The Mirascope: an explanation on a conceptual level

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Abstract
The main objective of this paper is to provide an explanation on a conceptual level of how the Mirascope and the occurring image formation work. The physics behind a Mirascope—a well-known device consisting of two concave mirrors—is very complex. In literature, only either high level or very simplified and deficient explanations can be found. These explanations often lack a basic but detailed description on a conceptual level of the phenomena observable with the human eye. Therefore, this paper aims to give a physical explanation on a conceptual level to support learning processes in optics. Phenomena such as the diverse direction of the projected real image and the formation of the virtual image are clarified. As the focus lies on providing a basis to foster a conceptual understanding, there is no claim for a full and detailed explanation on the level of an exact ray analysis. In addition to a clarification of the content on a conceptual and educational level, suggestions for further investigations of the Mirascope with everyday items are given. The Mirascope is seen as an appropriate device for creating a learning environment following an inquiry-based approach in physics (teacher) education. This paper focuses on describing and explaining aspects of the Mirascope on a conceptual level.

1. Introduction
The Mirascope—often also called ‘Mirage’ or ‘Illusion’—is an ordinary device consisting of two concave mirrors. It is widespread within the community of physicists and is mainly known for generating a wow-effect by the means of a projection of a real 3D-image. Therefore, it is often used to grab someone’s attention or to spark an interest. Explanations of the phenomena found in the literature and online range from very complex and high level descriptions to generously reduced explanations. A ray analysis (e.g. [1]) and mathematical modelling using mathematical software (e.g. [2]) cover the advanced level of physics while very simplified illustrations with two light rays\(^1\) just cover the main concepts of physics to explain the Mirascope at a low level. However, these descriptions appear to miss important aspects to encourage a deeper understanding. Furthermore, a precise observation of the phenomenon itself is often omitted and consequently, the concepts of physics behind this phenomenon are missing.

Observing the different orientation of the object and the generated image or the slightly different size of the real image and the object have

\(^1\) See e.g.: http://physicstoyos.blogspot.com/2018/02/the-mirascope.html (17 April 2019).
led to the demand of a further explanation for educational purposes not only in secondary level but also at the university level. Neither the explanation of the generated virtual image of the real 3D-image was found in the literature or online search nor observations and investigations of the two observable images (the real and the virtual image of the real images) are mentioned. To sum up, a lack of an overall conceptual based explanation of the observable phenomena was detected.

Therefore, this paper gives an overall description on a conceptual level. The main intention of this article is to use the Mirascope following an inquiry-based approach. Therefore, starting from the observable phenomena, explanations on a solid physical basis are aimed. The paper contains three main sections. First, the set-up of the Mirascope and the identified issues concerning its existing explanations are reported. Second, the clarification of basic subject-specific concepts behind the Mirascope on a conceptual level are focused. Third, concrete suggestions for experimental investigations of several phenomena are given. Therefore, hints for a possible implication of an inquiry-based learning arrangement in physics (teacher) education will be reported.

2. The set-up of the Mirascope and the problem with common explanations

The set-up of the Mirascope is shown in figure 1. The Mirascope consists of two concave mirrors of identical shape. These mirrors are placed opposite each other, so that their focal point is located at the vertex of the opposite mirror. For any observation, the upper mirror (M2) has an opening (a hole) in its center. By placing an object on the surface of the bottom mirror (M1), a real image of the object is generated above the opening of the upper mirror (M2).

The description above is common and could be found online effortlessly. There are several facets of this description that need to be considered. First, the image of the object in figure 1 is oriented in the other direction than the object itself. Simplified explanations often use spherically symmetric objects (e.g. [1, 3]). Moreover, these explanations use one object point in the middle of the object (O) with two light rays interacting right at the optical axis. Last, the generated image is represented to point in the other direction [4]. This variation of the direction cannot be explained with the mentioned simplified descriptions. Hence, reduced descriptions often lack the illustration of the different directions of the image (I\textsubscript{O-real}) and the object (O).

As mentioned above, explanations limited to the visualization of the object points located right at the main axis cannot explain the reversed orientation of the image (I\textsubscript{O-real}) and the object (O). The limitation is caused by the missing ray way(s) illustrating the formation of an image point of an objects point, located off the mirrors’ optical axis. Therefore, the comparison of two different object and image points cannot be accomplished easily and consequently it seems difficult to generate a logical explanation addressing the images’ orientations. In conclusion, as the image (I\textsubscript{O-real}) points in the opposite direction to the object itself, explanations reduced to the representation of light rays, originating from the object located at the main axis, do not explain the orientation of I\textsubscript{O-real}. Furthermore, these limited explanations and illustrations may be obstructive.

![Figure 1. Setup of the Mirascope.](image-url)
The Mirascope: an explanation on a conceptual level

3. The Mirascope and the phenomena behind

This chapter focuses on the physics behind the Mirascope. Therefore, it aims to describe the concepts behind the phenomena on a conceptual level. Following this purpose, a software will be introduced which supports the ideas of explanation. Moreover, this should lead to a better understanding of the phenomena caused by the Mirascope.

3.1. Fundamental principles behind the Mirascope

Before focusing deeper on the explanation, it seems worthwhile to think about the fundamental ideas behind the phenomenon. First, the concept of image formation and the concept of reflection of light by mirrors is essential. Second, image formation on concave and convex mirrors plays a major role. Finally, the concept of real and virtual images is important in order to understand several phenomena.

Following these thoughts, knowledge about the simple mirror equation (1) and the magnification equation (2) seems additionally helpful for supporting learners learning processes.

\[ \frac{1}{o} + \frac{1}{i} = \frac{1}{f} \]  
\[ M = \frac{i}{O} = -\frac{i}{o} \]

(\(o\) is the object distance, \(i\) the image distance, \(f\) the focal length, \(I\) the image height, \(O\) the object height, and \(M\) the magnification)

It must be mentioned, that image formation concerning convex and concave mirrors can be addressed beforehand as well as within the learning arrangement using the Mirascope at every point when it appears to support the learners understanding.

Moreover, it seems worthwhile for the teacher to keep in mind that combining two concave mirrors—like within the set-up of an ideal Mirascope—resembles a focal symmetric resonator.

3.2. Approach for the explanation of the real image

As mentioned in section 2, currently existing explanations do not address the phenomenon in an appropriate way. In this chapter, approaches for an adequate explanation of several connected phenomena concerning \(I_{O\text{-real}}\) will be given.

The first phenomenon that is addressed is the opposite orientation of \(I_{O\text{-real}}\) and the object itself. Therefore, representations including several light rays seem to address the demand of the explanation of the phenomenon of orientation change of the object (\(O\)) and the image (\(I_{O\text{-real}}\)). The interactive mathematical software GeoGebra could be one solution to address the conceptual clarification of the orientation change phenomenon. Alternatively, to GeoGebra, the 2D-simulation software Algodoo\(^2\) or the Geometry Software Cinderella\(^3\) may be used. Nevertheless, main arguments for using GeoGebra are: Firstly, the software and additional materials are freely accessible online \([2, 5]\). Secondly, its handling is intuitive and easily applicable. Thirdly, the online pre-prepared interactive worksheets make it possible to implement the materials in physics classes easily. Therefore, the modelling and illustration of the image formation of \(I_{O\text{-real}}\) can be performed with little effort. A detailed manual for how to use GeoGebra concerning the here mentioned modeling processes can be found in the appendix.

Figure 2 shows a ray model generated with a GeoGebra interactive working sheet accessible online. Within this working sheet, it is possible to generate a drawing of an object (blue) while simultaneously the formation of the image is generated (red). Within this application, it is possible to illustrate different light rays. Additionally, it is feasible to analyze how the image point will change its position when changing the distance between the mirrors (see figures 3 and 4). The shorter the distance of the two mirrors the higher the generated image, the greater the distance the

\(^2\) See: http://algodoo.com (19 April 2019).

\(^3\) See: https://cinderella.de/tiki-index.php (19 April 2019).
lower the image. The last phenomenon can easily be observed at the real device by moving the top mirror vertically up (and down). The downward situation is impossible to realize since the two mirrors would crush.

Even the limitations of the image formation itself and the generation of a clear image can be qualitatively investigated with this interactive GeoGebra working sheet. The intersection or divergence of the light rays can be illustrated in different distances of the mirrors or with different object locations (in all directions).

As mentioned before, the Mirascope generates a slightly bigger image of the object. Within the ray model generated with GeoGebra (see figure 2) this observation can be illustrated. Additionally, the description of the way a light ray takes when reflected by the bottom mirror first, can be addressed and carefully thought through.

Taking learning difficulties in optics into account [6] the illustration of the way of light by the means of light beams (see figure 5) should be considered and adequately addressed.

3.3. Approach for the explanation of the virtual image and the phenomenon of magnification

So far, the real image and the model of its formation have been described. As the surface of the

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4 See: https://maa.org/press/periodicals/loci/modeling-the-mirascope-using-dynamic-technology-4-using-the-simulation-explorations-and-exercises (19 April 2019) and https://geogebra.org/m/5TxYNCCr (19 April 2019).
Figure 4. Distance of the mirrors is shorter than the focal length.

Figure 5. Illustration with light beams.

Figure 6. The setup of the Mirascope with the real and the virtual image.
bottom mirror is also imaged, there is a virtual image ($I_{O\text{-virtual}}$) of the real image ($I_{O\text{-real}}$) generated as well. Due to the ordinary perception of the virtual image, it seems obvious to provide an illustration of the Mirascope where the virtual image is added. Therefore, figure 1 was amplified with the virtual image of the object ($I_{O\text{-virtual}}$). The illustration of the setup of the Mirascope with both perceptible images ($I_{O\text{-real}}$ and $I_{O\text{-virtual}}$) is shown in figure 6.

The explanation of the formation of $I_{O\text{-virtual}}$ is as follows: As the surface of the bottom mirror
the virtual image (\(I_{O\text{-virtual}}\)) of the real image of the object (\(I_{O\text{-real}}\)) follows the image formation rules of a convex mirror. Therefore, \(I_{O\text{-virtual}}\) is smaller than \(I_{O\text{-real}}\). The image formation of the virtual image of the bottom mirrors surface can be seen in figure 7. The overall image formation is shown in figure 8 and an additional enlarged detailed image construction (like the image formation with a convex mirror) is shown in figure 9. The latter shows the slightly shifted virtual image point and consequently, the conclusion of a smaller virtual image is explicable.

Therefore, besides the explorative approach using GeoGebra, the explanation of magnification of the images \((I_{O\text{-real}}\) and \(I_{O\text{-virtual}}\)) can be qualitatively supported by equation (2).

As mentioned above, another difference of size can be detected while observing the phenomena of the Mirascope—the size of \(I_{O\text{-real}}\) in comparison with the object \((O)\). Taking a closer look at figure 2 will help to understand the object-real image phenomenon in more detail. First, \(I_{O\text{-real}}\) seems just stretched vertically, but a closer observation of the enlargement exposes more. A closer look at image of the H—generated in figure 2—shows that \(I_{O\text{-real}}\) of the object H is slightly leaning. As \(I_{O\text{-real}}\) is 3D this slight leaning of \(I_{O\text{-real}}\) happens all around the image generated.
by the Mirascope. Consequently, the real image of the object ($I_{O\text{-real}}$) is extended radially outward. Hence, it is bigger than the object itself.

So far, the main aspects and perceptible phenomena of the Mirascope have been examined carefully and explained on a conceptual level. The illustrations of the mathematical software GeoGebra support these explanations. The next section will reveal hints for further investigation with everyday life items.

4. Ideas for an experimental investigation

The Mirascope represents a device of numerous observable and interesting phenomena. As the previous chapter has covered the main conceptual background for an understanding of these phenomena, it seems beneficial to enrich this theoretical background with practical implementation. Thus, this chapter addresses the demand of an experimental investigation of obvious observable phenomena and explicates experiments with everyday life materials.

4.1. Real and virtual image

First, one has to be very attentive while observing. If a very flat object is used (e.g. a coin), both images ($I_{O\text{-real}}$ and $I_{O\text{-virtual}}$) are very flat and may be perceived as just one image (see figure 10) due to their thickness. Using figures or marbles as objects will bare a better option when observing the two images (see figure 11).

Second, it seems obvious to investigate if real or virtual images or both are generated. Prior to deeper investigation of the images, the properties of real and virtual images have to be addressed briefly: Light coming from real images always comes from the location where the image occurs. Thus, divergent light rays can be perceived coming from one image point. When following these light rays straight back to their origin these light rays lead to the same image point. Consequently, the detection of light rays at the location of a real image is possible. In contrast, at the location of a virtual image no light rays can be detected. Thinking of a plane mirror, the virtual image is generated behind the mirror. Therefore, it is impossible that light rays originate within or behind the wall of the mirror. The light rays perceived while looking at a mirror take an indirect way into our human eye (reflection on the surface of the mirror). The human eye perceives the divergent light rays reflected at the surface of the mirror. Therefore, we detect the same information from different directions and no information about the origin of the light rays. The same process—following the extension of these light rays—as with perceiving real images takes place here. Behind the mirror, a point is found where all virtually extended light rays of one object point intersect. Consequently, the information seems to come from that intersection point resulting in perceiving a virtual image at the location where the light rays appear to originate.

Real and virtual images in an educational environment are for instance mentioned in the context of the image formation of lenses. In this case, 2D real images are generated and projected onto a screen and one characteristic of virtual images is the impossibility of projection on a screen. As the Mirascope generates a real 3D image, it is also impossible to get an image on a 2D screen. However, parts of the image should be detectable on a sheet of paper. As non-self-luminous objects are faint concerning their light emission, the detection of any image on a white paper is unobservable with human eyes. Therefore, the use of self-luminous objects like LED-lights is strongly recommended for the experimental verification of the 3D-image as a real image. LED-lights placed as objects on the bottom mirror and a piece of paper, placed in the area of the real image, lead to the detection of light points on the paper. Holding the piece of paper in the observed location of the virtual image, no light points can be detected (see figure 12).

4.2. Real image formation

The experimental analysis of the process of image formation with everyday life materials is a challenge. Nevertheless, one approach for a qualitative investigation can be following this question: ‘What would happen if half of the area between the mirrors of the Mirascope was covered with a sheet of paper’ (see figure 13).

Standing on the side of the sheet of paper (in figure 13 looking from West to East), it is possible to see the whole image of the object (as always
The Mirascope: an explanation on a conceptual level

![Image of Mirascope with virtual and real images]

**Figure 11.** Images of marbles and a figure.

![Image of Mirascope with real image and paper piece]

**Figure 12.** Verification of the real and virtual image with LED-lights and a piece of paper.

![Image of Mirascope with covered mirrors]

**Figure 13.** Covering half of the mirrors with a sheet of paper.

aligned in the other direction). Looking from the other side (East to West) it is impossible to perceive an image of the object. The view from South to North, leads to the observation that a view slightly on the Western side allows to perceive an image. When changing the view slightly to the Eastern side (still looking mainly from South to North) the image disappears. Consequently, the light rays reaching our eye come from the left part of Mirascope. Otherwise, no perception of the image would be possible. In other words, when looking from the other side it is not possible to detect an image because there is no way for the light rays to reach the human eye. Changing the point of observation gives a lot of information about the angle and the places where the image can be detected.

In order to investigate the orientation of the real image compared to the orientation of the object, a piece of paper with several different markings in the corner is suitable (see figure 14). The detection of the reversed view of $I_{O,real}$ in comparison of the object is observed. Therefore,
the light rays have to come from this direction via several reflections into our eye.

4.3. Virtual image formation

The origin of the reason for the virtual image is very easy to investigate. As known, the real image of the surface of the bottom mirror can be seen as a real image of a convex mirror. As a result, the diverging light rays of the real image of the object ($I_{O\text{-real}}$) are reflected at the real image of the surface of the bottom mirror. Consequently, a virtual image can be perceived (see figures 8 and 9). To conclude, the projection of the surface of the bottom mirror causes the virtual image $I_{O\text{-virtual}}$ of the real image $I_{O\text{-real}}$ of the object ($O$). In order to prevent the formation of this virtual image the surface of the bottom mirror has to be changed. Hence, when putting a piece of paper under the object, a real image of the paper is projected and as paper disperses light in every direction, no mirror imaging takes place and just one image can be detected (see figure 15).

4.4. Other phenomena

One more very fascinating phenomenon needs to be mentioned. A short string laid out straight on the surface of the bottom mirror results in an observation of a bent string (see figure 16). After pondering about the phenomenon, it is not surprising to see a bent string. Because of the curved bottom mirror the string has to be curved.

Additionally, as the Mirascope has two concave mirrors every investigation concerning image formation with concave mirrors or finding the focal point can be done as well.

5. Conclusion and perspectives

This article takes a conceptual and investigative view on the Mirascope. It gives a basic explanation on a conceptual level as well as easily realisable investigation hints for observable phenomena. There is no claim for any completeness neither on the level of explanation nor on investigation ideas. The focus lies on a description on a conceptual level which can be used in educational contexts.

It is commonly known that the Mirascope is a very complex device concerning an exact light ray analysis but it can also be seen as a device for triggering learning processes in optics. Therefore, this article aims at giving an idea of explanations on a conceptual level. In a next step, the implementation of a learning environment about the Mirascope following an inquiry-based approach in physics (teacher) education is planned. Additionally, further research will be conducted to gain insight in students’ learning processes while experimenting with the Mirascope.
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Appendix. Instruction guide for the GeoGebra worksheet

In this appendix, a short introduction of how to use GeoGebra is given in order to generate images such as the ones shown in the article. Therefore, the description focuses on the steps needed to use the worksheet properly.

(1) Use the URL to start the worksheet:

You can either use the GeoGebra worksheet online within a web browser (www.geogebra.org/m/dN5A3ucu) or you can download the worksheet (www.geogebra.org/material/show/id/dN5A3ucu) and then open it with the GeoGebra Software previously installed on your computer.

When you first install GeoGebra Classic (www.geogebra.org) and start the program you may see the interface as in figure A1. By clicking on the highlighted button, a menu pops up where you have to click on ‘Open’ and select the prior downloaded file of the worksheet.

(2) User interface of the used GeoGebra worksheet—a short introduction:

Figure A2 shows the interface of GeoGebra and its different parts. The construction/plotting area shows the generated objects. This area is important within the used worksheet. The toolbar provides several tools needed for generating geometrical objects. All objects used in the current construction are shown within the left column. The colored points show the color of the object in the construction area. By clicking on these points, you can decide if you want to show the items in the plotting area or hide them. The input area can be used to type in any object (straight lines, functions, etc.), which will be shown in the construction area.

(3) Parts of the construction / plotting area of the worksheet:

Within the above article GeoGebra is mainly used for the purpose of illustration and modeling of light ray ways occurring at the Mirascope. So the focus is to describe the steps of construction within the used worksheet. Therefore, the shown objects of the worksheet (see figure A3) will be shortly explained.

- **P**: an object point (shiftable point by dragging)
- **J**: an image point (is not moveable)
- **H, G**: points of reflection on the upper mirror (shiftable points by dragging)
- **I, E**: points of reflection on the bottom mirror (is not moveable)
- **b, d, e**: one light ray way
- **i, m, q**: one light ray way
- **p_u**: parabola which describes the bottom mirror
- **p_d**: parabola which describes the upper mirror
- **slider c**: distance between the bottom and the upper mirror
- **slider a**: curvature of the two parabolas

(4) Editing objects:

A right click on a geometrical object opens a side menu (see figure A4). Within this menu, you can decide (by ticking off) whether you...
I Krumphals

Figure A1. Interface of GeoGebra Classic.

Figure A2. GeoGebra interface.
Drag $P$ to draw a small picture; Right click on $P$ or $J$ to toggle trace On.

Figure A3. Used GeoGebra worksheet.

Figure A4. Editing objects in GeoGebra.
want the label of the object to be shown or the object itself. Additionally, ticking off ‘Show Trace’ leads to a trace being shown when the object is moved. By ticking off ‘Show trace’ at point $P$ and $J$, the drawing illustrating the object placed in the Mirascope will be shown while simultaneously the formation of its image will be generated (see figure 2 in the article). Furthermore, irritating or unessential labels for the learning process of the students can be hidden. The labelling of the created objects within any construction process can differ. If you want to stay with the labels used here you have to rename your objects (right click on the object and select the ‘Rename’ function).
(5) **Using the sliders:**

As mentioned in section 3, by means of the two sliders, parameters like the distance and the curvature can be modified and their effects on image formation can be investigated.

The equations for the two parabolas are $p_u = -ax^2 + c$ (upper mirror) and $p_d = ax^2$ (bottom mirror). The parameters $a$ and $c$ can be investigated systemically.

Figures A5 and A6 show the image point at $c = 1$ and $c = 2$ (see also figures 3 and 4 in the article). When parameter $a$ becomes bigger, the image point shifts downwards (see figures A7 and A8).
(6) Generating intersections—modelling the virtual image (recommended just for instructors):

It is recommended that the instructor prepares figures 8 and 9 of the article beforehand unless the students know GeoGebra very well and have fundamental knowledge of image formation on convex mirrors. Only then does it seem useful/feasible to assign this advanced task to students.

Figure A9 shows the overall generation of a virtual image point. The generation process is as follows:

Tools for generating figure A9:
In order to generate figure A9, three main tools are needed (see figure A10):

a) Generating a line with two given points:
Click on the tool ‘Line’ and then on two points in the construction area. A line will be created going through the two points.
The Mirascope: an explanation on a conceptual level

b) **Plot a point**: Click on the tool ‘Point’ and just click on a point in the plotting area to create a point right there.

c) **Intersect objects**: Use the tool ‘Intersect’ and click on the two objects you want to be intersected. The point of intersection will be created.

Steps for the generation of figure A9:

1. Create the focus of the upper mirror. It can be generated with the tool ‘Point’ at (0,0). Make sure that the point F is precisely at (0,0) by checking this in the input area of mathematical objects used for the construction. If necessary correct it to (0,0) by double clicking and typing in the required coordinates.

2. Create a line (the focal ray) with the points J and F.

3. Intersect the focal ray with \( p_d \). The intersection point \( K \) will be created.

4. Create a line parallel to the y-axis going through \( K \) (e.g. by defining an extra point \( M \) on the x-axis with the coordinates \( (K_x, 0) \) and create a line between \( K \) and \( M \) (parallel ray)).

5. Make a second parallel line through \( J \) (e.g. via the fourth tool on the tool bar, alternatively step 4 can be repeated with point \( J \)).

6. Intersect the parallel line through \( J \) with \( p_d \). The intersection point \( O \) will be created.

7. Create a line by connecting \( O \) and \( F \) (second focal line).

8. Intersect the parallel ray through \( K \) and the focal ray through \( O \). The **intersection point is the virtual image point** \( V \).

**Figure A10.** Tools used for generating the virtual image point.

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I Krumphals

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