: for each LED, compute E/f; this will give you h:
$$h = \frac{E}{f} \tag{3}$$
This is the so-called *Einstein relation*, which you may have already seen in a chemistry class.

4. At this point, you should have several possible values for h (one for each LED). Take their average; this is called your *best value*.

4.1 Discuss with your lab partners:

1. Look up the accepted value for h on the internet... how close was your measurement?
2. What are possible sources of error from your measurements?
3. Which of these sources is the most significant?

Congratulations... you've just validated quantum mechanics (specifically the *quantization of light*) in experiment!