QUANTUM (Q)-KIT

Light and Photons:

Laboratory for Secondary Level Students

Teacher Manual

WOMEN SUPPORTING
WOMEN IN THE SCIENCES

Mission Statement

The mission of this laboratory is to teach secondary level students (ages ~12-18) about light through experiments related to interference and the photoelectric effect, showcasing its wave-like and particle-like behaviors.

Contents

1. Introduction to WS2 Laboratory Kits

1.1. Information about WS2

Women Supporting Women in the Sciences (WS2), an international organization unifying and supporting graduate and professional-level women and allies in science, technology, engineering, and mathematics (STEM), was awarded an American Physical Society (APS) Innovation Fund in 2020 to form international teams to design and distribute low-cost physics and materials science lab kits to primary and secondary school students, predominantly in eastern Africa. The lab kits utilized local resources and included topics that are especially relevant to young girls in order to spur their interest in STEM subjects. From 2020-2023, over 5100 students from eastern Africa at over 40 school sites engaged with our lab kits, with 62% being girls.

WS2 was awarded their second APS Innovation Fund in 2025 to support another Lab Kit Initiative, though this time with a focus on quantum topics. For more information about WS2, please visit our website at ws2global.org.

WS2 is sponsored by the APS Innovation Fund, APS Forum on Education, Northwestern University Materials Research Science and Engineering Center, and Northwestern University Multicultural Student Affairs. WS2 is extremely grateful to the lab kit design volunteers for their hard work and external consultants (SciBridge and Projekt Inspire) for their advising. WS2 also thanks and acknowledges PhysicsQuest (https://www.aps.org/initiatives/physics-education/physicsquest) and Quantum Explorations Student Toolbox (QuEST) for example experiments that were used as foundation for the lab kit content.

1.2. Using this Guide

This manual is to be used by the teacher or facilitator of the laboratory kit, and it is similar in content to the student manual but may contain additional material, namely: Fundamental Science Concepts Covered, Practical Skills, Summary of Experiments, Teacher Pre-Lab, and Troubleshooting. These additional sections are intended to provide the teacher with the background and foundation critical for successfully implementing this laboratory kit in the classroom. It is recommended that the teachers of this laboratory kit go through the guide from beginning to end to familiarize themselves with the content prior to teaching the laboratory kit to students. Questions about the content can be directed at any time to ws2global.org@gmail.com, using the subject line "Question about Lab Kit Content".

IMPORTANT NOTES:

- This laboratory kit is intended for use with secondary-level students (ages ~12-18), but depending on the specific students' educational background, the content may need to be modified by the teacher to be made simpler or more complex. The teacher is encouraged to also cover the content at the pace that works best for the students; some younger students may need more time and attention from the teacher and/or facilitator to go through the questions and experiments, while older students may be more independent and require less attention from the teacher and/or facilitator. Thus, the content covered, depth of coverage, and pacing are left to the teacher's and/or facilitator's discretion.
- The content in this lab kit manual may not fit into the specific curriculum of the school in which it is being taught. It is up to the facilitator(s) and teacher(s) whether they would like to introduce new content or skip certain sections that are not applicable to their classrooms.
- In certain areas, modifications to the supply list may need to be made depending on the availability of the supplies in the specific area in which the lab is being taught. We have attempted to list some alternatives in the supply list, but we understand this list of alternatives is not exhaustive.
- In the experiments, the students are split into groups of three to four. If supplies allow, students may instead be split into groups of two.

1.3. Key Vocabulary

- Photon: a particle or quantized packet of light or other electromagnetic radiation
- Frequency: the rate at which a wave repeats its pattern
- Diffraction: the spreading of waves as they pass through or around an obstacle
- Interference: the occurrence of two waves meeting and the resulting net effect of their combination
- Work function: the minimum energy required to remove an electron from the surface of a metal

1.4. Key Questions

- What is light? Is light a wave or a particle?
  - *Answer: Light is electromagnetic radiation that can be detected by the eye. Light is both a wave and a particle, exhibiting so-called wave-particle duality.*

- What phenomena demonstrate the wave-like properties of light? What about the particle-like properties of light?
    - *Answer:*
    - *Wave-like properties: interference, diffraction*
    - *Particle-like properties: photoelectric effect*

1.5. Purpose

The purpose of this lab kit manual is to enable students to conceptualize the basics of light through theory, demonstration, and experiments. The manual introduces the students to the properties of light as a wave through wave properties including diffraction and interference. It will also introduce students to the quantization of light using the photoelectric effect.

1.6. Fundamental Science Concepts Covered

This laboratory kit introduces the topic of light as a wave and a particle, relevant to numerous fields including Physics, Chemistry, and Biology, to middle and high school/secondary-level students. Specifically, the lab kit encourages students to think about how light acts as a wave through diffraction and interference experiments and as a particle through the photoelectric effect analogy and simulation. Students will come away with the following key takeaways: (1) light passing through extremely tiny slits spreads out, or diffracts, and this creates an interference pattern; (2) photons of different color are different energy, and when they hit a metal surface, they can cause electrons to be ejected if they are of sufficient energy.

1.7. Practical Skills

- Students will understand light properties and how this leads to different phenomena observed.
- Students will gain practical experience with lasers and computer simulation.
- Students will connect concepts to everyday experiences at school and home (e.g., interference patterns, devices that produce and use light)

2. Background on Main Topics

2.1. What is Light?

Light is all around us. It comes from the Sun and appears in a dark room when you turn on a lamp. The basic question of "what is light?" is one that scientists have been asking for centuries, and the answer is not so basic. Light is electromagnetic radiation that can be detected by the human eye, and visible light is only one slice of electromagnetic radiation that also includes radio waves and X-rays (see Figure 1).

How did we get to this definition? Isaac Newton put forth the theory that light is made up of different parts, discrete particles called corpuscles, in his book Opticks in 1704. These corpuscles travel at high speeds and always in a straight line. Different colors are corpuscles that are different sizes. This particle theory of light, however, was not able to explain certain phenomena that were observed such as diffraction, the spreading of waves as they pass through or around an obstacle, and interference, the occurrence of two waves meeting and the resulting net effect of their combination. A Dutch physicist, Christiaan Huygens, put forth a wave theory of light that was able to explain these phenomena. Thomas Young's experiments with interference patterns confirmed this theory, and in 1864, James Maxwell proposed the existence of electromagnetic waves. Out of this proposal came the idea that light was a type of electromagnetic wave.

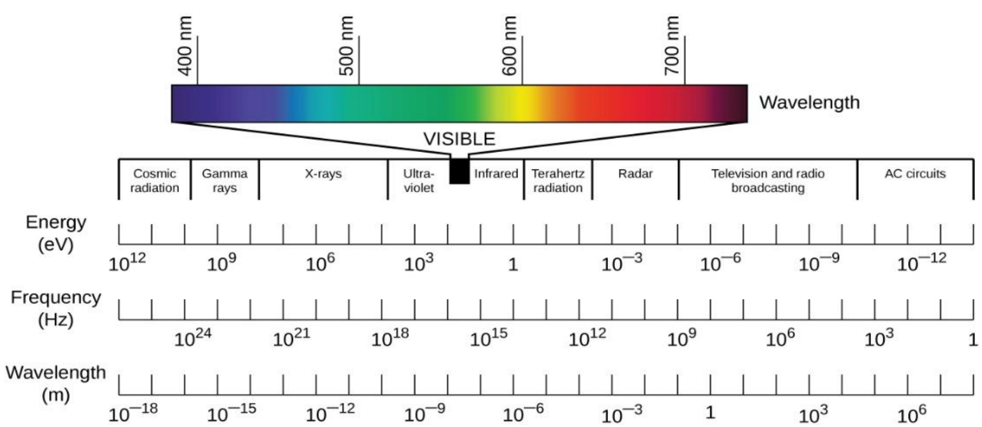


Figure 1. Visible light is a slice of the electromagnetic spectrum ranging from about 400-700 nm in wavelength. The corresponding energy and frequency of light is also shown. This image by Unknown Author is licensed under CC BY.

2.2. Wave-particle Duality of Light

The theory of light as a particle had been discounted until Albert Einstein revived it in his explanation of the photoelectric effect, which occurs when light hits a metal surface and causes ejection of electrons (see Figure 2). The minimum energy required to eject an electron from a metal surface is known as its work function. Einstein proposed that light travels as discrete packets of energy called photons. He incorporated Max Plank's theory of energy quantization and said that the light energy is quantized, and the energy is directly proportional to its frequency,

$E = hf$,

where E is the photon's energy, f is frequency, and h is Planck's constant, which is equal to ~6.63×10^{-34} J-s. Frequency is the rate at which a wave repeats its pattern, or in this case, the rate at which light waves repeat their pattern. Frequency is related to the energy of light, with higher frequency light corresponding to higher energy light. Frequency of light is inversely proportional to wavelength of light, which is distance between two identical points on a wave. Thus, with the quantum theory of light, it was proposed that light is both a wave and a particle at the same time, so-called wave-particle duality. This theory can explain both wave-like and particle-like behavior of light observed in daily life and the laboratory. Experiments, however, had never been able to capture *both* light's wave and particle nature at the same time until recently. In 2015, scientists at Ecole Polytechnique Federale de Lausanne (EPFL) used electrons to capture a snapshot of light behaving as both a wave and a stream of particles.

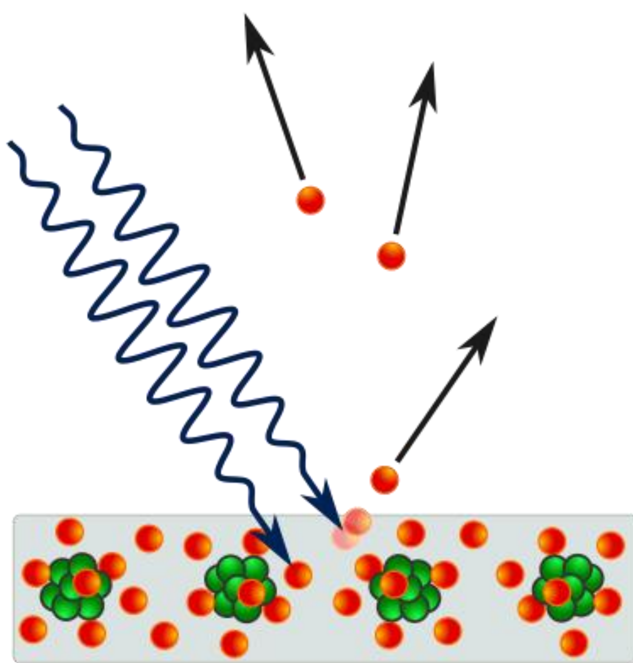


Figure 2. In the photoelectric effect, photons (packets of light shown in blue) hit a metal surface and cause emission of electrons (circles shown in red). This image by Unknown Author is licensed under CC BY-SA.

2.3. How is Light Produced?

There are many ways in which light can be produced. In incandescence, like with an incandescent light bulb, light is produced by heating a filament until it glows (see Figure 3). Incandescence is a simple and widely used lighting technology. Generally, in incandescence and also in combustion, which is the process of burning something, light is produced by excited atoms when electrons move from a higher energy level to a lower energy level to produce light with wavelengths equal to differences between the energy levels. The light from an incandescent bulb contains multiple colors (or wavelengths), which usually results in yellowish light.

In electroluminescence, light is emitted when excited electrons recombine with their counterpart, the hole, in a semiconductor material when current is passed through it. Light emitting diodes (LEDs) (see Figure 3) are examples of semiconductor devices that emit light through electroluminescence when electrons and holes recombine at a pn junction, which is an interface between a material rich in electrons (n region) and a material with many available spaces for electrons to fill, called holes (p region). The color of the emitted light depends on the energy band gap of the semiconductor, which is the minimum energy distance between an excited electron and its hole. LED technology is now widely used to make light bulbs by combining several LEDs in one bulb.

In a laser (see Figure 3), which stands for light amplification by stimulated emission of radiation, electrons in the lasing material are excited to a higher energy level. These excited electrons then return to their normal state and release photons, which can further stimulate excited electrons to release additional photons. The light in the laser bounces between mirrors, becoming amplified, and eventually a highly focused, coherent stream of photons escapes as a laser beam. The color of a laser is determined by lasing material band gap. A smaller band gap results in longer wavelength light (like red), and a larger band gap results in shorter wavelength light (like green or blue).

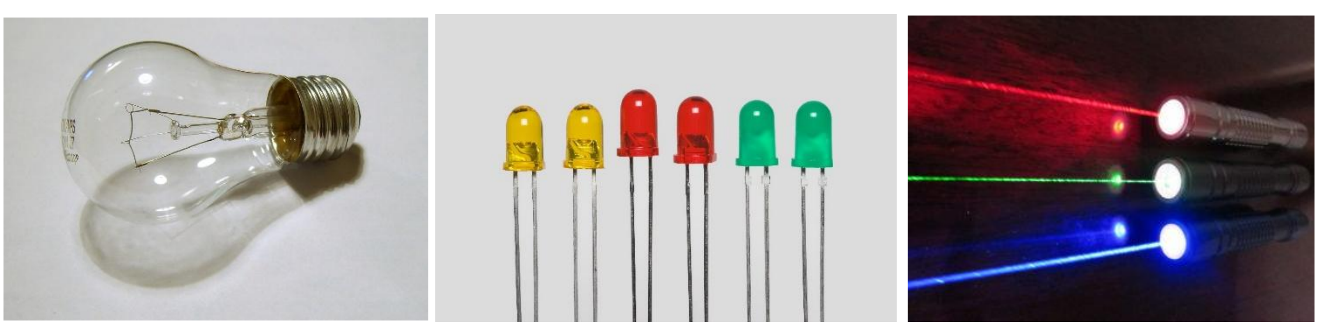


Figure 3. (Left) Typical incandescent light bulb. This Photo by Unknown Author is licensed under CC BY. (Middle) Examples of LEDs. This photo is licensed under CC BY-NC-ND. (Right) Three different lasers. This Photo by Unknown Author is licensed under CC BY-SA.

3. Summary of Experiments

This lab kit consists of two experiments, one optional computer simulation, and one design challenge to understand the concept of light and photons. This investigation will begin by providing background on light as a wave and particle, before demonstrating phenomena that emerge based on these descriptions. If your school does not have access to internet/computers, Part III can be skipped. The goals of the experiments and design challenge are the following:

Part I: To demonstrate how light interference enables measuring very thin objects

Part II: To observe how different energy photons can eject electrons in the photoelectric effect via an analogy with marbles and a ramp

Part III: To simulate the photoelectric effect and learn about light energy, frequency, wavelength, and intensity and their impact on electrons that are ejected from a metal surface

Design Challenge: To design a device that uses light to do something useful

3.1. Supplies List

- Laser pointer (red or green)
- Thin objects (hair, fishing line, jewelry wire)
- Large index card
- Paper
- Binder clip(s)
- Ruler or measuring tape
- Cardstock (heavy paper)
- Straws (or wooden dowels or sticks)
- Colored markers (or colored pencils or crayons)
- Marbles
- Tape
- Scissors

3.2. Safety Information

Before the students begin the laboratory, please take into consideration the following safety concerns:

- Students should never look directly at a laser point, as this can also permanently damage their eyes due to the laser intensity and emission as a tight beam.

3.3. Teacher Pre-Lab

Teachers can organize the supplies for the experiments ahead of time. For each student or each group of 2-4 students, the materials needed are: 2-3 thin objects (hair from humans or animals, fishing line, jewelry wire, etc.), 1 large index card, 1 piece of regular paper, 1 piece of cardstock (heavier) paper, 2 wooden dowels or straws, 2 marbles, 2 binder clips, and a pen or pencil. There should be laser pointers, tape, scissors, rulers, and colored markers that the classroom can share. If doing the optional simulation, each group should have access to a computer with internet access, or the teacher can project the simulation to the students on a screen or board.

4. Experiments

Note for teachers:

Encourage open discussion and questions from the class when introducing the experiments.

4.1. Part I. Measuring Thin Objects

This section is based on the Measuring the Width of Your Hair activity from Quantum Explorations Student Toolbox (QuEST).

4.1.1. *Additional Background*

Light exhibits interference and diffraction which indicates that it possesses the properties of a wave. When light passes through an opening, it spreads around the opening (see Figure 4). This is called diffraction. How much the light spreads, or how much it diffracts, is dependent on the size of the opening and the light's wavelength. If the size of the opening is similar to the wavelength of the light, the effect is more noticeable than if the size of the opening is much larger than the wavelength of the light. As the light waves pass through the opening, the waves spread out and interfere with each other. This creates an interference pattern that can be projected onto a screen. When there is constructive interference (the wave intensities are adding to each other), you will see a bright spot. When there is destructive interference (the wave intensities are cancelling each other out), there will be a dark space (see Figure 4).

In the single slit (one opening) configuration described above,

$\lambda/w = s/(2d)$,

where λ is the wavelength of the light, w is the width of the slit (in this experiment, w is also the width of the object as, according to Babinet's Principle, interference from a thin blocking object is the same as from a thin slit), s is the distance between the consecutive dark spots in the interference pattern (measured across the brightest middle spot), and d is the distance from the slit to the interference pattern (often projected onto a screen, wall, or piece of paper). In this experiment, you will use the interference of light to determine the width of thin objects, such as hair or fishing line.

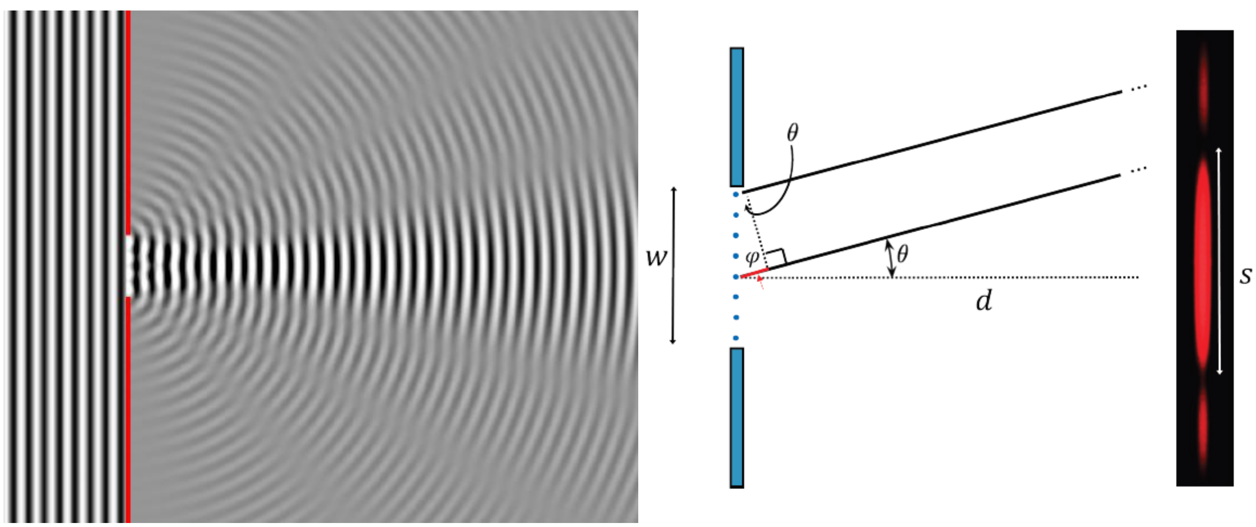


Figure 4. In a single slit experiment, light diffracts as it passes through a narrow slit opening, resulting in constructive and destructive interference (left, photo by unknown author licensed under CC BY-SA). Interference patterns are also observed when a thin object is placed in front of light, analogous to the single slit experiment. By measuring across the brightest center spot, we can solve for the width of the thin object in the path of a laser (right, QuEST materials).

4.1.2. *Pre-Experiment Questions*

1. How do you measure the width of objects? What about really thin objects?
    a. *Answer: You can use a ruler or caliper to measure the width of objects. If the object is really thin, you might need a microscope.*

2. How could you use an interference pattern to measure the slit width in a single slit experiment?
   a. <u>Answer:</u> *If you know the wavelength of light (**λ**), the distance between consecutive dark spots in the interference pattern (measured across the brightest middle spot) (s), and the distance from the slits to the interference pattern (d), you can solve for the (w) using **λ**/w = s/(2d), or w = (2d **λ**)/(s).*

3. What if instead of one slit there was a thin object placed in the path of light? Draw what this configuration would look like, referring to Figure 4.
   a. <u>Answer:</u> *The student should realize that a thin object placed in the path of the light will cause the light to diffract similar to the single slit experiment, leading to an interference pattern from the waves (like in Figure 4). This is according to Babinet's Principle.*

4. What is the wavelength of red light? Green light? What is special about a laser pointer's light wavelength?
   a. <u>Answer:</u> *The wavelength of red light is between 620-750 nanometers (red laser is usually ~650 nanometers) and green light is between 495-570 nanometers (green laser is usually ~532 nanometers). Laser pointers are special in that they emit light at one distinctive wavelength instead of a wider range of wavelengths.*

4.1.3. *Materials*

- Laser pointer (red or green)
- Thin objects (hair, fishing line, jewelry wire)
- Large index card
- Paper
- Tape
- Scissors
- Binder clip(s)
- Ruler or measuring tape

4.1.4. *Procedure (work in groups of 2-4)*

See Figure 5 for example of experimental set-up.

1. Cut square holes in index card (one hole per thin object). It is recommended to have at least 2 thin objects for measurement (human hair, animal hair, fishing line, jewelry wire, etc.).
2. Place one thin object over one hole and use tape to secure it taut. Repeat for other holes and thin objects.
3. Attach binder clip(s) to the bottom of the index card so the card can stand upright on its own. Place on tabletop or other flat surface.
4. Some distance (~1-3 meters) away from the tabletop, tape paper to the wall at the same height as the table.
5. Positioning the laser as close as possible to the thin object, shine the laser pointer directly at the thin object and toward the paper taped to the wall. Adjust the position carefully until you see an interference pattern on the paper. You may need to move closer to or farther away from the wall (note: for thicker objects, you may need to move farther away from the wall).
6. Mark on the paper the positions of two consecutive dark spots on the interference pattern (the brightest middle spot should be between the two dark spots). Measure this distance.
7. Measure the distance between the index card and the wall.
8. Record distances in table.
9. Choose another two distances between the index card and the wall and repeat steps 5-8.
10. Repeat steps 4-9 for other thin objects.

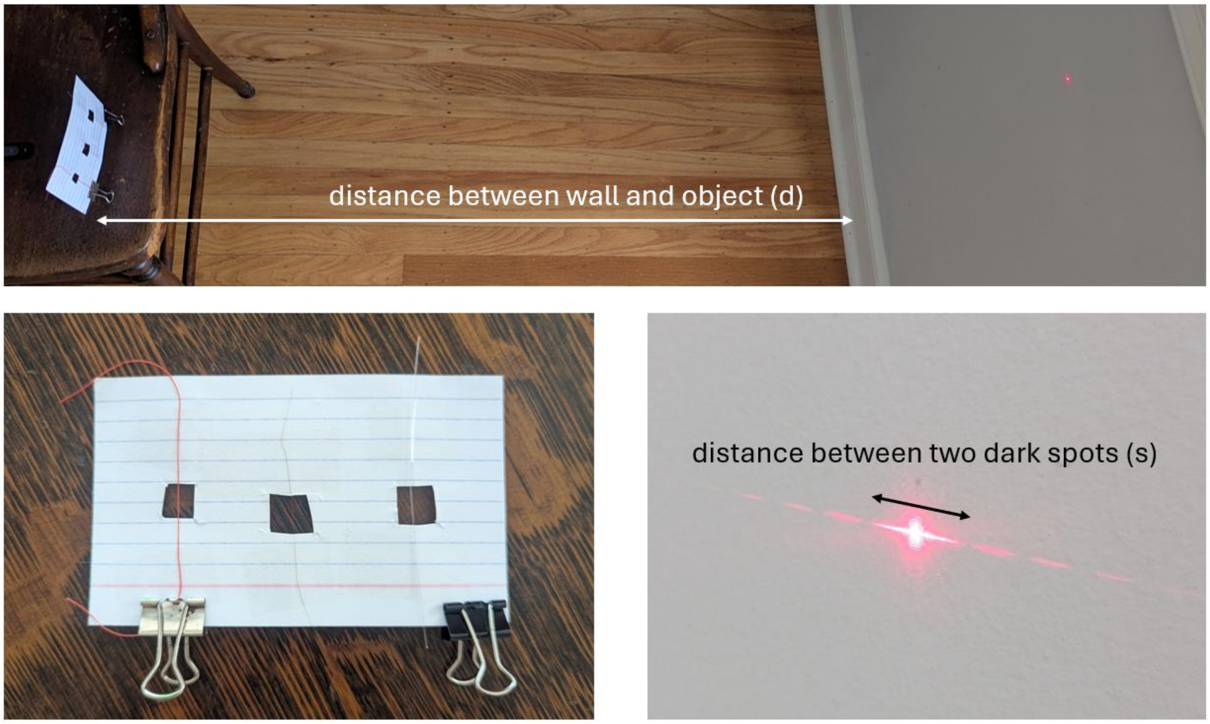


Figure 5. (Top) Example experimental set-up for Part 1. The index card should be placed on a flat surface, with the laser light shining toward the wall with paper taped to it. The distance between the wall and object is indicated (d). (Bottom left) Example of index card with three thin objects. (Bottom right) Example interference pattern with distance between two dark spots (across the brightest middle spot) indicated (s).

4.1.5. *Results*

Object:	
Distance between index card and wall	Distance between two dark spots on interference pattern
Object:	
Distance between index card and wall	Distance between two dark spots on interference pattern

Object:	
Distance between index card and wall	Distance between two dark spots on interference pattern

4.1.6. *Analysis*

1. Rearrange equation $\lambda/w = s/(2d)$ such that s is on one side of your equation and d is on the other side, yielding an equation of the form s(d).
   a. *Answer:* $s(d) = (2d\,\lambda)/w$

2. In the equation s(d), you should see a linear relationship. What is the slope in this equation?
   a. *Answer: In the equation $s(d) = md$, where m is the slope, the slope here is $(2\lambda)/w$.*

3. Using the graph paper below, plot s versus d for your different thin objects.
   a. *Note: Students should see an approximately linear relationship between s and d, and the slope of the line is found in the answer above. Each different object will fall on a different line.*

4. For your different datasets, draw lines through the data that also cross through the origin. Find the slopes for your lines. From the slopes, calculate the widths of your objects. Record these values in the table below.
    a. <u>Note:</u> *Students should be able to solve for w from their slopes, recognizing that the wavelength of the laser is fixed for all of their experiments.*

Object:	
Slope	Width of object
Object:	
Slope	Width of object
Object:	
Slope	Width of object
Object:	
Slope	Width of object

5. <u>Extension:</u> If you and your classmates measured the same objects, find the average width of the objects.
    a. <u>Note:</u> *Encourage students to find the average widths of the same objects by adding the widths of the objects together and then dividing by the number of values.*

4.1.7. *Post-Experiment Questions*

1. Draw an example of the pattern you saw. Why was an interference pattern produced?
    a. <u>Answer:</u> *An interference pattern was produced because the light was diffracted by the thin object and the waves then interfered constructively and destructively.*

2. How would you expect your data to be different if you had used a different color of laser pointer? Justify your answer.
    a. *Answer: We would still see the interference pattern, but we would need to change the value for the light wavelength in our slope to solve for the width of objects.*

3. What are your sources of error in this experiment?
    a. *Answer: Our measurements of length from using a ruler and the measurement of the distance between consecutive dark spots could all have some error. Additionally, the objects may have slightly different widths across the sample. Encourage students to come up with many ideas.*

4.2. Part II. Modelling the Photoelectric Effect

4.2.1. *Additional Background*

In 1885, Heinrich Hertz noticed that when he shined ultraviolet light on certain metals, he could measure a current across a gap. He concluded that electrons were being ejected from the metal (photoelectric effect) but also noted that other frequencies of light did not cause electrons to be ejected. This could not be explained through classical physics which defined light as a wave, until Einstein proposed that light is also discrete packets of energy called photons. When photons collide with electrons on the surface of the metal, there is a transfer of energy, and the electrons can be ejected from the metal if the photons carry enough energy. The electrons on different metals need different amounts of energy to break free from their atoms, and this amount of energy is called the work function. The frequency of light that carries this minimum amount of energy is called the threshold frequency. In this activity, you will build a model of the photoelectric effect using marbles and a ramp.

4.2.2. *Pre-Experiment Questions*

1. Recall the photoelectric effect from Section 2. How do you define the work function of a metal?

   a. *<u>Answer:</u> The work function is defined as the minimum energy required to eject an electron from a metal surface.*

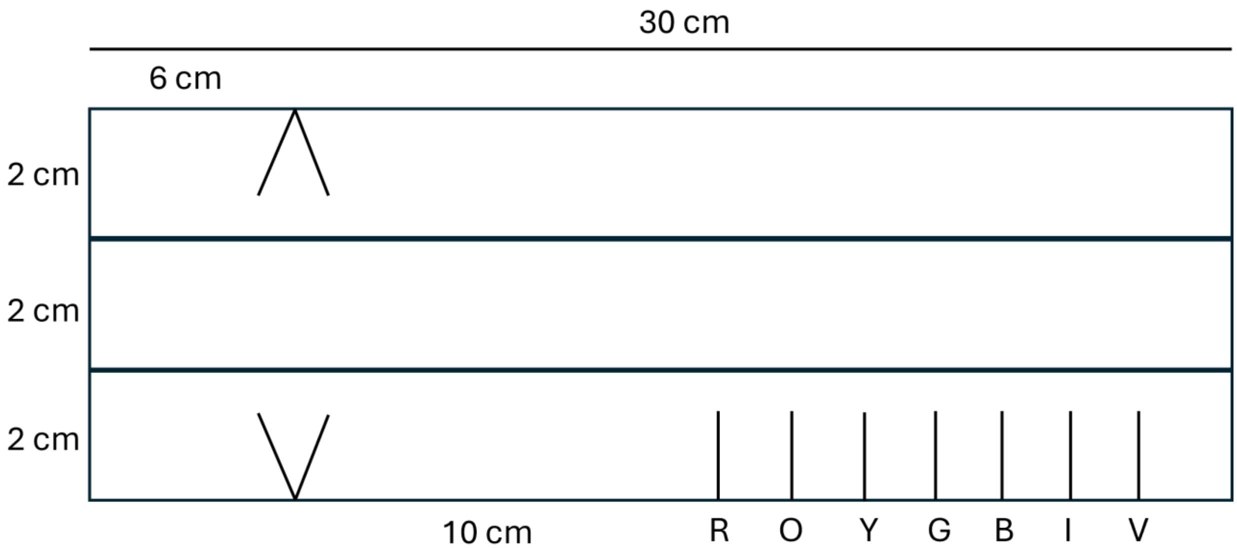
2. How does the work function of a metal relate to electrons being ejected in the photoelectric effect? You can make a sketch to support your answer and illustrate the photoelectric effect.
   a. *<u>Answer:</u> Encourage students to make a sketch that resembles Figure 2. They can show different colors of light by drawing waves with different wavelengths. Longer wavelengths of light are lower energy and less likely to eject an electron.*

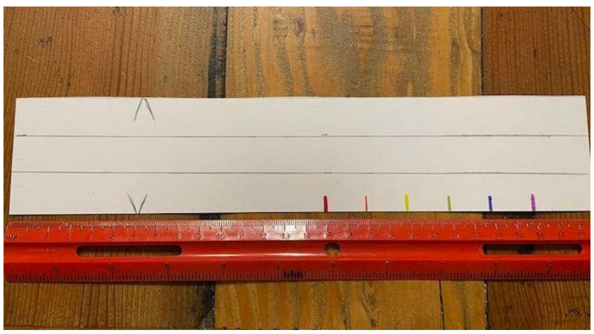
4.2.3. *<u>Materials</u>*

- Cardstock paper
- Straws (or wooden dowels or sticks)
- Colored markers (or colored pencils or crayons)
- Marbles
- Scissors
- Tape

4.2.4. *<u>Procedure (work in groups of 2-4)</u>*

1. Create ramp that will be used to model the photoelectric effect (see Figure 6). (This may have been done ahead of time by your teacher.)
   a. Draw the two middle lines with a pencil and cut the two "V" shapes 6 cm from the end.
   b. Draw lines starting 10 cm from the "V" cuts starting with red (R) and continuing every 3 cm until you have R, O, Y, G, B, I, V.
   c. Fold the paper on the middle lines and bend the end up at the "V" cuts, taping the sides near the "V"s. This should produce a ramp.
   d. Use the straws or dowels and tape to create legs to hold up the ramp.
2. Place marble 1 at the bottom of the ramp.
3. Hold marble 2 at the red (R) line on the ramp and release it so that it collides with the marble 1.
4. Record your observations.
5. Repeat steps 3 and 4 with the other colored lines.





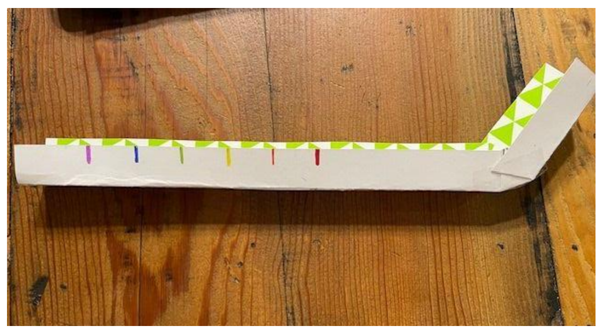


Figure 6. (Top) Dimensions of ramp to be constructed. Note that this is not drawn to scale and should not be directly printed and used. (Bottom left) Ramp construction prior to cutting and taping. (Bottom right) Complete ramp construction.

4.2.5. *Results*

Color	Observations	Did marble 1 launch off the ramp? (Y/N)
Red		
Orange		
Yellow		
Green		

Blue		
Indigo		
Violet		

4.2.6. *Post-Experiment Questions*

1. At what line does marble 1 launch off the ramp?
    a. *Answer: This will vary slightly depending on the construction of the ramp.*

    b. Extension question: Why do you think marble 1 was able to launch off the ramp when marble 2 was held at this line and not at the previous ones?
        i. *Answer: The marble 2 held at a previous line did not have enough energy to launch marble 1.*

2. What happens to marble 1 when you release marble 2 at "colors" higher up the ramp? How does the height on the ramp relate to energy, wavelength, and frequency of light of that color?
    a. *Answer: Marble 1 continues to be launched off the ramp but with more energy as the "color" of marble 1 changes higher up the ramp. Colors higher up the ramp are more energetic and have higher frequency and shorter wavelengths compared to colors lower on the ramp.*

3. Based on your knowledge of the photoelectric effect:
    a. What does marble 1 represent?
        i. *Answer: incoming photon*

    b. What does marble 2 represent?
        i. *Answer: electron in metal*

c. What does moving marble 2 up the ramp represent?
    i. *Answer:* *shining light with higher energy*

d. What does the first color where marble 1 is launched from the ramp represent?
    i. *Answer:* *This represents the minimum energy needed to eject marble 2, or the marble 2's "work function".*

4. How could you adjust the ramp to model a metal with a smaller work function? Predict where marble 2 should be released to just launch marble 1 from the ramp. Try it out!
    a. *Answer:* *A smaller work function metal means a marble 1 lower down the ramp (i.e., less energetic) will eject marble 2. This means the ramp should be steeper.*

4.3. Part III. Simulating the Photoelectric Effect

4.3.1. *Additional Background*

This optional activity will illustrate the photoelectric effect using the free PhET simulation: https://phet.colorado.edu/sims/cheerpj/photoelectric/latest/photoelectric.html?simulation=photoelectric). A computer and internet connection is required.

4.3.2. *Pre-Simulation Questions*

1. What is the relationship between the wavelength of light and its frequency?
    a. *Answer:* *Wavelength and frequency are inversely proportional. As frequency goes up, wavelength goes down.*

2. Which color of visible light is the most energetic? How do you know?
    a. *Answer:* *Violet is the most energetic. It has the smallest wavelength.*

3. Photographers use red light to illuminate their dark rooms when they are developing film. Why do you think they use red light instead of another color or white light?
    a. <u>Answer:</u> *Red light is the least energetic of the colors, so photographers can still see in the dark room, but they won't develop their film.*

4.3.3. *Materials*

- Computer with internet connection
- PhET simulation (https://phet.colorado.edu/sims/cheerpj/photoelectric/latest/photoelectric.html?simulation=photoelectric)

4.3.4. *Procedure & Analysis*

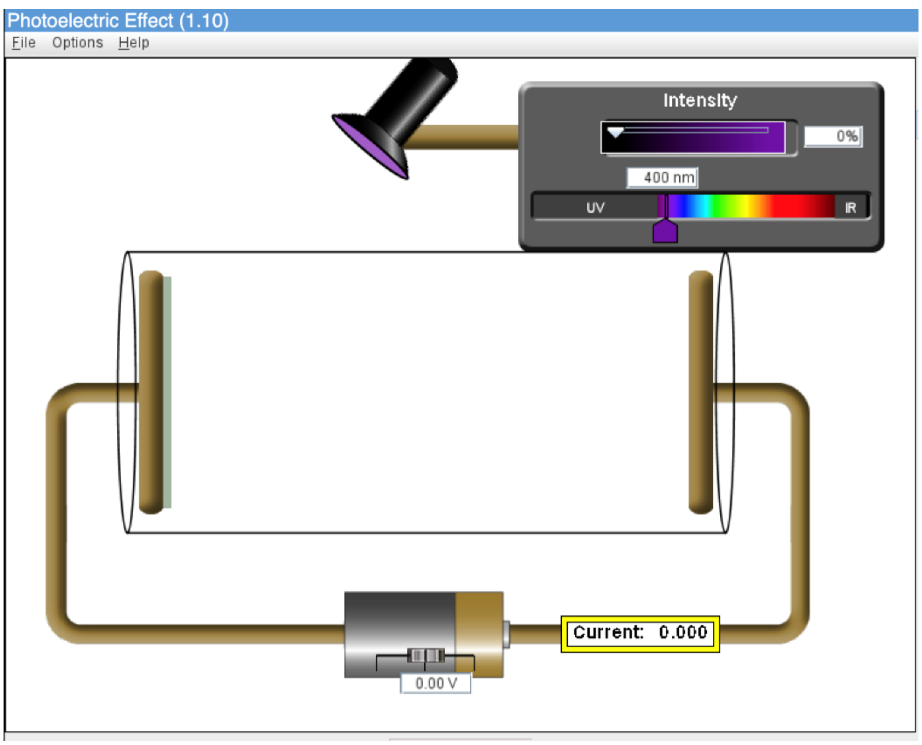
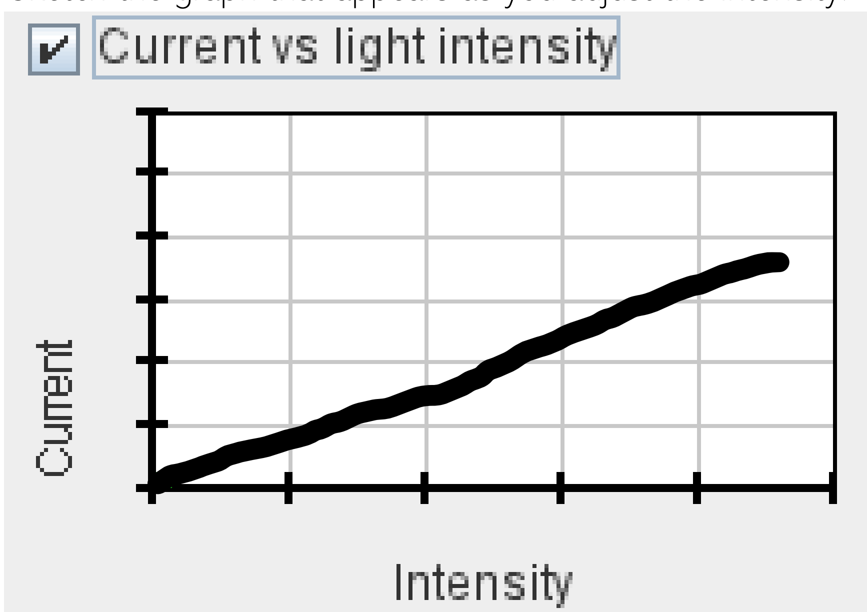


Figure 7. Initial PhET simulation screen upon loading webpage (https://phet.colorado.edu/sims/cheerpj/photoelectric/latest/photoelectric.html?simulation=photoelectric).

1. Open the simulation (the initial wavelength is set at 400 nm and the intensity of light is at 0%) (see Figure 7).
2. Using the Intensity slider, slowly increase the intensity of light.
    a. Describe your observations. What do the objects streaming across the screen represent?
        i. <u>Answer:</u> *Electrons*

    b. What happens to the current reading as the light intensity increases?
        i. <u>Answer:</u> *Current increases*

3. Open the current vs light intensity graph by checking the box next to "Current vs light intensity" and adjust the light intensity.
    a. Sketch the graph that appears as you adjust the intensity.

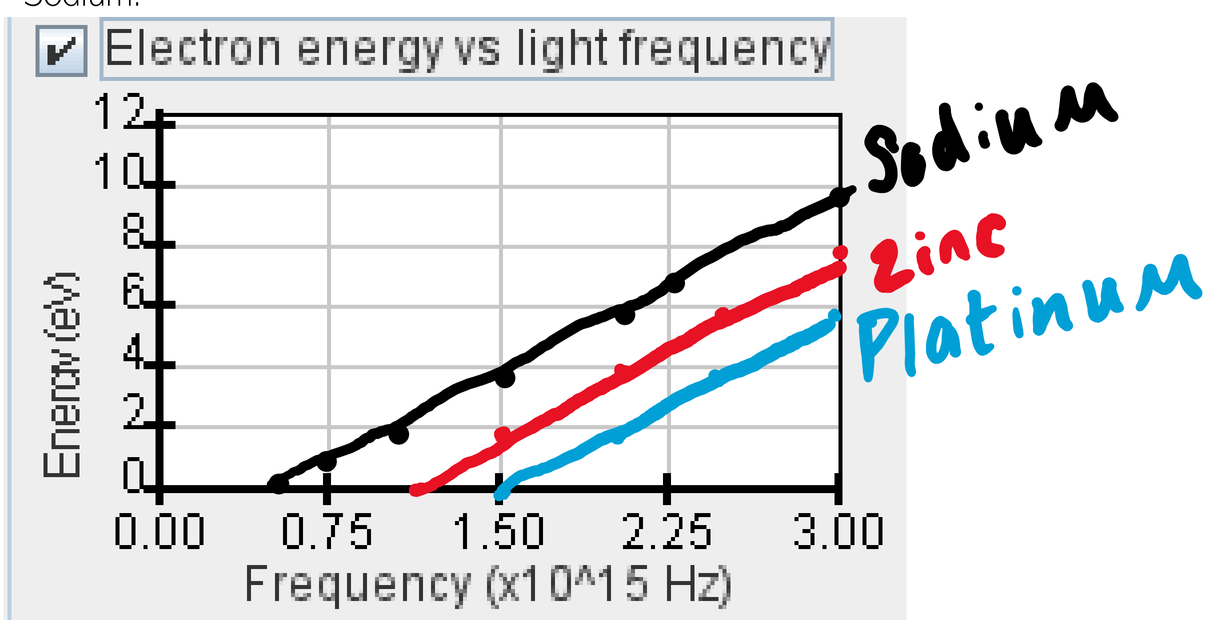


4. Set the intensity back to 0% and move the wavelength slider to the infrared (IR) range.
5. Slowly increase the intensity again using the Intensity slider.
    a. What do you notice? Why do you think the results are different in the IR range as compared to the UV range?
        i. <u>Answer:</u> *No electrons are ejected regardless of the light intensity. This is because the IR light does not have a high enough energy to eject electrons as compared to UV light.*

6. Set the light intensity to 50%.
7. Check the "Show only highest energy electrons" box.
8. Slowly shift the wavelength from IR to red, orange, and toward UV.
    a. At which wavelength do electrons just begin to be ejected from the metal?
        i. <u>*Answer:*</u> *About ~530 nm*

    b. What happens as you continue to decrease the wavelength (i.e., more toward UV)?
        i. <u>*Answer:*</u> *Electrons are moving faster.*

9. Open the electron energy vs light frequency graph by checking the box next to "Electron energy vs light frequency" and adjust the wavelength.
    a. Sketch the graph that appears as you adjust wavelength. Label the line Sodium.



    b. Does this graph change at all when you adjust the intensity of light? Why or why not?
        i. <u>*Answer:*</u> *No, the graph does not change because only light energy (frequency) impacts the electron energy.*

    c. What is the relationship between photon energy and the frequency of the light?
        i. <u>*Answer:*</u> *E = hf, where h is Planck's constant.*

d. What does the x intercept of the graph represent?
    i. Answer: *The minimum frequency needed to eject an electron, otherwise known as the threshold frequency (if converted to energy, this would be the work function).*

10. Change the target from Sodium to Zinc by navigating to the dropdown menu under "Target".
11. Adjust the wavelength of light by dragging the slider
12. Draw in the relationship for electron energy vs light frequency for zinc on the graph above and label it Zinc.
13. Repeat steps 10-12 for platinum.
    a. What is different about the 3 lines on your graph? What is the same?
        i. Answer: *The slopes of the lines are the same, because E is proportional to frequency by Planck's constant. The x-intercepts (threshold frequencies) are different because they are different metals.*

4.3.5. *Post-Simulation Questions*

1. Does the intensity of the light change the energy carried by the photoelectrons? Which observations from the simulation indicate this? What does change when the intensity of the light is increased?
    a. Answer: *The intensity of the light does not change the energy of the electrons. We can see this from the electron energy vs light frequency plot as we adjust intensity. Current (number of electrons ejected) does change as intensity increases.*

2. Which target metal had the largest threshold frequency? What observation from the simulation illustrates this? What characteristic of the energy vs frequency graph indicates the threshold frequency?
    a. Answer: *Platinum. We can see this from the electron energy vs light frequency plots. The x-intercept represents the threshold frequency, as this is where the electrons have no additional energy from the light and at larger frequencies have additional energy from the light.*

3. The max kinetic energy of a photoelectron can be found using the equation $KE=hf-\Phi$ where h is Planck's constant, f is the frequency of the incident radiation, and Φ is the work function. Using your understanding of the equation for a straight line ($y=mx+b$) where m is the slope of the line and b is the y intercept, what does the slope of the electron energy vs light frequency graphs represent? Does it make sense that all of the graphs have the same slope?
   a. *Answer: The slope of the line is Planck's constant. It does make sense all graphs have the same slope, as this is a proportionality constant.*

4. Use the electron energy vs light frequency graphs to determine Planck's constant.
   a. *Answer: Students should use one of their electron energy vs light frequency plots and find a slope. This corresponds to Planck's constant.*

5. What characteristic of the graphs indicates the work function of the target metal? How is the work function related to the threshold frequency?
   a. *Answer: The y-intercept indicates the work function. Here, you can find the work function by converting the threshold frequency into an energy using Planck's constant.*

6. In science, to better understand concepts we cannot see physically or recreate easily in the laboratory, we create models. Both the ramp and marbles (Part II) and the computer simulation (Part III) were models of the photoelectric effect. How were the two models similar? How were they different? List one pro and con of each model.
   a. *Answer: Students answers will vary, and creativity should be encouraged. Models were similar in that they both illustrated the photoelectric effect and work functions. They were different in that the computer simulation allowed us to easily plot and visualize the impact of light intensity on current and electron energy.*

5. Design Challenge

The Challenge: Design a device that uses light to do something useful!

We have seen in previous experiments that light can be described as a wave and as a particle, and we have learned that there are many ways to produce light. Now it is time to think about the ways in which light is and could be impactful in your life and design a device (made up or based on a real-life device) that uses light to do something useful.

5.1 Design Questions

1. Think about the needs of your community and in your life. What kinds of devices are or could be useful to you?

2. How could the properties of light be useful in a device? Consider the various phenomena that were discussed today including diffraction, interference, and the photoelectric effect. Think broadly about many types of devices and machines.

3. How will light be utilized in the device you are designing?

4. How can light energy be transformed into other types of energy (mechanical, electrical, etc.)? How could this be utilized in your device?

<u>Possible answers to questions (encourage discussion of class):</u>

Devices that employ or produce light are vast: flashlights, solar cells, cameras, TVs, and lasers are just a few. Many of these types of devices are or could be useful in communities. Light can be transformed into electrical energy by liberating electrons from a material. Light could cause materials to stretch or bend. The goal is to get the students thinking creatively and to encourage sharing of ideas.

5.2 Design Sketch

Sketch the design of your device below, describing the ways in which light will be important.

6. Sources

Diffraction and interference:

https://steamfest.woodlawnschool.org/activity/measuring-with-a-laser/

https://www.spsnational.org/file/201501/download?token=-lNzblr8

Measuring the width of your hair. Quantum Explorations Student Toolbox (QuEST): https://uwaterloo.ca/institute-for-quantum-computing/sites/default/files/uploads/documents/widthofhair_iqc_2024_quantime-educatorsguide-v2_0.pdf

Photoelectric effect:

http://phy.sites.mtu.edu/RETlessonplans/the-photoelectric-effect/

https://phet.colorado.edu/sims/cheerpj/photoelectric/latest/photoelectric.html?simulation=photoelectric

Zitzewitz, P. W.; Davids, M. (1999). *Glencoe physics: principles and problems.* Glencoe/McGraw Hill.

https://phet.colorado.edu/sims/cheerpj/photoelectric/latest/photoelectric.html?simulation=photoelectric