The Laws of Reflection and Refraction

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Among the most elementary laws of optics are those concerned with reflection and refraction. In this laboratory experiment, we attempt to verify the validity of two of these laws: the law of reflection and Snell’s law. Furthermore, we employed these laws in order to experimentally measure the index of refraction of a glass prism. Throughout the experiment, we utilized LEGO bricks and the camera on a smart phone as cost-efficient laboratory devices.

I. INTRODUCTION

The field of optics has a wide range of applications in modern technology, and virtually all of these applications are dependent on the validity of the laws of reflection and refraction. These physical laws form the basis of modern optics, and many of the more complex optical theories are built on the foundation provided by these laws. The goal of this project is to use a smart phone and LEGO bricks as accessible, convenient laboratory equipment to demonstrate the laws of reflection and refraction, thereby proving that the basis for many other optical principles holds true.

Reflection and refraction are concerned with how light acts as it encounters a boundary between two different media. The human eye utilizes reflection to allow for sight, and therefore reflection is fundamental to all optical experiments. The first formulation of the law of reflection can be found in Euclid’s Elements, circa 300 BCE, and has been essential for countless studies of geometrical optics ever since [1].

Refraction occurs when light changes its path as it enters a new medium with a different index of refraction [2]. The behavior of light as it refracts at the boundary can be described by Snell’s law, Equation (2). Willebrord Snellius was credited with formulating this relationship in the seventeenth century [3]. Refraction is the primary principle utilized by lenses, which are used in numerous optical devices, making refraction essential to the study of optics.

The basics of geometrical optics are often overlooked because they have become quite trivial in the academic world. However, as previously stated, the geometrical laws of optics are essential to understanding most optical phenomena. For this reason, the purpose of the following experiment is to take a step back and study these laws, which are the basis for so much else.

II. RELEVANT PHYSICS

The optical effects we explore in this experiment define the behavior of light as it passes through one medium and encounters another. As an electromagnetic wave, light propagates as a cyclical disturbance in the electric and magnetic fields and does not require a medium in which to travel. When light does encounter matter, it is scattered by interaction with the atoms that make up the material. This scattering occurs in all directions; however, assuming the medium is uniform and relatively dense, the scattering is canceled out in all but the forward direction [4]. Therefore, the direction of the propagation of a wave of light is not affected so long as it remains in a uniform medium. This is known as the law of transmission [5].

A. Reflection

We are primarily interested in the behavior of light as it encounters a novel medium. When this occurs, a portion of the incident wave is reflected at the boundary, another is transmitted into the new medium, and the rest is absorbed by the matter the light encounters. Here, we will discuss a specific type of reflection known as specular reflection, in which the incident light is perpendicular to a flat, reflective surface and the incident light, reflected light, and normal to that surface are all contained in a single plane. This is referred to as the plane-of-incidence. The familiar reflection effect we experience when looking into a mirror is specular [4].

This type of reflection is defined by an astoundingly simple law, known as the law of reflection. When light is incident on a surface at an angle \( \theta_1 \) to the surface normal, the beam will be reflected at an equivalent angle \( \theta_2 \) in the opposite direction [4].

\[
\theta_1 = \theta_2 \tag{1}
\]

This flipping of incident light rays maintains their wavelengths but inverts their order with respect to one another. This is the source of the mirror image we observe, which is inverted in one direction.

B. Refraction

The portion of the incident wave which is not reflected but instead continues into the second medium experiences a phenomenon known as refraction. The two media
interact with the light differently and impede its passage at different rates. Every medium has an optical property known as the index of refraction, \( n \), which is defined as the ratio between the speed of light in a vacuum, \( c \), and the speed of light in that medium. This change in speed at the interface causes the beam to bend, changing its direction. According to Snell’s law, also known as the law of refraction [4],

\[
n_1 \sin(\theta_1) = n_2 \sin(\theta_2). \tag{2}\n\]

Here, \( \theta_1 \) and \( \theta_2 \) denote the incident and refracted angles as measured from the normal, while \( n_1 \) and \( n_2 \) are the indices of refraction in the respective media. When the incident light is perpendicular to the interface, there is no refraction. However, as the incident angle increases, so does the effect of refraction. As a result, when a beam of light travels from one medium to another with a lower index of refraction, an incident angle above a certain point will cause the beam to refract so much that it is unable to leave the original medium and reflects across the barrier instead. This phenomenon is known as total internal reflection [4] and occurs whenever the incident angle is greater than a critical angle given by

\[
\theta_{\text{critical}} = \arcsin\left(\frac{n_2}{n_1}\right). \tag{3}\n\]

III. MATERIALS

This experiment was designed to be carried out using materials that the average person could easily acquire, as an exercise in proving the accessibility of optical experimentation. As such, we conducted this experiment with a $50 budget. The materials we utilized in this experiment were as follows:

- The camera on a Samsung Galaxy S6 smart phone, already owned by a member of the team
- An office laser pointer, in the possession of another team member
- A semicircular glass prism
- A small, silvered mirror
- A biconvex optical lens with focal length 50 mm
- A biconvex optical lens with focal length 200 mm
- A series of LEGO bricks, provided by the instructor
- Several assorted textbooks
- Various clamps and mounts
- Paper printed with angular measurements

The only items on this list we needed to purchase were the lenses and the glass prism, which cost us $24.10; the rest were all easily available to us.

FIG. 1: Our experiment apparatus, shown here including the laser, beam expander, angle grid, mirror, and smart phone camera.

IV. EXPERIMENTAL SETUP

Here, we describe the process by which we prepared our experiment and the methods we used to collect our data.

A. Testing the Law of Reflection

Both of our experiments depended upon analyzing the path that a beam of light takes as it is incident on the boundary between two optical media. As such, it was imperative that we were able to view the laser beam before, during, and after its interaction with that boundary. To achieve this, we angled a laser beam slightly downward against a flat sheet of white paper. The beam makes a streak against the paper, which is highly reflective and makes the streak clearly visible. However, the length of the streak is limited by the beam waist. Therefore, we constructed a beam expander to increase that waist and similarly lengthen the visible path of the laser. Our beam expander consisted of two biconvex lenses, having focal lengths of 50 and 200 millimeters. We placed them 250 millimeters apart to magnify our beam by a factor of four. We constructed our beam expander using LEGO blocks, creating an effective and highly modifiable apparatus at a low cost. The expander held the lenses upright and at the correct distance.

We used a laboratory clamp to hold the laser at the correct height, and we stacked a series of books to raise the white paper to that same height. We printed a semicircle marked with a series of angle measurements on the paper to make data collection easier. Then, we calibrated the apparatus. We adjusted the level of light in the room so that both the laser and the angle markings were clearly visible on the paper. Then, we directed the laser through the beam expander and angled it so that it produced the longest possible streak on the paper. A small, silvered mirror was then placed in the center of the semicircle.
at the edge of the page. A second semicircle page was placed under the first to allow for accurate measurements of angles as the incident angle of the mirror was changed. Beginning with the mirror perpendicular to the beam, the mirror and top semicircle page were rotated at increments of 5°, up to 40°. At every new location, a smartphone was used to take a picture of the beam pattern on the page, which showed the incident and reflected angles. We later processed this data by extending the beam lines to the edges of the angle grid, as per the law of transmission, to allow for exact measurements. This process was repeated three times to create error bars for our measurements.

B. Testing Snell’s Law

We used the same apparatus to test the validity of Snell’s law. We removed the mirror and replaced the semicircular angle measure with a full circle. Then, we placed a semicircular glass prism so that the midpoint of the flat side of the prism aligned with the center of the circle. The prism is designed so that light directed towards this point will be perpendicular to any point on the round side of the prism, preventing refraction from occurring. The path of the beam is only altered by the second, flat interface, simplifying our measurements. We passed the beam through the prism at 11 different incident angles, in intervals of 4° from 0° to 40°. Higher incident angles than this began to exhibit signs of total internal reflection, preventing us from accurately collecting data. We recorded the refracted angle at each orientation and repeated the entire process three times in order to put error bars on our data.

V. DATA AND ANALYSIS

Here, we discuss the data we collected and the methods by which we analyzed that data.

A. Reflection

The data collected for the reflection portion of the experiment, including error bars, is displayed in FIG. 4. As expected from Equation (1), the data appears to have a linear correlation. To test this, the data was fitted to a model described by Equation (1). The best fit line is plotted along with the data in FIG. 5. The best fit line for this linear model has 8 degrees of freedom and a
chi-squared value of 0.00006, giving a p-value of approximately 1. To obtain an even better idea of how well the curve fits the data, we can study the residuals plotted in FIG. 6. As shown, the residuals are centered around 0, have very small values, and are randomly distributed over the interval, suggesting that they are reasonably precise and do not introduce a significant bias into our system. If we assume the validity of the law of reflection, it is very likely that we would collect data similar to the results that we were able to draw in our experiment.

Having confirmed the linear relationship between the incident and reflected angles, we would also like to verify that there is no scalar factor in the relationship between the two. From Equation (1), it can be seen that when the reflected angle of the laser is plotted against the incident angle, the slope of the data should be equal to 1. When fitting our data with the linear model, a slope of 0.971 +/- 0.007 was calculated. This yields an error of 2.9%, which we believe to be well within reasonable error bounds.

Our refraction data also seemed to uphold the theoretical model. We collected the incident and refracted angles from our experiment and created error bars. Then, we took the sine of each of those angles and attempted to fit them to a linear model, as in Equation (2). The residuals take a sinusoidal shape because of this alteration. The resultant fit seems to follow the data very closely. This is supported by statistical analysis; the fit has 10 degrees of freedom and a reduced chi-squared value of 0.00018, suggesting that this data is well in line with what Snell’s law would lead us to expect. The error bars on the data points are small, suggesting that our data is precise as well. The fitting algorithm suggested that the index of refraction of our prism was 1.51 +/- 0.01; this yields only 0.59% error when compared to the accepted value of 1.517. Furthermore, this index of refraction suggests that total internal reflection will occur at angles above 41.81°; as we reported earlier, we were able to measure 40° but not 44° due to this effect, further supporting our results.

B. Refraction
VI. SUMMARY AND CONCLUSIONS

An experiment was designed to test the laws of reflection and refraction. The experiment employed LEGO bricks, a smart phone, and knowledge of some basic concepts in optics. A functional beam expander was the key to producing visible results which allowed us to measure angles of reflection and refraction.

The goal of the experiment was to study and confirm two basic laws in geometrical optics, and this goal was carried out successfully. With the use of the above mentioned materials, statistically significant data was collected, and the laws in question were confirmed by several different statistical techniques for analysis. Refraction of light passing from glass into air was found to obey Snell’s law, as expected. In addition, light from the laser reflecting off a mirror was shown to reflect at an angle that equaled the incident angle.

We feel confident in reporting that both the law of reflection and Snell’s law have conclusively been verified by our experiment. The data we collected matched the theoretical models to a high degree of statistical significance. What small error we did experience is easily explained by a few minor flaws in our experimental setup. Namely, the width of the laser beam we measured occasionally made measuring a precise degree value difficult, and error could creep into our system at any point where the optical instruments were not exactly centered on the angle grid we used for measurement. The refractive index of a medium shifts slightly due to atmospheric conditions. Additionally, we were not certain of the exact wavelength of our laser, and the index of refraction differs slightly between different wavelengths.

Overall, we consider this experiment to be a success. We confirmed our theoretical model, and we also demonstrated the use of commonplace, low-cost optical equipment in the process. We believe that useful optical instruments can be constructed from devices such as LEGO bricks, smart phone cameras, and laser pointers and that the use of such devices can make the experimental study of optics more accessible.

VII. REFERENCES