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QUANTUM (Q)-KIT

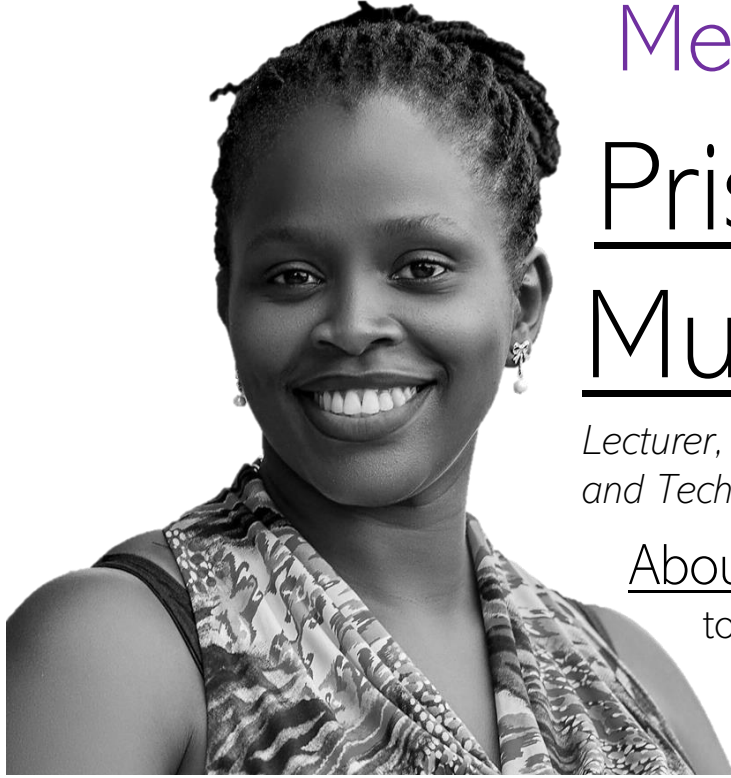
# Light and Photons:

Laboratory for Secondary Level Students

*Student Manual*



WOMEN SUPPORTING  
WOMEN IN THE SCIENCES



## Meet a Scientist

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About me: I was born in a small town in Uganda where it was believed that the sciences were meant for boys and arts for girls like in most African

communities. When I joined secondary school, I was so attracted to science especially Physics and Mathematics. This led me to study fundamental Physics courses like quantum mechanics and astrophysics at University, and I eventually earned my PhD in Physics specializing in Astronomy. I am interested in studying energetic phenomena, like flares, that take place on the surface of stars. Sometimes astronomers apply the principles of quantum mechanics to understand what is happening in stars. For example, atoms in stars' atmospheres where flares occur can exist in multiple energy states simultaneously, so-called superposition. This means that an atom might be in a state where it's both excited and unexcited until it interacts with another particle and its state is "collapsed".

My experience managing career and life: Don't think that if you pursue your dreams and career, you will lose out on your personal and family life. I am married with children, and I still manage to pursue my career. It is all about how you balance your boat. You can do anything you set your mind to, just believe, believe and believe.

# 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.

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# 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](https://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. 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

## 1.3. Key Questions

- What is light? Is light a wave or a particle?
  
  
  
  
  
  
  
  
  
  
- What phenomena demonstrate the wave-like properties of light? What about the particle-like properties of light?

## 1.4. 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.

## 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.

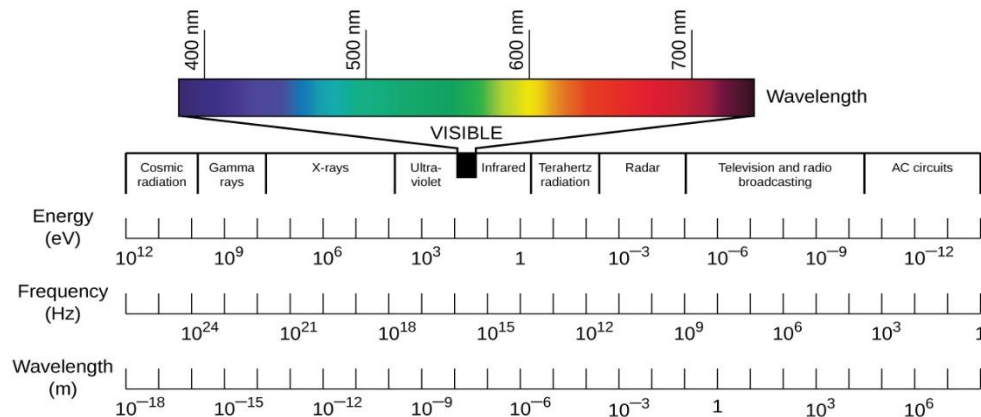


Figure 1. Visible light is a slice of the electromagnetic spectrum ranging from about 400-700 nm in wavelength. The corresponding energy and frequency of light is also shown. This image by Unknown Author is licensed under [CC BY](https://creativecommons.org/licenses/by/4.0/).

## 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 Planck'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  $\sim 6.63 \times 10^{-34}$  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

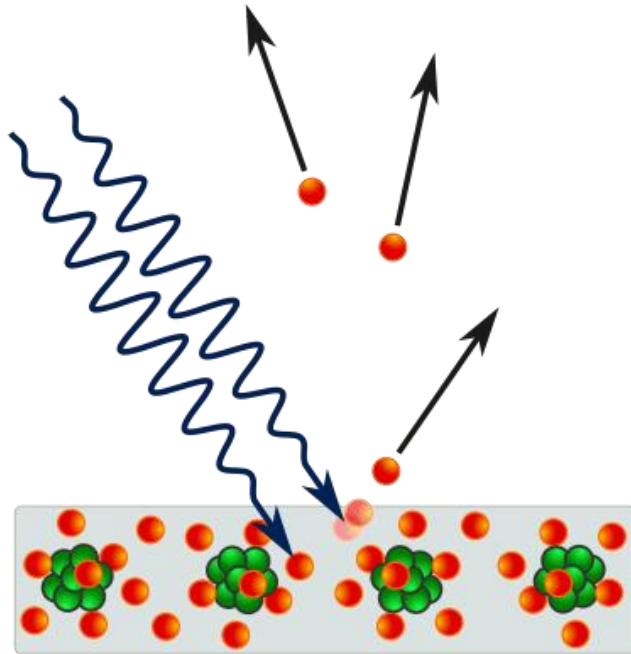


Figure 2. In the photoelectric effect, photons (packets of light shown in blue) hit a metal surface and cause emission of electrons (circles shown in red). This image by Unknown Author is licensed under [CC BY-SA](https://creativecommons.org/licenses/by-sa/4.0/).

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.

## 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).

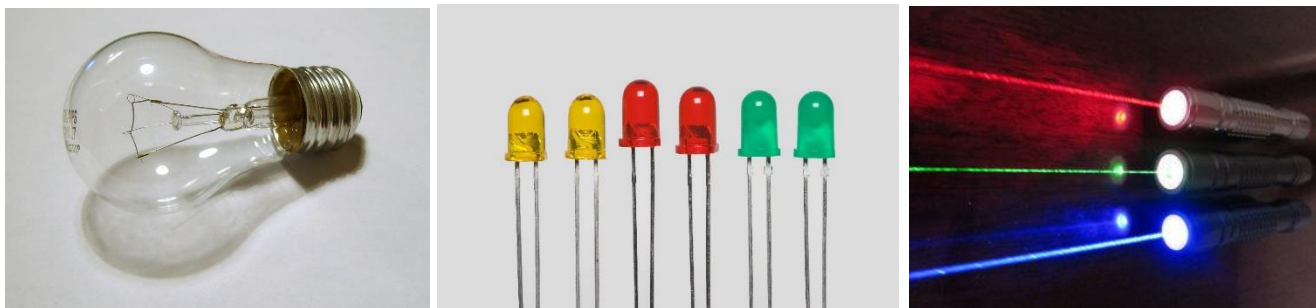


Figure 3. (Left) Typical incandescent light bulb. [This Photo](#) by Unknown Author is licensed under [CC BY](#). (Middle) Examples of LEDs. This photo is licensed under [CC BY-NC-ND](#). (Right) Three different lasers. [This Photo](#) by Unknown Author is licensed under [CC BY-SA](#).

## 2.4. 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

## 2.5. 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. Experiments

### 3.1. Part I. Measuring Thin Objects

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

#### 3.1.1. 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  $\lambda$  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.

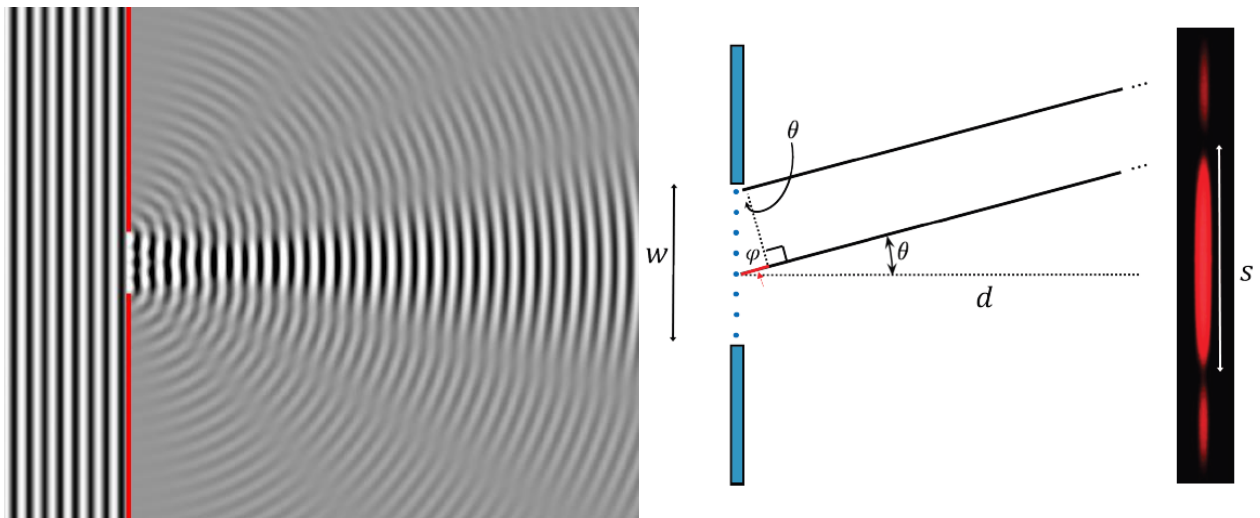


Figure 4. In a single slit experiment, light diffracts as it passes through a narrow slit opening, resulting in constructive and destructive interference (left, photo by unknown author licensed under CC BY-SA). Interference patterns are also observed when a thin object is placed in front of light, analogous 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).

### 3.1.2. Pre-Experiment Questions

1. How do you measure the width of objects? What about really thin objects?



- Paper
- Tape
- Scissors
- Binder clip(s)
- Ruler or measuring tape

### 3.1.4. 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.

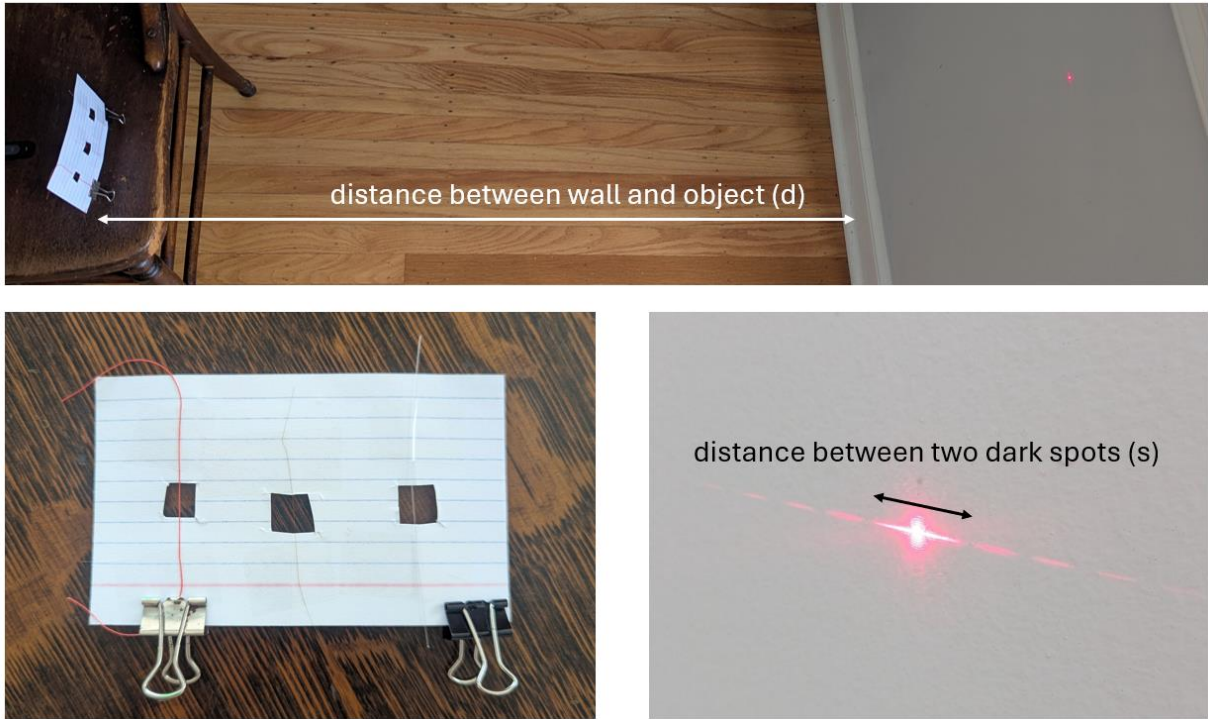


Figure 5. (Top) Example experimental set-up for Part 1. The index card should be placed on a flat surface, with the laser light shining toward the wall with paper taped to it. The distance between the wall and object is indicated ( $d$ ). (Bottom left) Example of index card with three thin objects. (Bottom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

### 3.1.5. Results

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

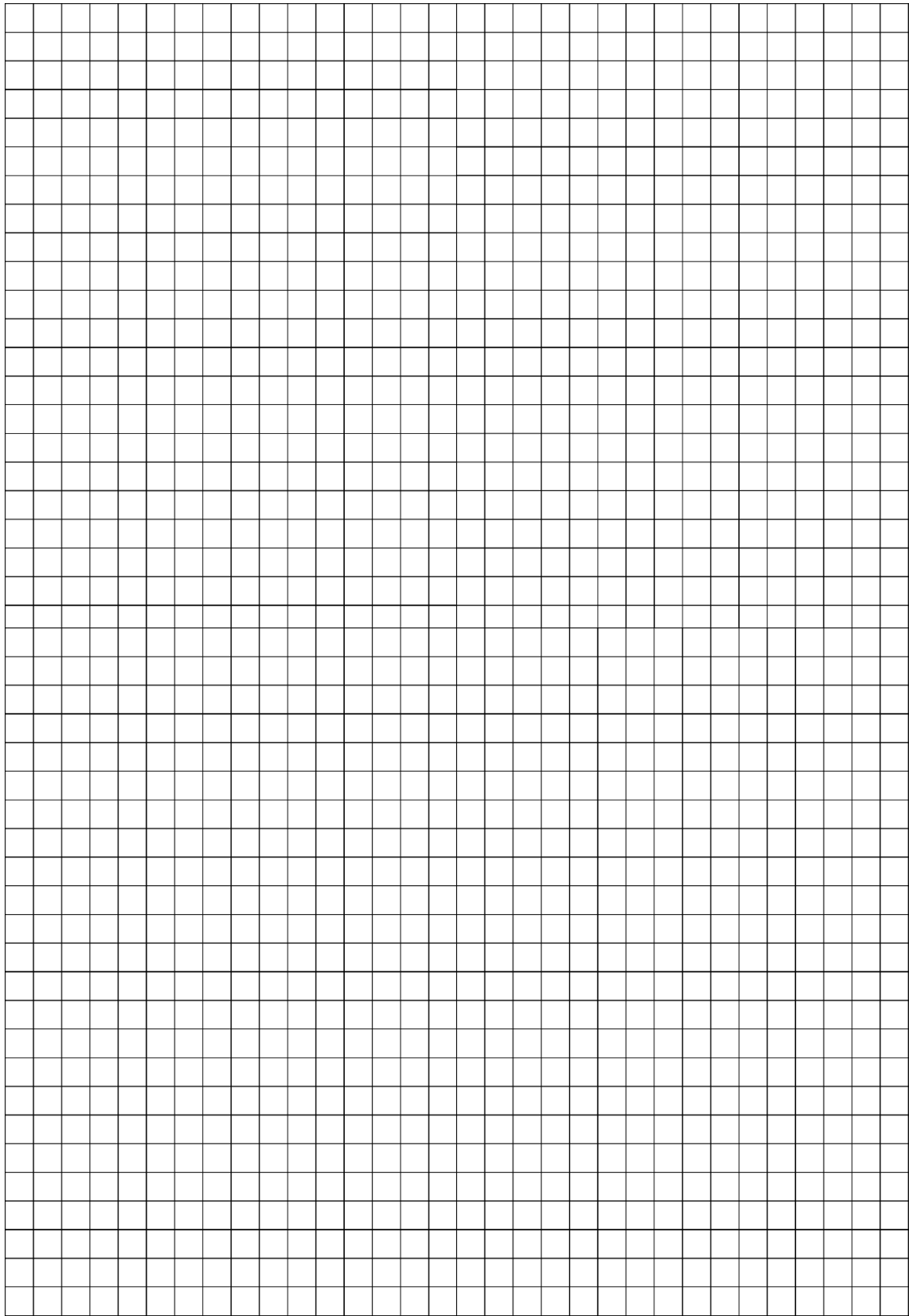
Object:	
Distance between index card and wall	Distance between two dark spots on interference pattern
Object:	
Distance between index card and wall	Distance between two dark spots on interference pattern

### 3.1.6. 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  $s(d)$ .

2. In the equation  $s(d)$ , you should see a linear relationship. What is the slope in this equation?

3. Using the graph paper below, plot  $s$  versus  $d$  for your different thin objects.



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.

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

5. Extension: If you and your classmates measured the same objects, find the average width of the objects.

### 3.1.7. Post-Experiment Questions

1. Draw an example of the pattern you saw. Why was an interference pattern produced?

2. How would you expect your data to be different if you had used a different color of laser pointer? Justify your answer.

3. What are your sources of error in this experiment?

## 3.2. Part II. Modelling the Photoelectric Effect

### 3.2.1. 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



- Colored markers (or colored pencils or crayons)
- Marbles
- Scissors
- Tape

### 3.2.4. Procedure (work in groups of 2-4)

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.

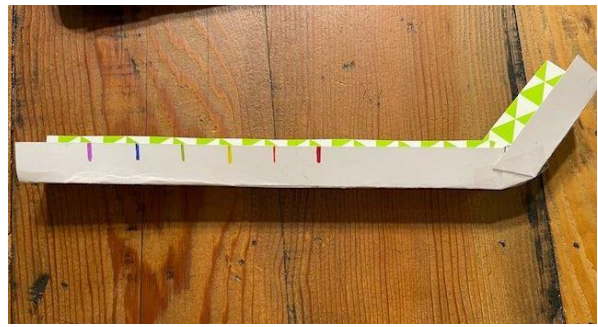
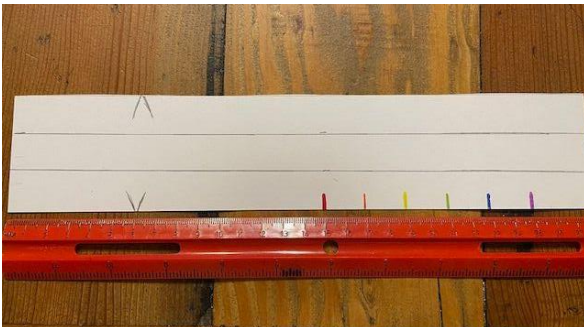
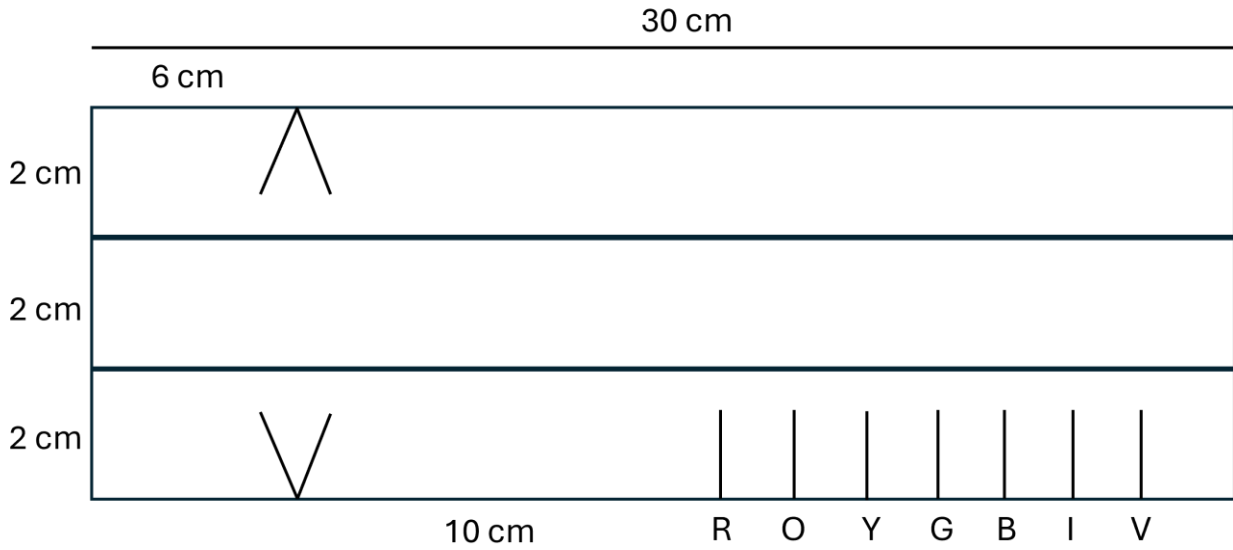


Figure 6. (Top) Dimensions of ramp to be constructed. Note that this is not drawn to scale and should not be directly printed and used. (Bottom left) Ramp construction prior to cutting and taping. (Bottom right) Complete ramp construction.

### 3.2.5. Results

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

Green		
Blue		
Indigo		
Violet		

### 3.2.6. Post-Experiment Questions

1. At what line does marble 1 launch off the ramp?
  - a. 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?
  
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?

3. Based on your knowledge of the photoelectric effect:
  - a. What does marble 1 represent?
  
  - b. What does marble 2 represent?
  
  - c. What does moving marble 2 up the ramp represent?
  
  - d. What does the first color where marble 1 is launched from the ramp represent?
  
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!

## 3.3. Part III. Simulating the Photoelectric Effect

### 3.3.1. 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.

### 3.3.2. Pre-Simulation Questions

1. What is the relationship between the wavelength of light and its frequency?
2. Which color of visible light is the most energetic? How do you know?
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?

### 3.3.3. Materials

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

### 3.3.4. Procedure & Analysis

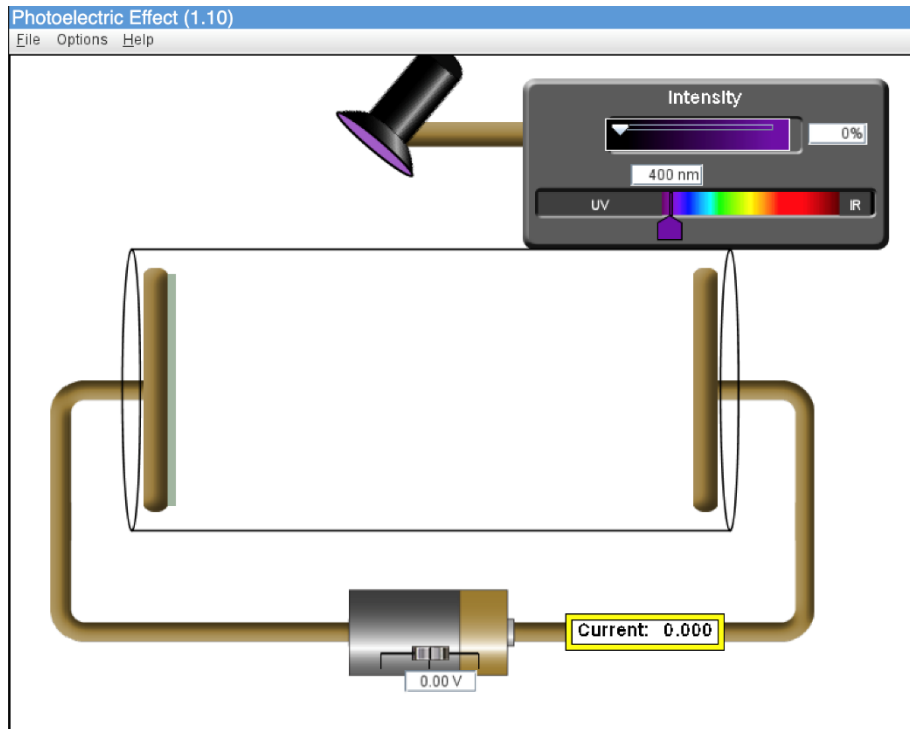
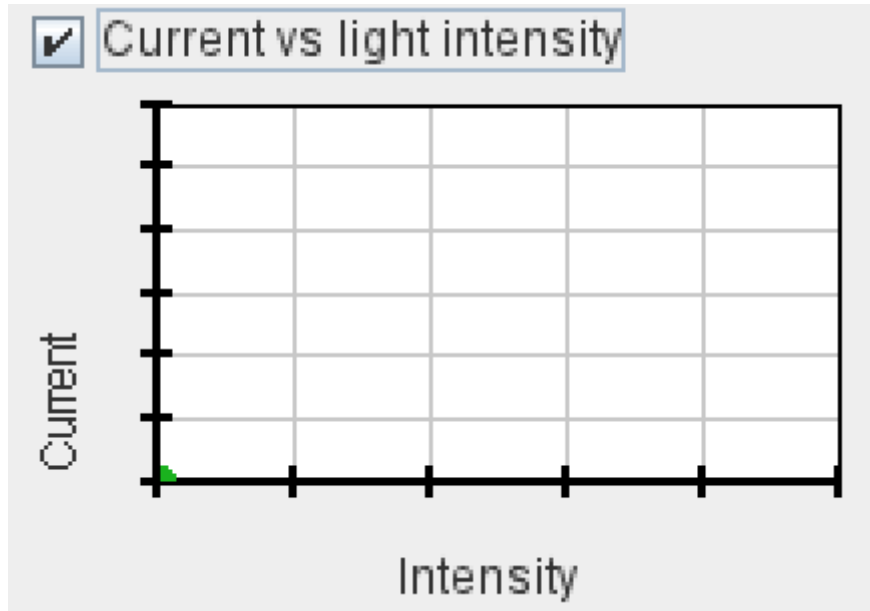


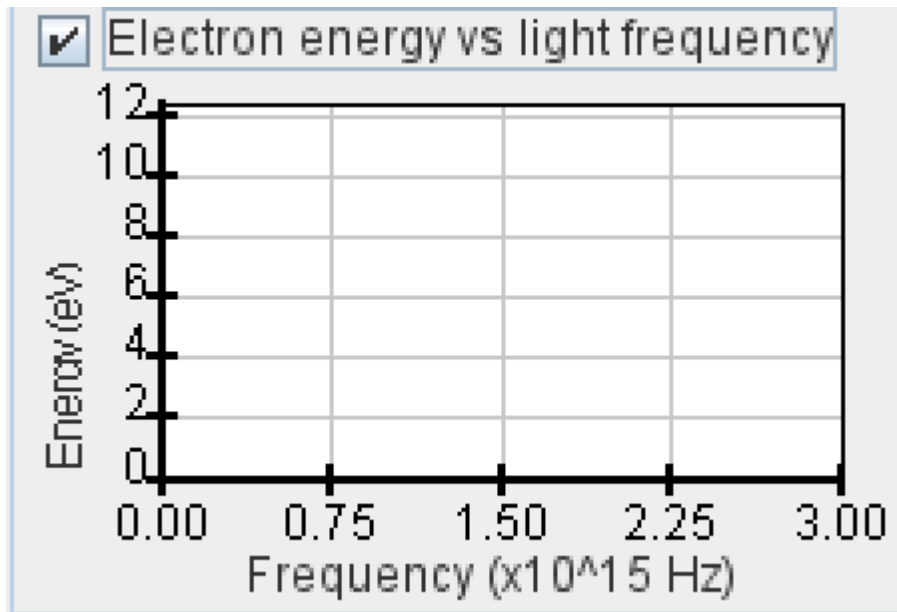
Figure 7. Initial PhET simulation screen upon loading webpage (<https://phet.colorado.edu/sims/cheerpi/photoelectric/latest/photoelectric.html?simulation=photoelectric>).

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?
  - b. What happens to the current reading as the light intensity 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?
  
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?
  
  - b. What happens as you continue to decrease the wavelength (i.e., more toward UV)?
  
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?

- c. What is the relationship between photon energy and the frequency of the light?

- d. What does the x intercept of the graph represent?

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



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  $\Phi$  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?
4. Use the electron energy vs light frequency graphs to determine 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?

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.

## 4. 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.

### 4.1 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?

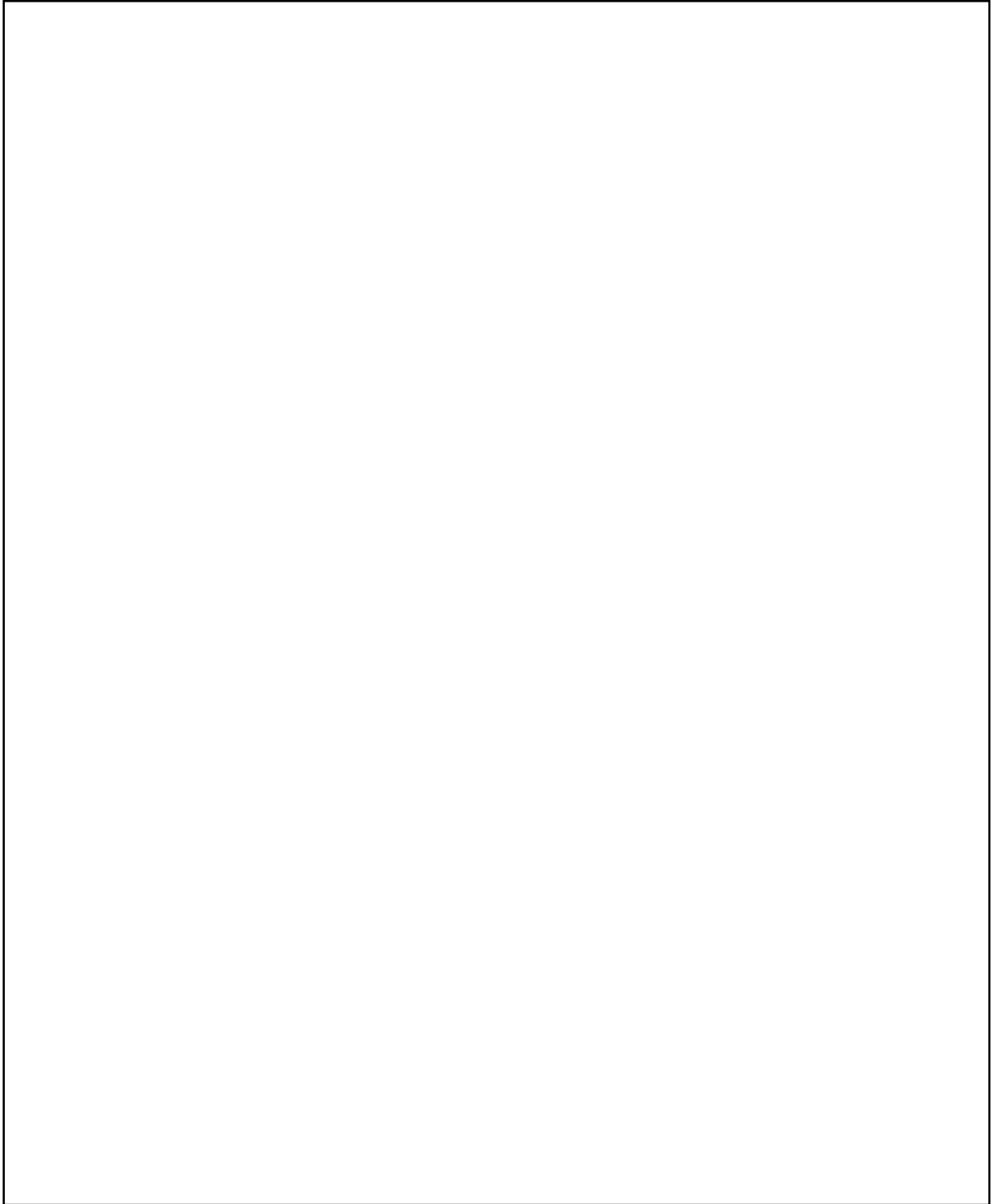
2. How could the properties of light be useful in a device? Consider the various phenomena that were discussed today including diffraction, interference, and the photoelectric effect. Think broadly about many types of devices and machines.

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?

## 4.2 Design Sketch

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

A large, empty rectangular box with a thin black border, intended for a student to draw a design sketch of a device. The box occupies most of the page below the instructions.

## 5. 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).

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>