



## The Multi-Platform Optics and Photonics Educational App

### Mr. Tristan Ventura, Rutgers University

Tristan Ventura is a third year undergraduate student at The Honors College of Rutgers University, majoring in Electrical and Computer Engineering with a minor in computer science. His interests include processor design and computer architecture. As the era of Moore's law is beginning to come to a close, he seeks to be at the forefront of future advancements in the field, which will require innovative, out-of-the-box thinking. He also enjoys designing and writing applications and envisions their potential to serve as innovative solutions to inefficiencies in the world.

### Dr. Abdallah Khreishah, New Jersey Institute of Technology

Abdallah Khreishah received his Ph.D and M.S. degrees in Electrical and Computer Engineering from Purdue University in 2010 and 2006, respectively. Prior to that, he received his B.S. degree with honors from Jordan University of Science & Technology in 2004. During the last year of his Ph.D, he worked with NEESCOM. In Fall 2012, he joined the ECE department of NJIT where he is currently an Associate Professor. Abdallah is an active researcher. His research spans the areas of visible-light communications, network coding, wireless networks, congestion control, cloud computing, network security, intelligent transportation systems, and database systems for large projects. His research projects are funded by the National Science Foundation (NSF), New Jersey Department of Transportation (NJDOT), and the UAE Research Foundation.

### Dr. John D. Carpinelli, New Jersey Institute of Technology

Dr. John D. Carpinelli is a Professor of Electrical and Computer Engineering at the New Jersey Institute of Technology and Associate Director of its Institute for Teaching Excellence. He has served as coordinator of activities at NJIT for the Gateway Engineering Education Coalition and as a member of the Coalition's Governing Board. He previously chaired NJIT's Excellence in Teaching Awards Committee and is Past Chair of the University Master Teacher Committee.

### Prof. Durga Misra, New Jersey Institute of Technology

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## Abstract

The Multi-Platform Optics and Photonics Educational App was developed through the REU Site: Optics and Photonics: Technologies, Systems, and Devices program at the New Jersey Institute of Technology. Optics and photonics is an important field of physics, but students often receive only minimal exposure to it during their undergraduate studies. Students frequently find this topic difficult to comprehend, as it requires a great deal of visualization skills. The current approach of teaching optics and photonics relies heavily on mathematical models, without connecting these models to the visual aspects in terms of ray tracing. The educational app was created to help students develop a strong understanding of the basic principles of this field. By placing a strong emphasis on graphical paraxial ray-tracing, a method taught widely to demonstrate the formation of images by various optical elements, the app allows students to explore fundamental optical elements and how they interact with light and images. The app transitions from short, explanatory demonstrations to interactive simulations that allow students to test their understanding of the material. This paper describes the app, its functionality, and plans for its pilot use by students in sophomore physics courses.

## Introduction

With the advent of personal mobile phones, the average individual is capable of accessing the vast knowledge contained in the World Wide Web using a device not much larger than a calculator. As a result, mobile phones are an underutilized educational tool with the potential to serve as a classroom supplement or even replacement. Their use has barely been explored, likely due to their (initially) low computational power and their ability to distract students. However, these devices are now powerful enough to run some of the most versatile programs. This allows educators and developers to exploit the teaching potential of mobile devices.

This paper presents a multi-platform educational application with a focus on university level geometric optics. This is an extremely important topic of physics, which is not always covered adequately in most university physics courses. Often, the topic is part of a course designed to cover ten to fifteen other topics in one semester. This results in students having a weak understanding of geometric optics and not understanding its importance in modern research. In addition, this coverage of optics and photonics in the classroom environment results in a lack of proper exposure to the current state of research in this field. It is important to encourage students interested in conducting research to explore all of their options and, as such, optics and photonics deserves more visibility. The most direct goal of this application is to facilitate the development of a strong understanding of the fundamental concepts of geometric optics by students taking the course.

On a broader level, this project also seeks to establish a framework for future work on mobile-learning applications. As previously stated, the availability and computational strength of personal mobile phones has granted educators and developers the power to develop some of the most intricate applications. There are numerous tools available to facilitate the advancement of mobile-learning as a supplement to classroom learning, but there has been little innovation in the

field so far. This is unfortunate, as the ability to teach a subject whenever desired has the possibility to revolutionize the educational process. Thus, establishing a strong foundation on which future mobile-application researchers can base the designs of their project is imperative. Hopefully, this will contribute to a greater emphasis on mobile-learning using the benefits of modern technologies, and eventually result in the widespread usage and implementation of mobile-learning principles and resources in modern educational management software.

The rest of this paper is organized as follows. The next section gives some background information on educational application programs in optics and photonics, as well as the use of simulations in virtual laboratories. The following section describes the Optics and Photonics Educational App, its capabilities, and its user interface. This section also includes the link to the code repository for this app. Finally, concluding remarks and an outline of future work are presented.

## **Background**

Current forays into developing an educational application with a focus on geometric optics are, at best, limited in their teaching capabilities. While, at first glance, they are capable of conveying a lot of information, this information is not apparent unless explained by an instructor. It is clear that these tools are designed for use by an individual already knowledgeable in geometric optics, and that they are designed as visual tools for demonstrating certain concepts rather than as educational tools for teaching these same concepts. Take, for example, the PhET geometric optics simulator [1]. It is capable of illustrating the basic principles behind ray-tracing and image formation. However, these principles first must be explained by an instructor, as the application itself does not explain the processes that occur in the simulation. Furthermore, this simulator is limited to convex lenses, and does not address the differences that other optical elements make in the ray-tracing and image formation processes. As such, while this software might be helpful to a professor as a demonstration tool, its usefulness as a stand-alone educational tool is limited. Other similar tools currently accessible on the internet or app market suffer from the same shortcomings as the PhET simulation. In fact, many are just digital reproductions of textbook examples, failing to exploit of the many advantages a mobile application has over digital or physical textbooks.

In regards to the use of software to supplement the educational process, many academic papers have been published exploring this topic. Many researchers have acknowledged the value of having a virtual laboratory to explore physical phenomenon, noting it is an efficient, cost-effective alternative to physical laboratories, and as a potentially suitable replacement when physical laboratories are not available [2]-[6]. Many studies report the value of simulations to student learning, noting their ease of introduction into pre-existing curricula [7]-[10]. Educational technology has demonstrated the ability to stimulate more interactive and cooperative teaching methods and student learning, in addition to saving time and money in the process [11]-[12], as well as to improve the conceptual understanding of students [13]. This has been attributed to the ability of simulations to allow students to act as their own investigators due to their dynamic and interactive representation of physical systems or phenomena. Students can, at their own pace, develop and test their own models in order to develop an understanding of the physical system in a way unique to each student's learning process [13]-[18]. This versatility

allows simulations to cater to a wide range of individuals, especially those who find “hands-on” activities more effective than lectures and reading material. Furthermore, simulations provide opportunities for exploration that lectures and physical laboratories cannot offer [13].

## **Optics and Photonics App**

To address this issue, several geometric optics lessons and curriculums were analyzed to determine the most important aspects of this subject. Using this information in addition to valuable feedback provided by professors regarding the topic, it was determined that the most appropriate approach to teaching geometric optics was an educational mobile app. Studies have shown that learning scientific topics through interactive activities significantly improves students’ understanding of various scientific concepts. When learning about an idea with the assistance of an activity, it was found that recalling that idea later activated the same region of the brain responsible for interacting with said activity. The improved comprehension of the taught scientific topics was directly explained by the brain’s activation of these regions [2]-[6].

With this in mind, the application was designed around the premise of allowing students to have a more active and exploratory learning experience than is typically provided in a classroom or lecture hall environment. The content of the educational modules specifically focused on paraxial ray-tracing. As in geometric optics, almost all calculations are made assuming that rays of light that hit any optical elements have small angles relative to the optical axis and also lie close to the axis. Furthermore, the modules contain a very strong focus on image formation, as it is one of the most important topics covered in geometric optics. Being able to understand how light behaves as it interacts with different optical elements and how the resulting rays of light form images is a good indicator of a strong understanding of many of the fundamental concepts behind geometric optics. The application seeks to assist in teaching and understanding these fundamental concepts. Finally, the modules use a very visually-heavy approach to teaching its users. Describing phenomena using numbers and expressions is very important, but being able to see the phenomena occurring can also provide a strong contribution to an individual’s understanding. It assists in developing the connections behind the equations and symbols, and the actual physical properties that the math represents.

To develop the application, an integrated development environment was needed that had easy-to-use, but powerful graphics and physics libraries, as well as the ability to be optimized for personal mobile devices. In addition, the application needed to be accessible by as many students as possible, requiring the environment to support development for multiple platforms. Almost all mobile phones run either Android OS, or iOS. So, these were the platforms that the application sought to support. With these requirements in mind, it became evident that Unity [19], a popular cross-platform game engine, was an ideal environment to use to develop this application. As a game engine, Unity has many powerful and simple physics and graphics libraries, in addition to a very large and diverse asset store that provides any features not natively supported by Unity’s libraries.

This application was designed around a touch-based interface, since this is the most prominent method of interacting with a mobile device, in addition to being a very natural process. The user-

interface was designed with the screen size of an average smartphone in mind, averaging around 5 inches when measured diagonally, and having an aspect ratio of 16:9.

When designing the experimental modules, it was desirable to allow the user to have some form of control over the environment such that they could explore the different events occurring in the physical system. However, certain constraints were also implemented so that users who were not as knowledgeable in the field of geometric optics received a more guided learning experience. To accomplish this, requirements were set for a “sandbox” mode, where users can pick and choose between the various optical elements, in addition to guided educational modules where users can be walked through the processes of ray-tracing and image formation. In the sandbox module, users should be able to adjust certain properties of each optical element, providing near full control for any scenarios the user may want to investigate. In the educational modules, the user is guided by the simulation, but also allowed some degree of freedom, namely drawing the individual rays required for ray-tracing.

In order to meet these requirements, light rays were defined as projectiles in Unity. When it came to the sandbox mode, the application was responsible for determining the collision of light rays with optical elements and calculating the new trajectory of the light rays. The calculation was done using Ray Transfer Matrix Analysis, a common method of predicting light ray behavior in laser optical systems. Essentially, rays of light are given a height and angle, and each optical element has a transfer matrix designed by its optical properties. The transfer matrix and ray matrix are multiplied to acquire the new trajectory of the light ray, in the form of another ray matrix. This process is illustrated in Figure 1.

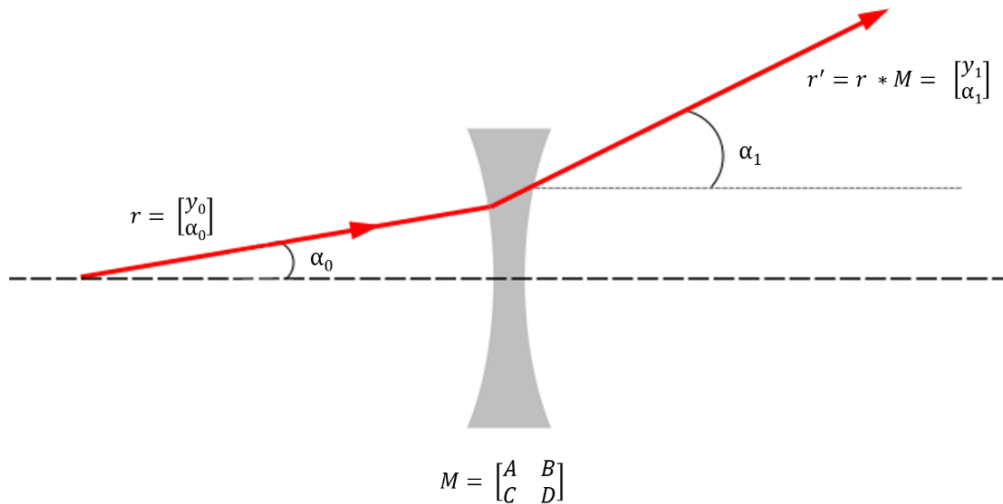


Figure 1. Ray Transfer Matrix Analysis

To define the transfer matrix for each optical element, one could simply predefine each matrix for each optical element programmatically. However, this is a fairly difficult method of implementation as the properties of each optical element must be dynamically modifiable by the user at runtime in order to meet the requirements set for the sandbox module. To address this issue, the optical elements were modelled in Blender [20] and given a mesh collider in Unity so

that they can interact with the light rays, as illustrated in Figure 2. Due to the paraxial ray assumption made in the majority of geometric optics, we can simplify every calculation by assuming that every collision a light ray makes with an optical element is identical to the light ray colliding with a very small plane. Taking advantage of this assumption, every optical element was defined as a large number of small faces combined to form the desired shapes of each element. Unity is able to extract all of the necessary information required for the determination of the transfer matrix from the collision. Thus, transfer matrices are calculated dynamically rather than being pre-defined.

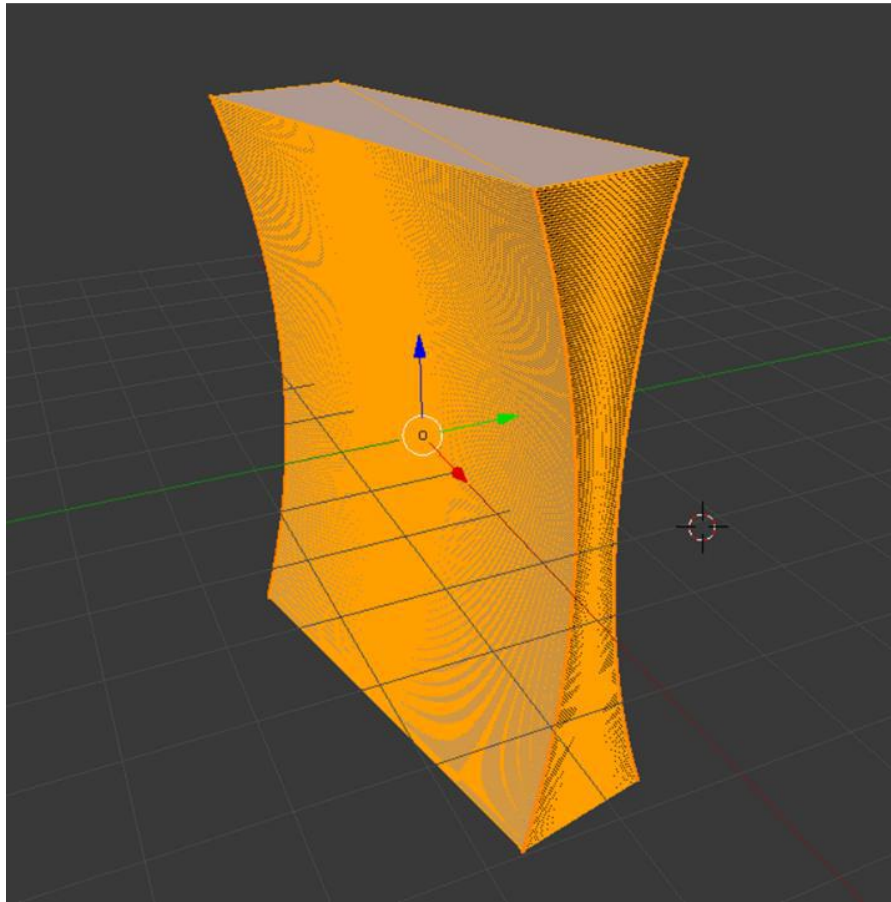


Figure 2. 3D Model of Concave Lens in Blender

The algorithms used to render the light rays are very simple in design. For the sandbox mode, the user does not define the position or trajectory of the rays. They are determined through the matrix analysis and rendered automatically by Unity. For the educational modules, the software walks the user through a step-by-step ray-tracing process. Unity calculates the correct trajectory of the light rays, and the user is allowed to draw their own light rays. If the trajectory/hit point of the user-defined rays at a given step in the ray-tracing process matches the trajectory of the rays calculated by Unity, the user-drawn ray becomes permanently rendered on the screen and they proceed to the next step of the process. These algorithms are modeled in flow charts in Figures 3 and 4.

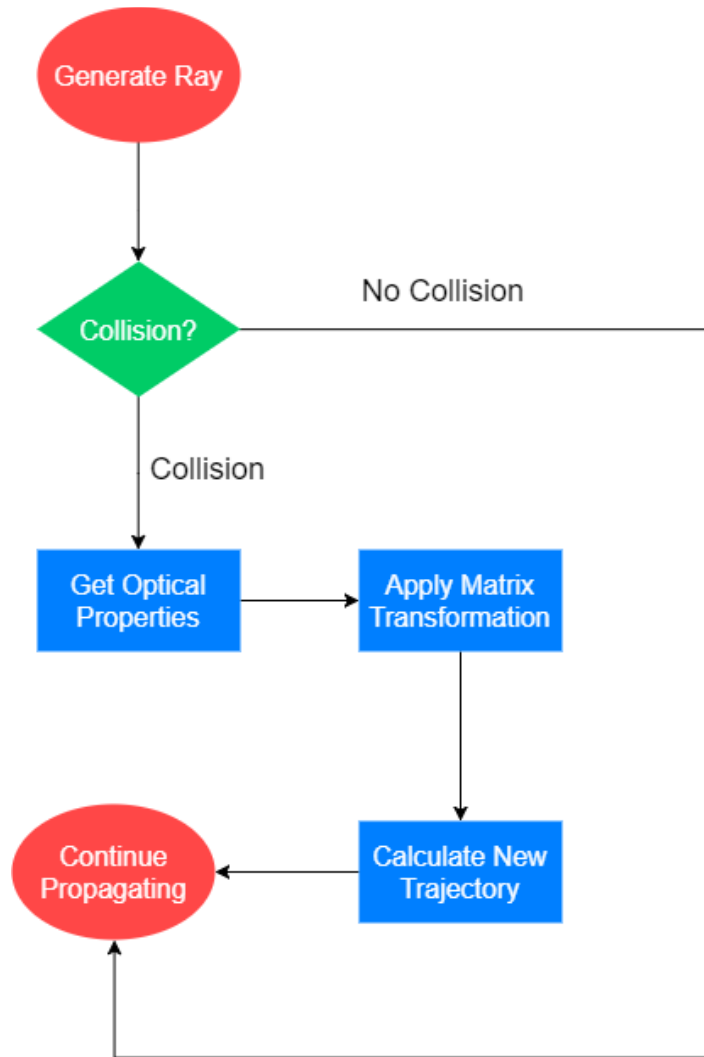


Figure 3: Application-Defined Ray Tracing

Finally, the application was equipped with database functionality for feedback collection. The user can provide feedback through a button in the main menu. The feedback is uploaded to a database where future developers can use this information to improve the functionality of the application. It is also designed in such a way that if more user data needed to be collected, it is possible to do so without prompting the user.

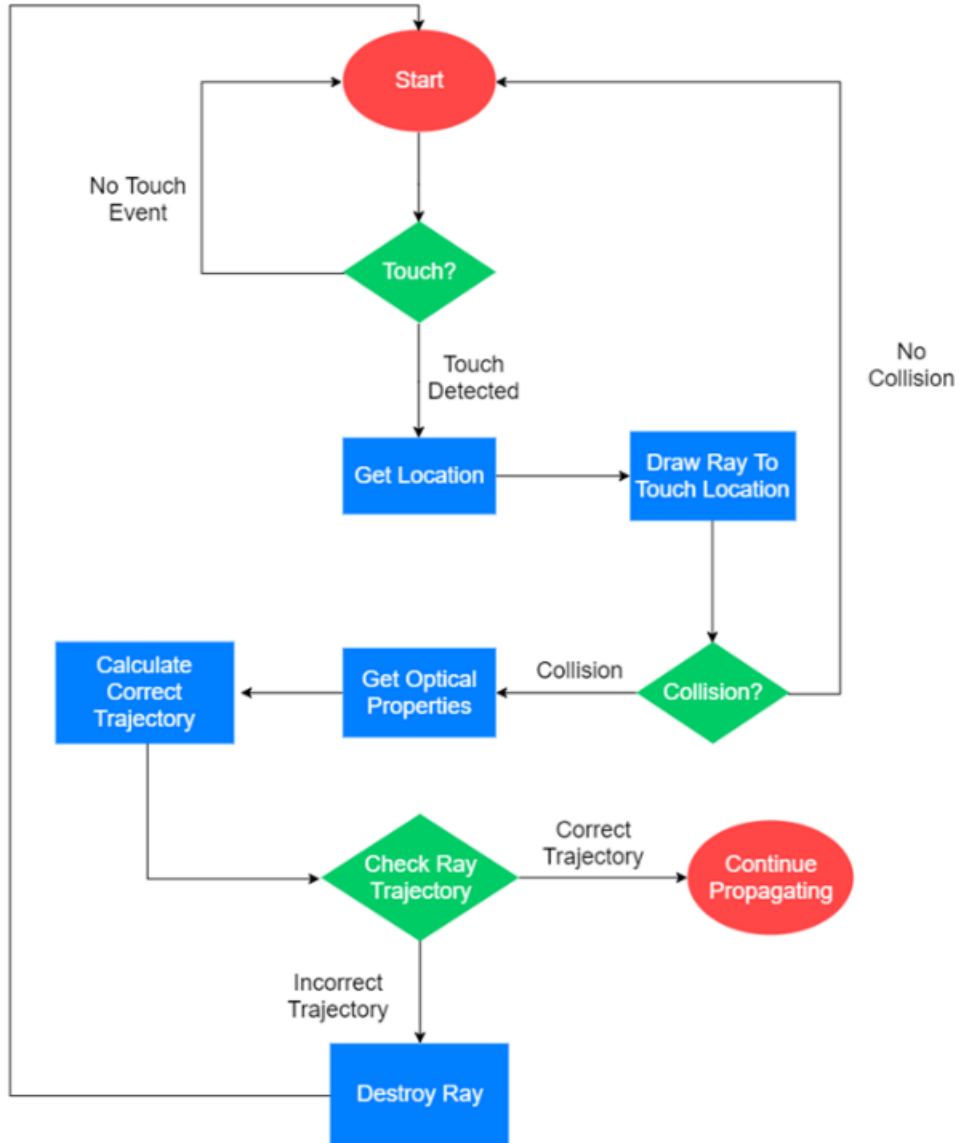


Figure 4: User-Defined Ray Tracing

The resulting application has four modules. Three of the modules are educational and focus on the main optical elements, i.e. concave lenses, convex lenses, concave mirrors, plane mirrors, and convex mirrors. The educational modules contain instructional prompts that guide and educate new users on the basic properties that govern geometric optics. The user has the option to skip the introductory lesson and proceed straight to the scenario, or “quiz”, generation. Here, an object is placed in front of an optical element (depending on the current module active) and the user must determine the properties of the image formed through an interactive, graphical ray-tracing approach. If needed, the user is also given hint prompts, as shown in Figure 5. There are markers indicating the position of the focal points of each optical element.



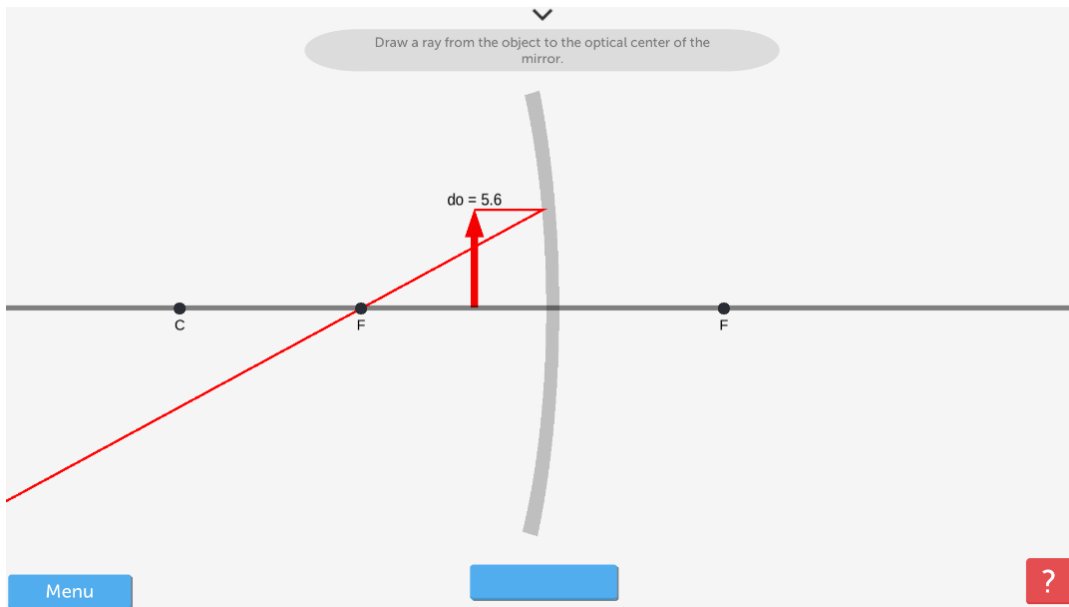


Figure 5. Hint Prompt

After successfully completing the multi-step ray-tracing process, the image will form on the display, followed by a blue panel that includes relevant information about the newly formed image, such as whether it is virtual or real, magnified or diminished, or upright or inverted. This is shown in Figure 6.

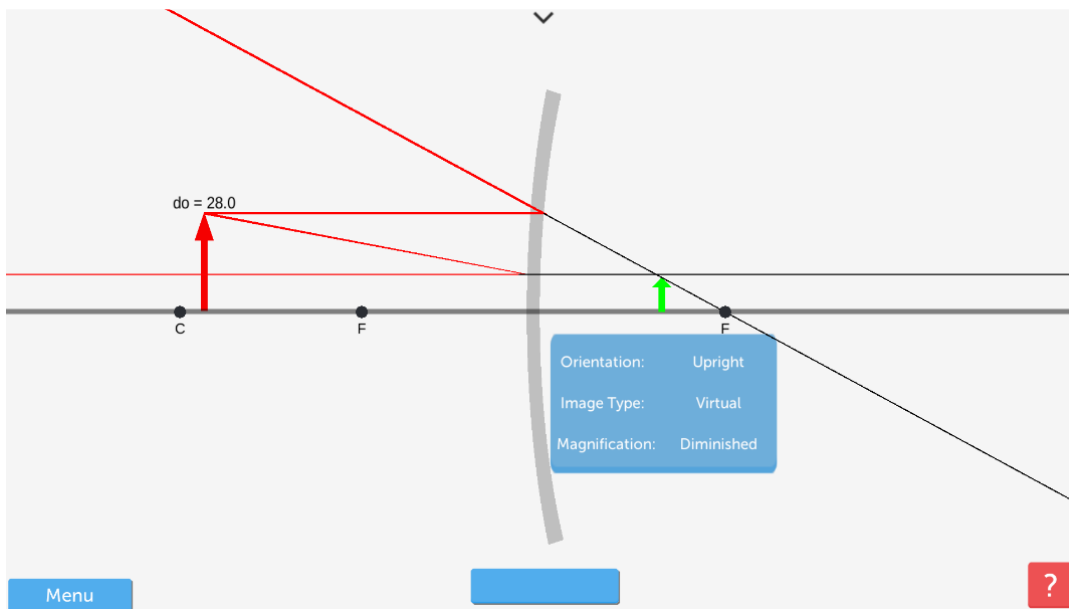


Figure 6. Image Information Panel

Finally, the educational modules include an equation panel, shown in Figure 7, which allows the users to use the two most prominent equations in geometric optics, the thin-lens/mirror equation and the lateral magnification equation. The equations, by default, are found in an empty state,

with variable names used as placeholders for actual values. Users are able to enter values into the fields in the equation panel and the equations will be used to calculate the appropriate results. If the user does not place any values into the equation panel, then the values will simply be pulled from scene, unless the user has not yet completed a ray-tracing quiz.

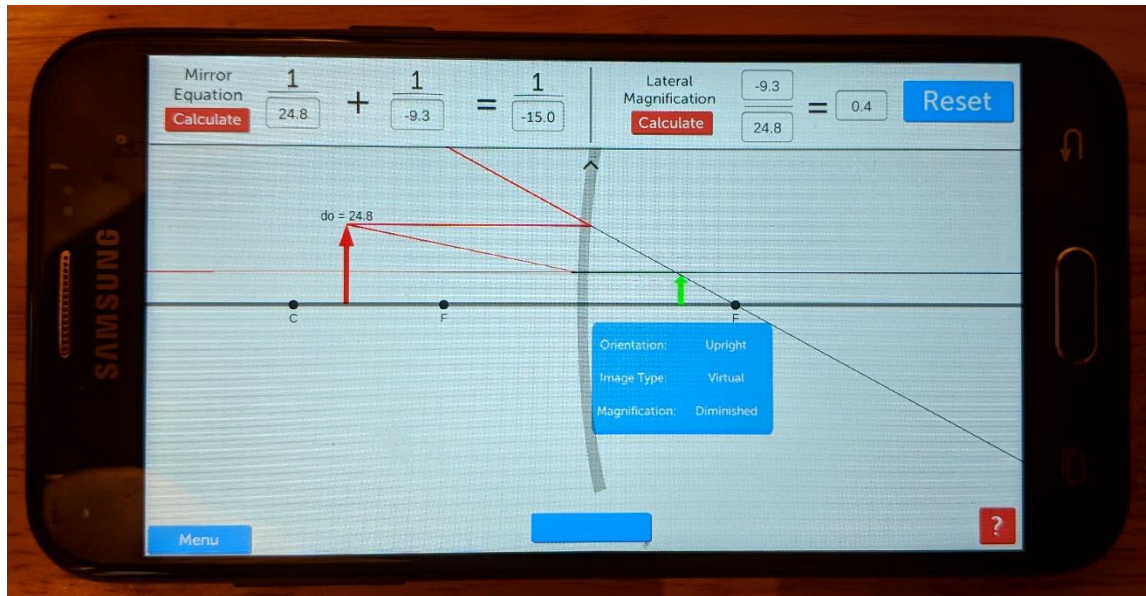


Figure 7. Equation Panel

For the sandbox module, the objects are represented by a small black cube from which emanates a ray of light. The user is able to add up to four additional objects to the scene in order to observe the effect of various optical elements on the rays of light. The user is able to move the objects around to any point on the screen, as long as they remain on the left side of the optical element. The user can adjust the following properties on the currently active optical element: refractive index, radius of curvature, and height. These changes are applied in real-time. There is no need to reload the module or reload the optical element. Finally, the user may change the currently active optical element to any of the four that are found in the educational modules. Thus, they have the option of investigating convex lenses, concave lenses, convex mirrors, and concave mirrors. While they are not able to move the optical element and observe the change in the system, the ability to move the object serves the same purpose because motion is relative. Figures 8 and 9 show the sandbox module and optical element selection.

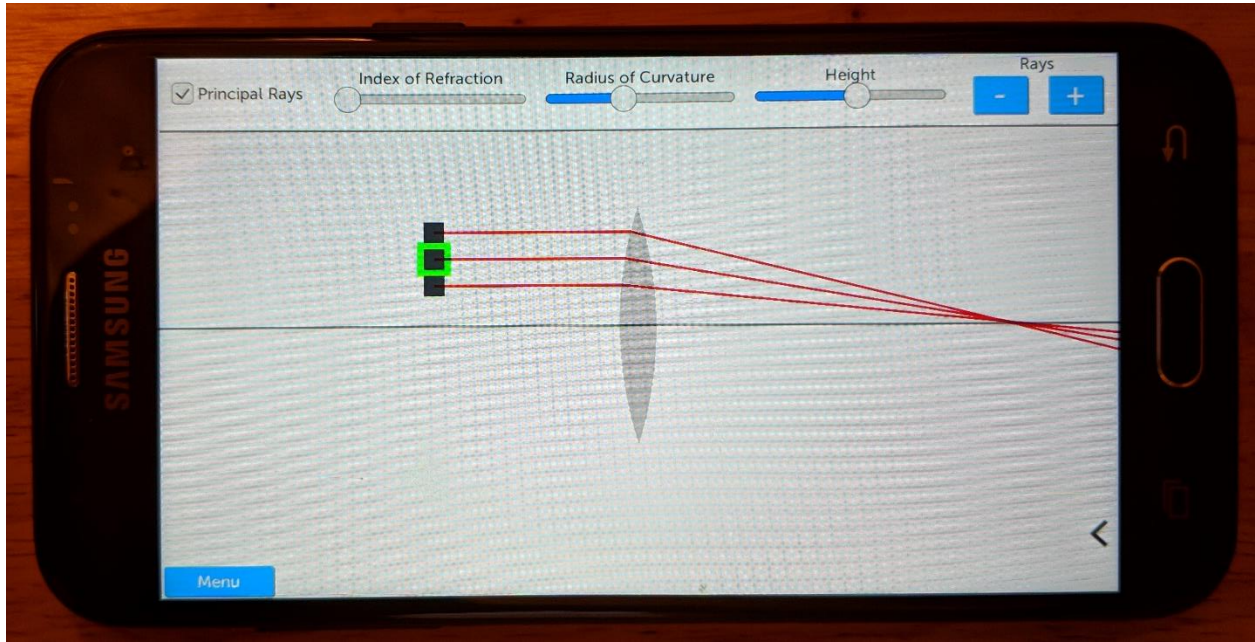


Figure 8: Sandbox Module

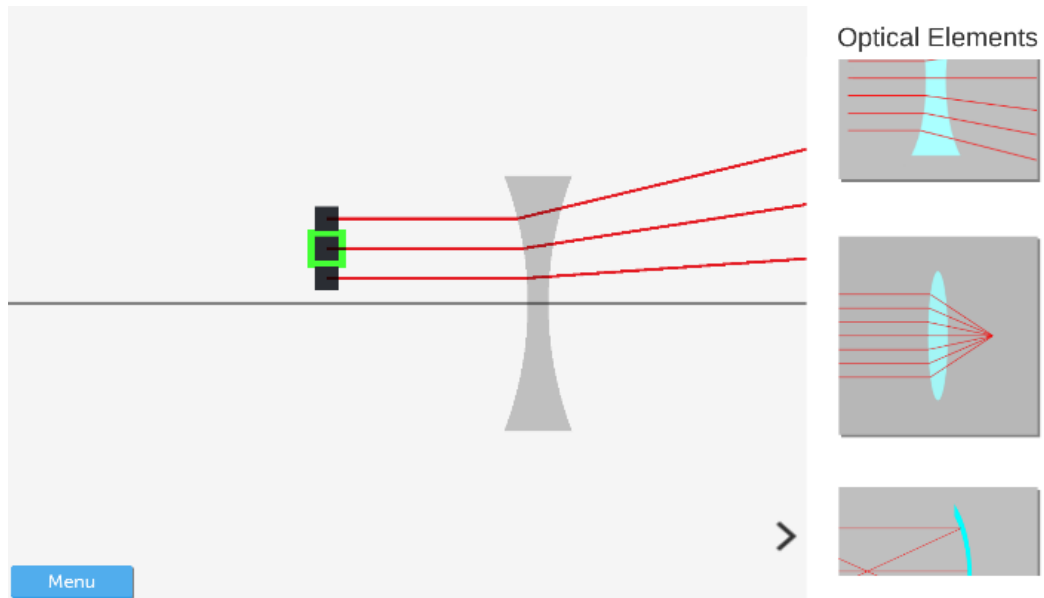


Figure 9: Optical Element Selection

Finally, for the implementation of database functionality, Firebase was used. Currently, the method of feedback collection is little more than a button on the main-menu; when pressed by the user, it opens a prompt requesting the user's name, grade level, and feedback. The text in these fields is converted to a JSON object and uploaded to the database. However, functionality exists within the code to collect more types of feedback, if necessary. This must be specified, implemented and added to the custom class that defines a "Feedback" object.

This application will be piloted during the spring 2018 semester in a sophomore physics course. Feedback will be used to inform revisions to be made to the application during the summer 2018 Research Experience for Undergraduates program.

This application can be downloaded as a Unity project at <https://github.com/tventura97/Learn-Optics---Unity>. After cloning the repository, the user can open it in Unity and compile it to the platform of choice.

## **Conclusion and Future Work**

As this project demonstrates, Unity acts as an ideal base for the creation of educational applications that seek to emphasize touch-interactivity and require accessibility on multiple platforms. The value of such applications has been recognized by many studies, but few ventures into this type of teaching style currently exist. While this application cannot, on its own, replace an entire curriculum, it is a powerful tool that can supplement existing teaching material. Its advantage lies in its ability to provide a meaningful educational experience without requiring the presence of a professor to explain the information it attempts to convey to the user. As such, it may be possible to use the app outside of the classroom environment with a reasonable degree of success.

There are a few things that remain to be accomplished. The first is the implementation of multi-element optical systems. Due to the short duration of the REU program, only ten weeks, there was not enough time to develop this feature. We expect to incorporate this feature in the next development cycle, and the application was designed with the future implementation of this feature in mind. As such, it does not have to be recreated from the ground up in order to add support for multiple optical elements. In addition, the user-interface could be enhanced based on user feedback.

Next is the testing of the application in a classroom or lecture hall environment, and collecting feedback from the students and professors to see its impact on their learning experience. This feedback can be used to further improve the application.

Finally, in the long term, this project seeks some kind of implementation into educational management software in order to broaden the usage of mobile-learning applications and to make the introduction of this technology much simpler and easier for professors. Ideally, this will also encourage the development of more interactive mobile-learning applications that use the application as a framework or as a basis for its own development.

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