Teaching rainbows with simulations: revisiting Minnaert's lab experiment

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This work presents an educational simulation to support student's learning about the formation of the rainbow. The main aim of the simulation is to provide our students with a didactic tool in addition to their traditional laboratory practice, which can be easily implemented in e-learning teaching platforms. A system consisting of a flask filled with water and a screen with a rounded aperture placed between the sun and the flask was simulated; this way a faint rainbow was seen on the simulated screen. The interactive nature of the simulation allowed the students to perform some alterations that would be impossible to do in the real world; thus, the observed rainbow deviated from the simplest model. Additionally, all these modifications could be rendered into an animation, in order to observe changes in real time.

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1. INTRODUCTION

In 1937, Dutch astronomer Marcel Gilles Jozef Minnaert published his book *De natuurkunde van 't vrije veld. Licht en kleur in het landschap* [1], later released in English translation as *The Nature of Light and Color in the Open Air* (first by G. Bell and Sons in 1940 [2] and reprinted in 1954 by Dover [3]). Little did he know that his book would become a classic among nature observers, and it would inspire new generations of researchers on the optical phenomena in nature that can be observed with humankind's first scientific tool: the naked eye. As L. Seymour states in the foreword of the 1993 translation [4] of the book, Minnaert's work is an invitation to rejoice in nature and science.

On the chapter devoted to rainbows, Minnaert shows a classic experiment to investigate the path of light in a drop of water (Descartes' Theory of the Rainbow). The experiment was not an original idea of Minnaert (see [5] for example), but it is one of the most popular renditions. The experiment can be summarized as follows: A flask is filled with water and held in the sun; a screen with a rounded aperture (a little larger than the flask) is placed between the sun and the flask. This way a faint rainbow will be seen on the screen. Its shape is a closed circle, its angular radius is about 42°, and the color red is on the outside, just as in a real rainbow (Figure 1).

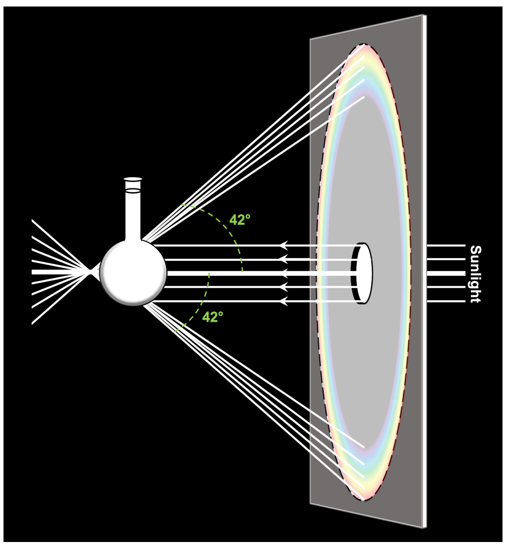

Fig. 1. Setup of the experiment, adapted from [3].

Of course, one of the main problems students have with Minnaert's experiment is relating it to the rainbow they actually see in the sky. The experiment is useful to recreate a rainbow from a big, single drop, but it fails to represent an accurate description of the real rainbow, were myriad raindrops send sunlight into our eye to produce the bow (the rays of the bow form a cone, with its tip at our eye. Its axis is parallel to the sun's rays and directed downwards to the antisolar point). In the results section we provide a clue that can help our students to make the required conceptual change.

In this work, a computer simulation of the classic experiment is presented. The main aim of the simulation is to provide our students with a didactic tool that can be easily implemented in e-learning teaching platforms, in addition to their traditional laboratory practice.

The simulations were used with our students at the University of Extremadura (Spain). Many of them are pre-service primary teachers (undergraduates) at the Faculty of Education, with little programming skills, but we also have Physics and Mathematics undergraduates at the Faculty of Sciences, who are accustomed to using programming languages. There are as well students from the Master's Degree in Teacher Training in Secondary Education, a joint degree of both faculties with graduates from various scientific disciplines or diverse branches of engineering and architecture, with different levels of programming competence. As we intended the simulation to be used by as many of our students as possible, it was developed with different levels of interaction. Thus, the modifications in the simulation could be made by editing user-friendly parameters, or modifying the code directly.

2. METHODOLOGY

We have developed a realistic 3D simulation of the experiment using POV-Ray [6] (the Persistence of Vision Raytracer), an open-source raytracer previously used in our research [7-9]. POV-Ray uses a scene description language (SDL) to represent objects internally with mathematical functions, enabling the user to render even complex scenes quite efficiently. This is a major advantage, as the user only has to be concerned with the geometric description of the optical system, and is the main reason to use POV-Ray instead of other more recent software. POV-Ray scripts are small and intelligible ASCII files, and its syntax has been unaltered for years. There is also an extensive user documentation, a large collection of third party support and a significant number of scenes, models and tutorials can be found online. In addition, the program is free to use, open-source, and it is available for almost all computer platforms.

One inconvenience with POV-Ray is that, internally, it uses an additive RGB representation of color. This is a main disadvantage when working with simulations involving color, as it introduces color distortion and produces physically incorrect images [10]. To avoid this, a POV-Ray developer [11] implemented a spectral rendering system for POV-Ray. It works by rendering a set of grayscale images, each representing a specific wavelength. The output of our simulation is a set of 36 OpenEXR (a high dynamic-range image file format [12]) images representing the wavelengths from 380 to 730 nm in steps of 10 nm. In order to show true color, the 36 images are finally combined using the CIE color matching function. As way of example, in Figure 2 we have rendered a scene where the camera is looking directly through an Amici Prism [13] at an emitting lamp (in our example, a cool white Osram 36 Watt fluorescent lamp) to illustrate how spectral rendering works in POV-Ray.

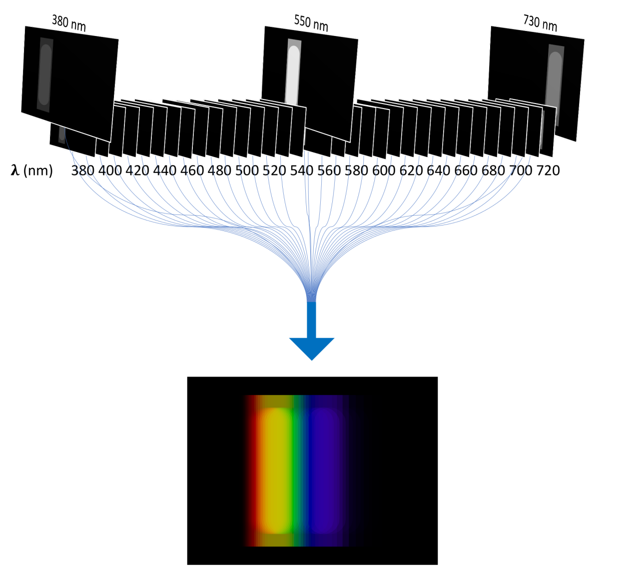

Fig. 2. Spectral rendering in POV-Ray. The rendered set of grayscale images, each representing a specific wavelength (from 380 to 730 nm in steps of 10 nm), is combined in the final composite image using the CIE color matching function.

The first step in our simulation was to emulate faithfully the real setup of the experiment. Thus, a glass flask filled with water, a white screen with a rounded aperture and the sunlight were simulated (Figure 3). We used parallel rays in our simulation, but the actual angular size of the sun can be taken into account. Some additional elements were added in order to provide realism to the scene. Thus, the flask is held with a rod on a table, to prevent the flask from magically floating in the air. The screen is also placed on the table. All these elements are placed within a closed room, with just two windows on its right side, as in our real laboratory, which allow sunlight to enter.

This environment was designed to serve as an educational resource to help the students to better understand light propagation in geometric optics, and it was intended to complement observations made in the real system.

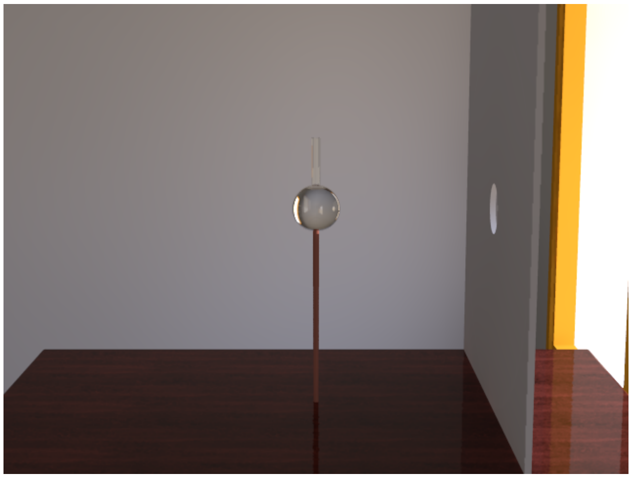

Fig. 3. Simulation of a flask filled with water in front of a white screen with an aperture (sunlight coming from the right).

The flask and the screen were then placed in a dark room, in order to better see the resulting rainbow (Figure 4).

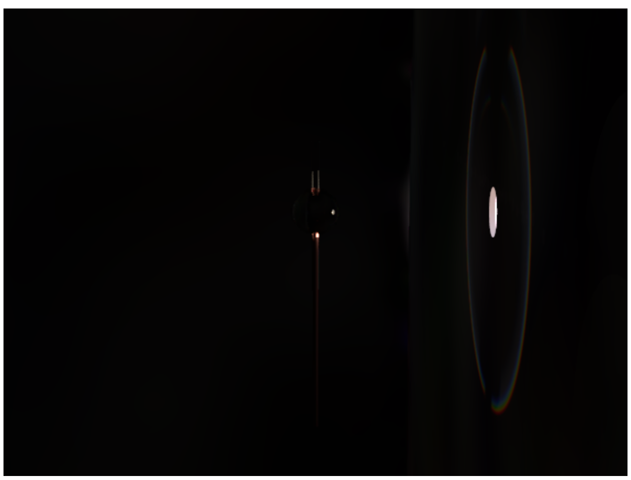

Fig. 4. The simulation from Figure 3 in a dark room.

As expected, a rainbow was observed on the screen, and the images obtained were quite similar to the real setup (Figure 5).

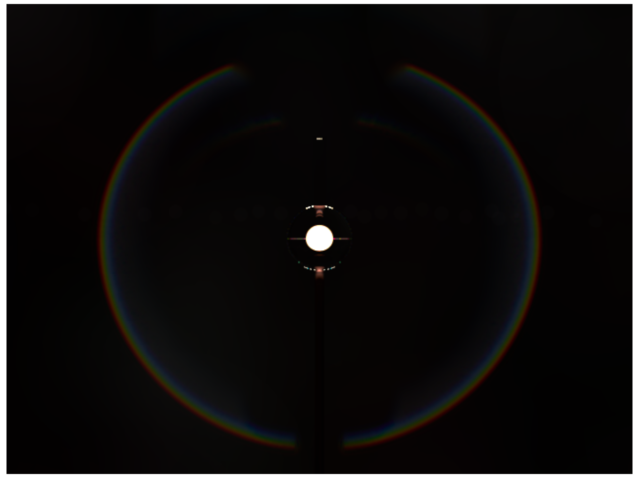

Fig. 5. Front view of the resulting simulated rainbow.

In addition, the simulation included the possibility to measure the resulting angles, both within the virtual environment (simulating several protractors and a Hartl optic disk) or superimposing a graduated grid over the resulting picture.

3. RESULTS

Our aim was not only to achieve an accurate duplication of the real system, but we also intended to further expand the didactic value of the experience. The interactive nature of the simulation allowed the students to perform some alterations to the experiment which would be impossible to do in the real world.

The students could modify the geometry of the flask, in order to see how this influenced the shape of the rainbow formed. In Figure 6 we have elongated the flask along the y-axis (left), the x-axis (center) and the z-axis (right). The resulting modified rainbows can be seen under each flask.

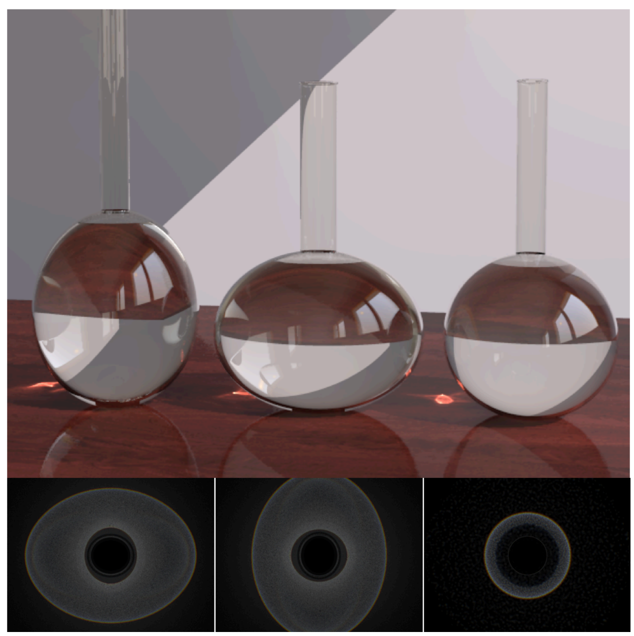

Fig. 6. Deformed flasks and resulting rainbows.

The student could, as well, control the thickness of the flask, as seen on Figure 7. On the right of the figure we can observe what happens if the thickness is reduced to zero: the flask is essentially removed from the simulation and, as a result, we obtain just a big water drop, the simplest model for our rainbow simulation. We could also see the cross section of the flasks, with the path of the rays inside the optical system.

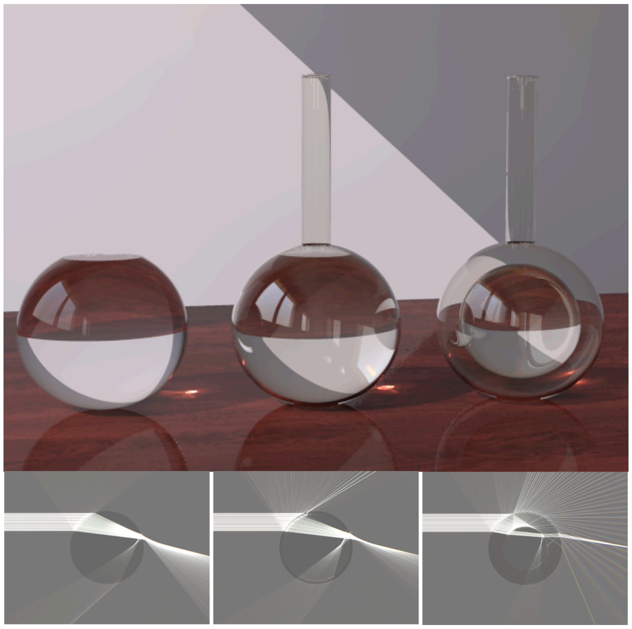

Fig. 7. Top: Different thickness of the flask: 2 cm (right), 0.2 cm (center) and 0.0 cm (no flask, left). Bottom: Cross section of the respective flasks.

A small thickness changes slightly the resulting rainbow. However, as the flask's thickness increases, the rays that pass through the system may undergo additional internal reflections that can result in split rainbows with complicated patterns.

Another possibility was to change the index of refraction of the liquid. Figure 8 shows a big drop of water next to a big drop of a liquid with a higher index of refraction (n = 1.50). A comparison between the different rainbows can be seen on Figure 9.

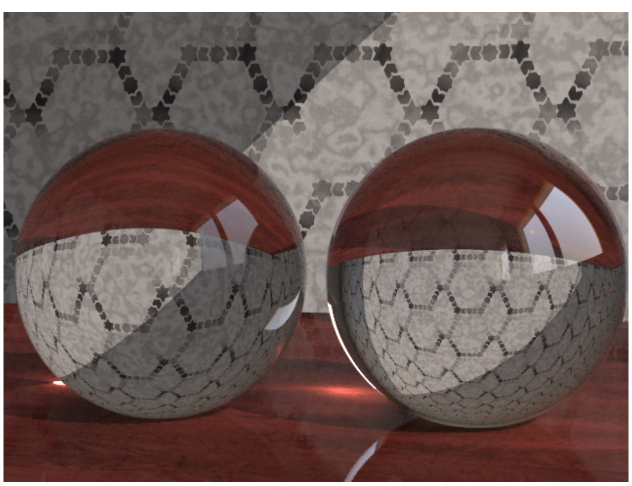

Fig. 8. Two drops with different indexes of refraction: n = 1.33 (left) and n = 1.5 (right).

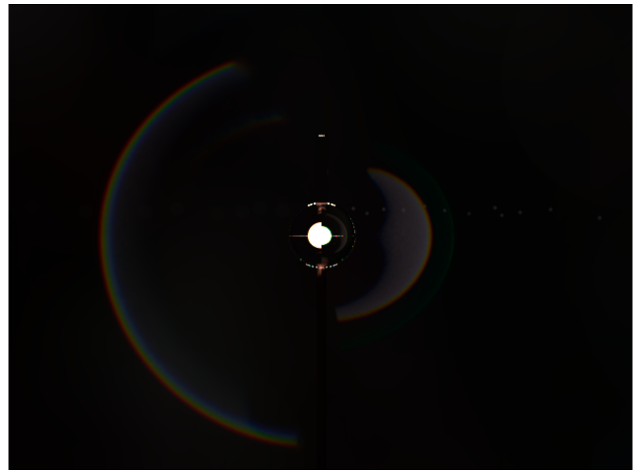

Fig. 9. Comparison between the resulting rainbows obtained with two drops with different indexes of refraction: n = 1.33 (left) and n = 1.5 (right).

We can clearly see the difference in the angular size of the bow obtained from the water drop (left) versus the bow obtained with the glass ball (right). The simulation gives angular radius of 42° and 23°, respectively, matching theory [14].

Further modifications in material, color and shape are shown in Figure 10. In the top row we have, from left to right, a pure ice ball, a flint glass ball and a diamond ball. On the middle row we have different colored balls, and in the bottom row we have water drops cut in half along different axis.

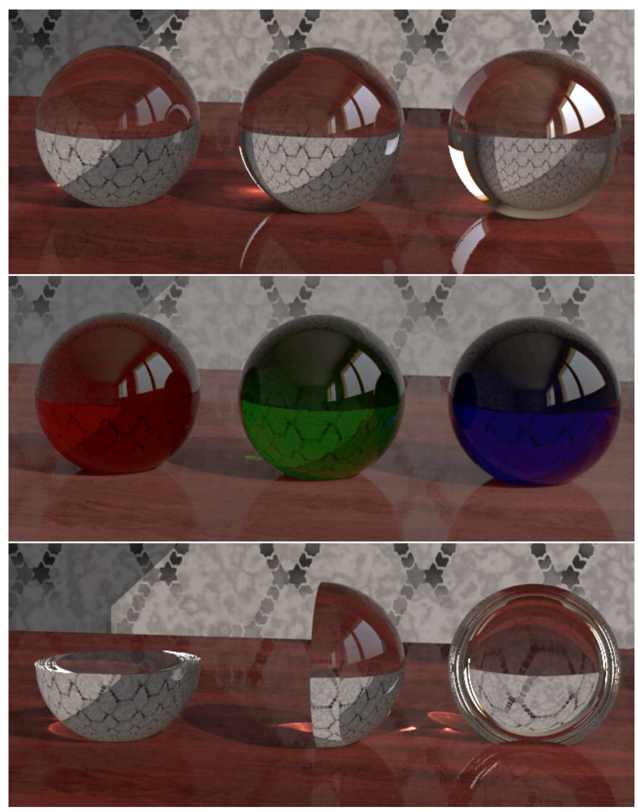

Fig. 10. Several modifications of the systems, changing index of refraction (top row), color (middle row) and shape (bottom row).

A remarkable modification is shown in Figure 11. Next to a drop of water there is a drop with a negative index of refraction, an impossible object in real life with which we introduce the concept of metamaterials to our Physics students, and how they can be rendered in a photorealistic way using POV-Ray [15-18]. As way of example, a comparison between the cross sections of a drop of water and a drop of meta-water (water with a negative index of refraction) obtained in our simulation is shown in Figure 12.

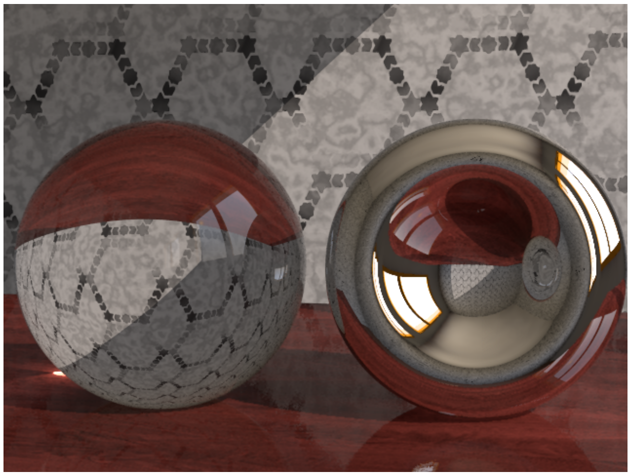

Fig. 11. A water drop (left) and a meta-water drop (right).

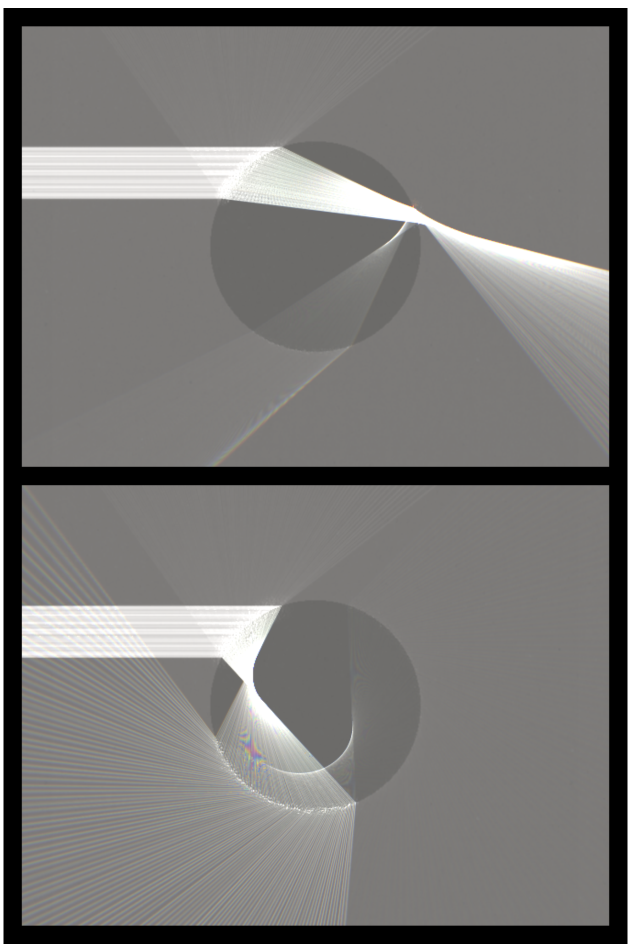

Fig. 12. A drop of water (top) and a drop of meta-water (bottom) scattering light.

Finally, the light source could also be modified. We could change its spectral distribution, simulating the most usual illuminants or even other stars instead of the Sun. We could also add more sources, thus creating multiple rainbows on the screen from a single drop.

All these modifications could be rendered into an animation, in order to observe the changes in real time.

In order to assist the students in the conceptual change required to relate Minnaert's experiment to the real rainbow, we present them with another experiment to recreate rainbows, where small glass beads are glued onto a black surface. If the students look at the surface with the sun behind their heads (as in real rainbows), a small bow about 23° in radius (because glass is more refractive than water) will appear in front of them. This phenomenon can be usually seen on a dry road surface after resurfacing and painting [19]. We propose our students to replicate this new experiment with our simulation, creating a randomly-placed array of drops, that can be easily implemented using a loop.

To guide the students in their learning process some tutorials were developed, with instructions on how to use the simulation and scientific content. At the end of each tutorial the students were asked open *"what if"* questions, that were answered using the simulation. We prefer to use this type of question over of direct questions, in order to engage our students in active learning. For example, instead of asking *"What would happen if we changed the index of refraction of the content of the flask?"*, we ask *"What would happen if, instead of water, we had liquid methane, as on Titan?"* The students must do some research on the subject, in order to find that liquid methane has an index of refraction of 1.29, so the resulting rainbow would be greater (about 49°) than a water rainbow, as they can check with the simulation. Some other questions were: *What would happen if we changed the size of the flask? What would happen if the flask were half empty? What would happen if we hold a coin in front of the flask? What would happen if the Sun were closer to the flask? What would happen if we change the Sun for Betelgeuse?*

4. CONCLUSIONS

A didactic simulation of the classic experiment to explain the formation of the rainbow has been developed, intended to provide our students with a didactic tool in addition to their traditional laboratory practice.

The interactive nature of the simulation allowed the students to perform some alterations to the experiment, which would be impossible to do in the real world, and the observed rainbows deviated from the simplest model.

Along with rainbow formation, the student learned transversely other concepts such as dispersion, refraction, geometry, programming, etc. In addition, this type of simulation allows independent learning, as the students can use them in e-learning teaching platforms when a real laboratory is not at hand.

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