SPREADSHEETS IN PHYSICS: DIDACTIC TOOLS FOR LEARNING CONCEPTS OF GEOMETRICAL OPTICS

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Abstract

One of the most important tasks in teaching of physics is to use a suitable method for understanding and developing of theoretically acquired knowledge. The Excel spreadsheets increase students’ interest in the theoretical subject taught in the class and help their learning. This paper describes two didactic tools made with Excel spreadsheets for an interactive approach to the teaching and learning of certain concepts of geometrical optics. With the first tool we can simulate the phenomena of reflection and refraction of light at the interface between two different optical media. There is a graphic representation of the path of light rays in the two optical media and the dependence of the angles of reflection and refraction on the angle of incidence. The tool also allows the simulation of the phenomenon of total internal reflection, highlighting the critical angle on the graph rendering the angle of refraction according to the angle of incidence. The second tool helps in the study of light refraction in the optical prism. The graph of the tool renders the angles of refraction, of emergence and deviation according to the angle of incidence. Depending on the input data, on the graph, we can visualize the domain of values of the incidence angle to satisfy the condition of emergence. Moreover, the graph helps to determine the conditions for the minimum deviation of the light beam through the optical prism. The graphic representation of deviation of angle depending on the angle of incidence is used as an alternative to the analytical method for determining the angle of minimum deviation. With the help of these two tools students can easily understand the phenomena of reflection and refraction of light and clarify a number of concepts, such as the critical angle, the emergence or minimum deviation. It is thus demonstrated that the benefits and facilities of spreadsheets can be used in the study of geometrical optics. Based on these two tools students can build their own Excel tools to study other phenomena from optics.

Keywords: Spreadsheets, reflection, refraction, total internal reflection, optical prism, didactic tools and physics education.

1 INTRODUCTION

The concepts concerning the light in everyday thinking and in the scientific thinking have been presented comparatively in the literature and, in this regard, examples have been given for the interpretation of phenomena related to the propagation of light, light perception, image formation, the colors of objects etc. For students to adopt the scientific way of thinking, authors plead for the teaching of optics in the form of scientific research. To this end, teaching sequences have been proposed to generate results of practical usage of the knowledge acquired by students [1]. It has been shown that students face many difficulties when they have to interpret the optical phenomena involving both the geometrical model and the wave model. For example, there have been reported difficulties in the interpretation of colors, diffuse reflection, object-image correspondence, Young’s experiment or the determination of the diffraction figure of an object observed in the focal plane of a lens. In order to help students correctly interpret these phenomena, some authors propose a teaching strategy based on the notion of “backward selection” [2-3]. The way in which the wave theory of light is used to explain various optical phenomena has been studied on lots of students from France and Turkey. The data collected showed that students have difficulties in explaining the phenomena of refraction, interference and diffraction. Remedies have been proposed and the pedagogical implications of this approach have been discussed [4-5]. It was noted that by the previous revision of geometrical elements necessary and sufficient for the building of images provided by reflection and refraction on plane surfaces, students can interpret, represent and describe these images at a higher level of conceptualization of physical phenomena [6]. It was discussed how the instructional materials are designed in the teaching of optics in the context of the link between the critical details of the practice and the teaching sequences. They were given examples of “critical details”, such as the difficulties met when explaining phenomena like the visibility of the laser beam or color formation in nature [7].
Designing computer simulations and the way in which teachers integrate them into practical training can influence the conceptual understanding of physical phenomena by students. For example, it has been proved the beneficial role of the simulation of image formation in convergent lenses when the object is partially covered [8]. With the help of the simulation medium RAY students were able to explicitly restate their knowledge of optics. This simulation environment encourages students to build diagrams of the images using any rays, not only “special rays” [9]. After identifying and analyzing students’ difficulties in understanding the light wave model, a set of tutorials was designed to supplement instruction in the physics course at the introductory level [10]. It has been shown how optical phenomena can be analyzed quantitatively in a simple manner with the video analysis software “Tracker”. The advantages of experimental activities were highlighted based on this software with video modeling examples to study the laws of reflection and refraction of light or to highlight the focal lengths in mirrors and lenses [11]. Various concepts and phenomena from optics can be explored by students using interactive spreadsheets. These tools initially conceal the mathematical complexity, which may be later disclosed and learnt. Thus, it was described how students can explore Snell’s law and the absorption of light [12], or how to calculate the intensity of the scattering light in Young’s experiment [13]. Spreadsheets also help describe a method to reduce the scattering of acquisition data in the light diffraction experiment. The scattered light was collected by a photodetector placed on a screen in a direction parallel to the plane of the slit. The values obtained on the graph for the locations of the secondary maximums have proven to be the same as those predicted by the theory within the limits of the experimental errors [14].

This paper describes two teaching tools made with Excel spreadsheets for the interactive teaching and learning of concepts of geometrical optics. The first tool allows the simulation of the phenomena of reflection and refraction of light at the surface of separation of two different optical media. Depending on the input data, we calculate the angles of reflection, refraction and the critical angle. Two graphs are associated to the analytical results. The first graph renders the path of the light rays in the two optical media. The second graph renders the variation of the reflection and refraction angles in relation to the angle of incidence. Also, this graph highlights the critical angle if the refractive index of the medium from which the light comes is greater than the refractive index of the medium in which the light enters. The second tool allows the study of light refraction through the optical prism. The graph of the tool renders the variation of the angles of refraction and of incidence on the second side of the prism, the angles of emergence and of deviation in relation to the angle of incidence. The graph shows the value range of the angle of incidence to satisfy the condition of emergence. Combining the graphical method with the numerical method, we can determine the minimal deviation angle and the corresponding value of the incidence angle at minimum deviation. Also, this tool can verify the formulas of the prism in particular circumstances, such as the approximation of the deviation angle for small values of the prism angle and the angle of incidence.

2 EXCEL TOOLS

The structure of the tools presented resembles that of the tools described by the authors on the topic of using spreadsheets in Physics lessons [15 - 20]. Several spreadsheets are interconnected so that the main results are rendered next to the input data to easily trace the feedback, both analytically and graphically, when the data are changed. Thus, each tool is made up of the main spreadsheet with the section “Input data” and “Results”, plus the area of the graph associated to the results. Alongside the main spreadsheet, there are the secondary sheets where the source tables of the graphs are situated. The main spreadsheet of the first tool, destined for the simulation of the phenomena of reflection and refraction of light, is rendered in Figure 1. In the section “Input data”, limited by the domain A13:B16, are introduced the values for: the refractive index of the optical medium 1, n1, in cell B14; the refractive index of the optical medium 2, n2, in cell B15; the angle of incidence, i, in cell B16. The section “Results”, limited by the domain A18:B22, is divided in two subsections. The first subsection is given by cell A19, displaying the message “REFLECTION+REFRACTION” if the light passes from an optical medium to another or the message “TOTAL INTERNAL REFLECTION” if there is a total internal reflection. The second subsection is given by cell A18, displaying the message “TOTAL INTERNAL REFLECTION” if there is a total internal reflection. The calculation of the critical angle is done only if n1>n2, otherwise the message “NO” is displayed. In order to track more easily the calculations in Excel we have introduced names of cells, such as: “Index_n1” for cell B14, “Index_n2” for cell B15, “Angle_I” for cell B16, “Angle_L” for cell B22.
Considering the mathematical relations of the laws of reflection and refraction of light [18]:

\[ i^* = i \rightarrow n_1 \sin i = n_2 \sin r \]  

we have written the Excel formulas in the cells of the section “Results”. For example, utilizing the logical function IF, to calculate the angle of refraction in cell B21 we have written the formula:

```
=IF(Index_n1<Index_n2;DEGREES(ASIN((Index_n1/Index_n2)*SIN(RADIANS(Angle_I))));IF(Angle_I <Angle_L;DEGREES(ASIN((Index_n1/Index_n2)*SIN(RADIANS(Angle_I))));"NO"))
```

When \( n_1 > n_2 \), the critical angle, \( l \), was calculated in cell B22 according to the relation [21]:

\[ \sin l = \frac{n_2}{n_1} \]  

If, when \( n_1 > n_2 \), the angle of incidence is bigger is the critical angle, then there is total internal reflection and the message “NO” is displayed in cell B21 for the angle of refraction.

The first graph of the tool, presented in figure 1, renders the path of the rays of light in the two optical media. The incident ray is colored in blue, the reflected ray is colored in green and the refracted ray is colored in red. The extension of the incident light beam in the optical medium (2) is traced in a dotted line colored in blue. In order to render correctly on the graph the values of the angles of incidence, of reflection and refraction we have traced the beams of light in relation to a reference circle. The centre of the circle represents the point of incidence, and the vertical axis Y coincides with the normal in the point of incidence. When modifying the input data we simulate the reflection and refraction of light by turning the light rays in relation to the reference circle chosen.

If \( n_1 < n_2 \), we have a graphic verification that the angle of refraction is smaller than the angle of incidence as observed in figure 1. By increasing \( n_2 \) in comparison to \( n_1 \), it can be observed on the graph how the refracted ray comes closer to the normal. If \( n_1 > n_2 \), we have a graphic verification that the angle of refraction is bigger than the angle of incidence as observed in figure 2. In this case, in cell B22 the value of the critical angle is displayed. By increasing \( n_1 \) in comparison to \( n_2 \), it can be observed on the graph how the ray refracted goes farther from the normal.
Fig. 2 - The main spreadsheet of the tool to simulate the phenomena of reflection and refraction of light with the graph of the rays of light when $n_1>n_2$.

The second graph of the tool renders the angles of reflection and refraction according to the angle of incidence. The dependence of the angle of reflection on the angle of incidence is represented by the green straight line. The curve of the dependence of the angle of refraction on the angle of incidence is traced in red.

Figure 3 presents the dependence of the angles of reflection and refraction on the angle of incidence when $n_1>n_2$, for two pairs of values of the indexes of refraction: a) $n_1=1.33$, $n_2=1$; b) $n_1=1.55$, $n_2=1$. For the first pair of values of the indexes of refraction, the critical angle is $\theta=48.75^\circ$, and for the second pair $\theta=40.18^\circ$. It is thus verified that with the growth of the refraction index of medium (1) in relation to medium (2), the critical angle has smaller and smaller values. Also, the difference between the angle of refraction and the angle of reflection becomes bigger and bigger. The graph from figure 3 highlights two distinct domains in this case. The first domain corresponds to the refraction accompanied by reflection, when the angle of incidence is smaller than the critical angle, while the second domain corresponds to the total internal reflection, when the angle of incidence is bigger than the critical angle. The value of the critical angle is highlighted by the straight line traced in pink. The dotted lines colored in brown highlight the angle of incidence from the input data together with the value calculated for the corresponding angle of refraction.

To generate the series of data in the source table of the graph of the rays of light we have employed the equation of the straight line and the equation of the circle. We have considered on the axis Ox an interval limited, on one side and the other of the origin, by the ray of the circle arbitrarily fixed at a given value. We have chosen a distance quantum equal to the 100$^{th}$ part of the ray. The series of data for tracing the rays of light have been limited to two pairs of values for each series. We have thus proceeded because we have built each ray from two points whose coordinates are determined from the input data.
Fig. 3 - The main spreadsheet of the tool for the simulation of the phenomena of reflection and refraction of light with the graph of the dependence of the angles of reflection and refraction on the angle of incidence when $n_1>n_2$.

To generate the data series in the source table of the graph of the dependence of the angles of reflection and refraction on the angle of incidence we have adapted the Excel formulas from the main spreadsheet. The formulas have been propagated from the first to the last line of the table. The values of the angle of incidence have been generated with the step of 0.05° in the interval 0-90°. To also consider the case $n_1>n_2$ we have utilized a series of supplementary data to highlight the critical angle.

Figure 4 renders the main spreadsheet of the second Excel tool. In the section "Input data", limited by the domain A17:B21, we introduce the values for the following measures: the index of refraction of the medium where the prism is, $n_1$, in cell B18, the index of refraction of the prism, $n_2$, in cell B19, the angle of the prism, $A$, in cell B20 and the angle of incidence, $i$, in cell B21.

The section "Results", limited by the domain A23:B31, is divided in three subsections. The first subsection is given by the cell A24, which displays the message "EMERGENCE" if the ray of light exits the prism or the message “TOTAL INTERNAL REFLECTION ON THE SIDE OF AC if there is a total internal reflection on the AC side of the prism. In the second subsection, limited by the domain A25:B29, we calculate the angles $l$, $r$, $r'$, $i'$ and $\delta$ whose names are specified in the figure. In the third section, limited by the domain A30:B31, we analyze the conditions of minimum deviation of light. Thus, in cell B30 the message "YES" is displayed if the condition of minimum deviation is fulfilled, or the message "NO" in an opposite case, and in cell B31 we calculate the angle of minimum deviation, $\delta_{\text{min}}$.

Fig. 4 - The main spreadsheet of the tool for the study of the optical prism when the ray of light exits the optical prism.
In the Excel formulas we have used names of cells, as for example: Index_n1 for cell B18, Index_n2 for cell B19, Angle_A for cell B20, Angle_I for cell B21, Angle_L for cell B25, Angle_R for cell B26, Angle_RP for cell B27.

To do the calculations in the main spreadsheet we have taken into account the formulas of the optical prism inferred from the laws of refraction and from geometry [22]:

\[ n_1 \sin i = n_2 \sin r \quad n_2 \sin r' = n_1 \sin i' \quad r + r' = A \quad \delta = i + i' - A \]  

(3)

For example, the Excel formula to calculate the angle of emergence, \(i'\), has been written in cell B28 under the following form:

\[ =IF(\text{Angle}_\text{RP}<\text{Angle}_\text{L};\text{DEGREES(ASIN(Index_n2/Index_n1*SIN(RADIANS(\text{Angle}_\text{RP}))));"NO"});\]

Analogously, we have written other Excel formulas in the spreadsheet. The logical function IF has been used to consider both the case of the emergence, and the case of total internal reflection on the AC side of the prism.

### Fig. 5 - The main spreadsheet of the tool to study the optical prism with the graph of the tool for the emergence at any value of the angle of incidence.

The graph of the tool, placed next to the input data, shows how the angles \(r, r', i'\) and \(\delta\) vary with the angle of incidence \(i\). The curve \(r=r(i)\) is rendered in a continuous blue line, while the curve \(r'=r'(i)\) is rendered in a continuous green line. It is verified that with the growth of the angle of incidence, \(i\), the angle \(r\) grows, while the angle \(r'\) decreases. The curve \(i'=i'(i)\) is presented discontinuously in the points colored in pink and the curve \(\delta=\delta(i)\) is also presented discontinuously by the points colored in red.

The graph highlights the value range of the angle of incidence \(i\) for which the ray of light exits the prism and the value range of the angle of incidence for which there is a total internal reflection on the AC side. Thus, the value range of the angle of incidence for which there is a total emergence horizontally limits the graphs \(i'=i'(i)\) and \(\delta=\delta(i)\).

In the source table of the graph, the values of the angle of incidence have been generated with a step of 1° in the interval 0-90°. To generate the values of the angles \(r, r', i'\) and \(\delta\) we have adapted the Excel formulas from the main spreadsheet and propagated them from the first to the last line of the table.

The graph of the tool together with the last subsection from "Results" helps us find the conditions for the minimum deviation of light through the optical prism. Thus, we can trace on the graph the minimum of the function \(\delta=\delta(i)\) correlated with the point in which the graphs \(r=r(i)\) and \(r'=r'(i)\) intersect. The coordinates of the minimum point represent the angle of incidence for which the minimal deviation.
occurs and, respectively, the angle of minimal deviation. In order to improve the information extracted from the graph we appeal to a procedure numeric try based on the condition that the angles \( r \) and \( r' \) are approximately equal. We can choose, for example, a difference between \( r \) and \( r' \) smaller than half of a hexadecimal degree. Consequently, in cell B21, we put in different values of the angle of incidence around the minimal value read on the graph until the message “YES” is displayed in cell B30. The angle of incidence for which the message “YES” is displayed in cell B30 represents the angle of incidence for which the minimal deviation of light occurs. To calculate the angle of minimal deviation, \( \delta_{\text{min}} \), in cell B31, we utilize the function MIN applied to the domain from the source table of the graph in which we calculate the values of the angle of deviation.

By gradually modifying the input data, we can generate various situations for the study of the refraction of light through the optical prism. For example, we can change the angle of incidence from a value smaller than 30° keeping, though, constant the other input data. In this case, the message “TOTAL INTERNAL REFLECTION ON THE AC SIDE” is displayed in cell A24 and the message “NO” in cells B28-B31. Modifying the angle of the prism at the value \( \Delta=10^\circ \) and keeping unchanged the other input data, we obtain the situation rendered in figure 5. As observed in the graph, in this case, the ray of light exits the prism for any value of the angle of incidence \( i \). Also, it can be observed that from a certain value of the angle of incidence, the angles \( r' \) and \( i' \) have negative values. The sign minus is interpreted taking into account the direction in which the angles \( r' \) and \( i' \) are measured in relation to the normal in the point of incidence on the AC side of the prism.

The tool allows the verification of certain calculus relations for the study of the optical prism in some particular cases. For example, the approximate calculus relation of the angle of deviation when the angle of the prism and the angle of incidence take smaller values \([23]\):

\[
\delta \cong (n-1)\Delta
\]

For smaller angles of the prism, relation (4) shows that the angle of deviation practically does not depend on the angle of incidence for smaller values of the angle of incidence. This aspect is highlighted by the graph \( \delta=\delta(i) \), as observed in figure 5 when the angle of the prism is \( \Delta=10^\circ \).

### 3 CONCLUSIONS

The classroom use of these two tools presented is beneficial for the interactive teaching and learning of the phenomena of reflection and refraction of light.

With the first tool students can check the laws of reflection and refraction of light and study the conditions in which the phenomenon of total internal reflection occurs. With the graphs obtained, students can easily grasp the significance of the critical angle when the light passes from a denser optical medium to a less dense one. The graphical results allow students to gain a general understanding of the phenomena of reflection and refraction of light at the surface of separation of two different optical media.

With the second tool students can better understand how light refraction occurs in an optical prism. The graph of the tool allows the direct visualization of the value range of the angle of incidence to satisfy the condition of emergence. Moreover, the graph of the tool allows the determination of the conditions necessary for minimum deviation. The graphical representation of the angle of deviation depending on the angle of incidence is used as an alternative demonstration to the analytical method to determine the angle of minimum deviation. Thus, the exploration of the graphical facilities of the spreadsheet leads to the same result as the exploration of the minimum condition of a function using derivatives. Also, this tool helps students to check the formulas of the optical prism in a variety of situations with a rapid feedback to data change.

The two teaching tools can be a source of motivation and incentive for students so that they can build new tools for the simulation of other phenomena in physics.

Use of computers and software ICT tools in classrooms and laboratories, can make physics-science easier to understand \([24]\). There are numerous studies which prove that using interdisciplinarity \([25-29]\), simulations, virtual experiments and real experiments the understanding of concepts becomes easier and deeper \([30-33]\).
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REFERENCES


