CONSIDERATIONS ON NEWTON'S AND GOETHE'S THEORIES OF COLOR[1]

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1. Introduction

This article originated from an email commenting on some aspects of Newton's theory of light and Goethe's theory of color, which I sent to the interesting *Boletim Dia e Noite* [Day and night bulletin], edited by astronomy students from the Astronomy, Geophysics and Atmospheric Sciences Institute (IAG) of the University of São Paulo (USP), regarding articles published in the Bulletin. In response, one of the bulletin's editors invited me to write an article of no more than four hundred words for publication. I started authoring the article, and in the first draft it was already around nine hundred words long. Then I gave up on limiting myself to four hundred words, and as ideas came, I kept adding to it. The first, almost final, version had no structure, so I decided to reorganize everything, dividing the topics into sections, and took the opportunity to insert more text and figures. Since this article is very much on my mind, I have often had new ideas of what to include in it, so it is interesting for the reader to always use the latest version.

This article is organized as follows. It first discusses Newton's theory of light, which was based on a very particular experiment using triangular cross-section prisms and invites the readers to conduct their own experiments with a prism. It then presents a brief history of how Goethe arrived at his theory, and how it generalized Newton's basic experiments. It also presents various aspects of Goethe's theory, such as the color circle, complementary colors, colored shadows, afterimage, and the origin of colors, with comments on Goethe's scientific method and on other areas of scientific research, and the practical application of his theory.

All translations of non-English quoted excerpts and book or article titles are *ad hoc* translations.

2. Newton's theory of light

Newton (1643-1727) published his theory on colorless or white light in his book *Opticks* of April 1st, 1704, with a second edition in 1717 [see reference]. In it, he sets out a formal theory, with definitions, axioms, propositions, and theorems.

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[1] Original in Portuguese: https://www.ime.usp.br/~vwsetzer/Goethe-vs-Newton.pdf

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However, he started from an extremely particular experience. In Prop II, Theor. II. Exper. 3, he describes it as follows (sic):

> "In a very dark Chamber, at a round Hole, about one third Part of an Inch broad, made in the Shut of a Window, I placed a Glass Prism, whereby the Beam of the Sun's light might be refracted upwards toward the opposite Wall of the Chamber, and there form a colour'd Image of the Sun."

(By the way, it should be noted that English was probably written then as German is today: with nouns capitalized.)

Therefore, Newton started from a certain beam of light (in this case, sunlight) immersed in darkness (his dark room).

The colors described in this experiment are the seven normally mentioned, seen in a rainbow, in the sequence, red, orange, yellow, green, light blue, dark blue, and violet.

It is interesting to note that the hole in the solid window was later referred to as a *Foramen exiguum*, a tiny hole. However, it was not small at all: one-third of an inch is a little more than 8 mm, that is, it could have been much smaller. Newton makes a mistake in this chapter of the book:

> "Now the different Magnitude of the hole in the Window-shut, and different thickness of the Prism where the Rays passed through it, and different inclinations of the Prism to the Horizon, made no sensible changes of the length of the Image. Neither did the different matter of the Prisms make any. …"

All these factors influence the image obtained by passing a beam of light through a prism in a dark environment, not only in terms of the size of the image but also in the colors produced. This can be easily verified by using a prism placed with its axis in the horizontal and looking through it at the figures below, paying attention to the colors that appear on the borders between black and white, ignoring other colors that appear in other transitions of black lines with the white background, and varying the distance from the prism to the figures and its vertical rotation. The white stripes function as the hole used by Newton. It is necessary to find the correct inclination of the prism to see the dispersion in the colors, because with certain inclinations in relation to the eye and the object being observed, it acts like a mirror – used in certain binoculars to correct the image, which would be inverted without the prism.


Fig 1a


Fig1b

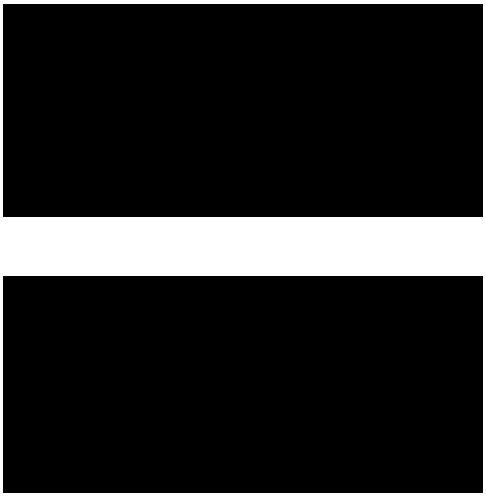
Fig 1c

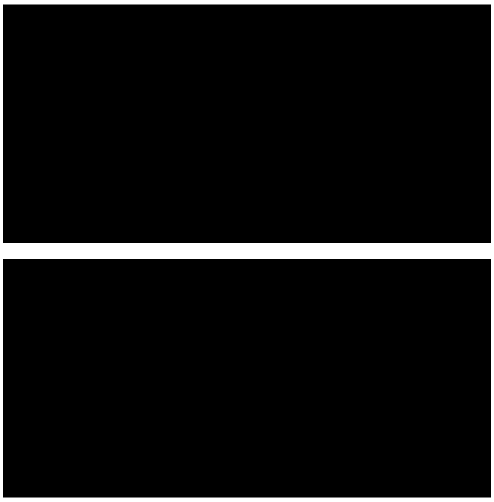
Fig 1d

The material of the prism and the angles of its triangular cross-section also alter the images.

These same experiments can be performed with sheets of white and black paper, acting as light and darkness, respectively. Take one sheet of white paper and two sheets of black paper (e.g., plastic covers used to assemble spiral notebooks). By placing the black sheets, with parallel edges, on the white paper and looking at the white stripe through a prism, with its axis parallel to the edges of the stripe, one can see the colors of the dispersion. By moving the black sheets apart, as in Fig. 1a, leaving a relatively wide beam of white and looking at it through the prism, the person will see red, orange, and yellow on the side of one of the black sheets, in the direction of the white stripe. On the other side of the white stripe, s/he will see violet, dark blue and light blue (yellow and light blue are on the side of the white stripe because they are light colors, unlike red and violet, which are dark, on the side of the black). Note that the colors on one side of the white stripe are quite symmetrical to those on the other side. By bringing the two black sheets closer together, decreasing the width of the white beam, at a certain point the light blue will touch the yellow.

Perhaps this effect is produced by looking at fig. 1b or 1c; in these, one can also change the distance of the prism to the video screen, keeping it close to the eye. Narrowing the white stripe a bit more, there is an overlap of light blue with yellow. Green appears – the overlap of the "colors of light" ("colors of light" as opposed to the "colors of pigments" of paints) yellow with light blue gives green, as it could not be otherwise. These are the seven colors of the rainbow, as seen by Newton in his specific experiment. By bringing the black sheets even closer, at a certain point only the RGB colors (red, green, blue) appear! Perhaps Fig. 1d gives this effect. So, according to Newton, should one say that "white" light is composed of the seven colors or just RGB?

Therefore, the general experience is having a white stripe wide enough to leave white between the colors, with dispersion appearing at the edges between light and darkness. The rest is a particular case, easily understood by the superposition of 'colors of light'. Thus, Newton started from a very particular situation to derive his entire theory, the core of which would be the fact that colorless or white light is composed of "all colors." In fact, it would be just the seven colors of the rainbow that do not have distinct boundaries since the transitions are continuous.

3. Newton's experimentum crucis

Based on his own experiments, Newton formulated the theory (note, this is not a scientific fact, it is an interpretation, it is a theory!) that colorless or white light is composed of the colors of the rainbow. It is wrong to say that it is composed of "all colors." According to him, each color has a different degree of refraction (refrangibility), and thus the prism decomposes colorless or white light into its different components. In his book, in Prop. II, Theor. II, he wrote: "The Light of the Sun consists of Rays differently Refrangible." In his experiments, he always used beams of sunlight passing through prisms in a dark room, that is, he used beams of light immersed in darkness.

At the end of an interesting article published in the Am. Journal of Physics, Torger Holtsmark [1970] wrote: "The basic contradiction involved in Newtonian terminology seems to be this: Newton thought that he explained the existence of a spectrum by means of a physical model of light, whereas he in fact used the image of the spectrum to explain one possible physical model of the light."

To demonstrate that the colors resulting from his experiment were "pure" and could not be decomposed, Newton devised what became known as the *experimentum crucis* (Prop. II, Theor. II, Exper. 6), in which he used two prisms. Isolating a color produced by the first prism, always in a dark room, he noticed that the second prism did not decompose it, that is, it was “pure.” See more details in section 7 below. We will see later how Goethe criticized this result.

4. Goethe appears

Goethe, known for his extraordinary literary and poetic work, was, however, a great scientific observer, for example having discovered the intermaxillary bone. His scientific method begins with a completely unbiased observation on the part of the researcher, that is, the researcher must observe a phenomenon and describe it without being interfered with by his preconceived ideas or judgements. This would be a “pure observation;” therefore, his method is phenomenological. According to him, the observer should wait for the phenomenon itself to reveal something of its nature.

A typical example contradicting this method was Darwin's theory of evolution by natural selection. He imagined something extremely simple, easily understandable physically, hence the persuasive power of his theory: the individuals best adapted to the environment survive better and, as a result, leave more descendants, who inherit their characteristics and become increasingly adapted as the generations pass. Darwin was not present during the steps of evolution to prove his theory, which, therefore, in Goethe's sense, was not phenomenological. Today, there is much evidence of this selection of the most adapted, such as in the case of birds that migrated between islands, bacteria that became more resistant to antibiotics, etc. However, it is important to recognize that no one has followed or follows the two factors that lead to selection: genetic mutations (neo-Darwinism) when they occur and, in the case of animals, the meeting of a couple for selection to occur. However, most scientists refer to neo-Darwinian evolution to justify anatomical and physiological changes over time. Worse still, they use the same reasoning in several areas, such as for social evolution, the so-called “social Darwinism,” for example to explain the consequences of structural racism in Brazil. A possible extension of Darwinian theory is that not all mutations and meetings of couples were random, as widely assumed in scientific and academic circles. With this, one can admit that evolution had an objective, to reach the human being, clearly a pinnacle of evolution. That is, evolution would have been directed, at least partially. An objective is completely excluded in classical Darwinism, which is based on randomness. Furthermore, an objective would be an idea and would transcend the physical world.

Having mentioned Darwinism above, it is interesting to note that Darwin was not the only one to formulate the theory of natural selection. The famous British biologist and naturalist Alfred Russel Wallace (1823-1913) had developed the same theory in parallel with Darwin. Both published articles on the subject in the same issue of the *Journal of the Proceedings of the Linnean Society* in 1858, cf.

the excellent biography of Darwin by Johannes Hemleben [1976, p. 101]. However, Russel Wallace is generally ignored. How many high school students have learned that the theory of natural selection is due to Darwin and Russel Wallace, and not just to the former? Perhaps this is due to the fact that the latter was a spiritualist; he was a non-religious spiritist (Kardecist). When he went to teach biology courses in the USA he also ended up teaching courses on mediumship, declared that natural selection should not be applied to human beings, and this was enough for everything else being almost ignored. In fact, this had already been expressed by Pascal (1623-1662): "It is dangerous to point out too much the kinship of the human being with the animal, without at the same time recognizing its greatness." [p. 153]. Interestingly, Darwin was a theist [p. 150]. About Russel Wallace, see the Wikipedia article [Wallace] in the references.

Neo-Darwinian evolution has become practically a dogma in academic and scientific circles. Another example of dogma is precisely Newton's theory that colorless or white light is the composition of the seven colors of the rainbow (or the continuum between them).

Returning to Goethe, the famous physicist Herman Helmholtz (1821-1894) in a lecture in 1853 [1889] tells how Goethe described how he became interested in prisms and the origin of colors. At the end of his excellent edition of Goethe's color theory [Goethe 1971], Ruprecht Mattatei has a chapter "On the Author's Confession", transcribing a selection of what Goethe wrote about the history of his color theory at the end of one of his books. Goethe reveals several interesting passages from his life. In No. 7 he tells the story reported by Helmholtz. As a curious scientific observer, he wanted to study Newton's theory of light, which he had learned at the university, and borrowed a box with some prisms from a friend, *Hofrath* [court counselor] Bütter, from the city of Jena, near Weimar, Goethe's city. He left these prisms aside, until his friend, tired of asking for the prisms back, sent a letter with a messenger to get them.

In front of the messenger, Goethe picked up a prism and looked through it for the first time. Pointing it at a wall, he found that there was no dispersion in colors, which disappointed him; however, he realized that there was dispersion wherever there was a color boundary between or within objects. "The windowsills, against the light of the cloudy day, presented the most intense colors." At that moment he had an inspiration that the boundaries between colors were fundamental to the appearance of colors through a prism, and that "by an instinct I heard a voice that Newton's theory was wrong."

The case of the white wall was a mistake by Goethe, as pointed out by Helmholtz [1889], but it did not harm what Goethe researched later. He did not return the prisms and began to do his experiments, which culminated in his book *Farbenlehre* [Theory of Colors], from 1810 [1980; see also excerpts in 1971 –

this work with many comments and colored plates –, 1992 and 2011]. For Goethe's theory of colors, see the references Ott [1979], Pedrosa [1982], Proskauer [1968] and also the very interesting and detailed video by the physicist PehrSall, where he documents extremely well the experiments thoroughly reported by Goethe, not only with prisms. It is interesting that these experiments were never contested.

In the work mentioned above by Hemlholtz, which seeks to reduce Goethe's scientific importance by considering him primarily as a poet, he analyzes not only the theory of colors, but other research by Goethe, such as his anatomical studies (which led to his discovery of the intermaxillary bone) and his well-known Metamorphosis of Plants of 1790 [Goethe 2020]. On Goethe's scientific work in general, see [Steiner 1984].

Goethe's mistake in finding it strange that the prism did not produce color dispersion when looking at a white wall is explained by Helmholtz by the fact that each particle in the wall produces dispersion, but so do its neighbors, thus creating a composition of colors that produces white. From the point of view of Goethe's theory, in this case there is no dispersion because there is no color transition, or, as will be shown, a transition between a lighter color and a darker one. It is worth noting that Helmholtz's explanation is based on reductionism, the existence of particles, unlike Goethe's, as it will become clear later.

5. Goethe generalizes Newton

As shown above, Newton's experiments dealt with a beam of light of a certain diameter, immersed in darkness, passing through a prism in certain conditions. Goethe generalized (1) to beams of light of any diameter; and (2) to beams of darkness immersed in light. Thus, Goethe showed that Newton had developed his entire theory based on a very particular case. Case (1) has already been described in section 2 above, using a white stripe flanked by black stripes, on a video screen or by a white sheet beneath two black ones, varying the width of the white stripe.

Case (2) can be verified by anyone, using the colors white instead of light, and black instead of darkness. The figures below show black stripes between white parts, the dual situation (in terms of light and dark) of Newton's experiments.

Fig. 2a Fig. 2b

Fig. 2c Fig. 2d

Looking at these figures with the axis of the prism positioned horizontally, one can notice the dispersions of colors on the upper and lower edges of the black stripes. Analogously to the cases of the white stripes in Figs. 1a-1d, one can take a sheet of black paper and two sheets of white paper on top of the first, forming a black stripe. This is the dual situation of the one made with a white stripe. If the black stripe is very wide, as in Fig. 2a, looking at it through the prism one can see the dual situation in relation to the white stripe in Fig. 1a. A black stripe appears with the darker colors, red and violet, on the border with the white part. In the case of the white stripe in Fig. 1a, next to this stripe and inside it, the lighter colors, yellow and light blue, appear.

In Fig. 2a, the colors are inverted, again with the lighter colors near the white part, and the darker colors near the black part. As the white sheets get closer, and the black stripe decreases, there comes a moment when the red touches the violet. As the white sheets get even closer, the red overlaps the violet, giving rise to the wonderful magenta color, which Goethe called *Pfirsichblüte* (peach blossom). Goethe called magenta the “complementary color” of green (see section 6 below). In this situation, instead of the seven colors of the rainbow, starting from the border with a white sheet, we have light blue, dark blue, violet, magenta, red, orange, and yellow. Thus, light blue is complementary to red, and so on.

As the white sheets come even closer, reducing the height of the black stripe, at a certain point only three colors appear: violet (cyan), magenta and yellow, abbreviated as CMY, the complementary colors (according to Goethe) of those obtained in the very narrow white stripe. Perhaps Fig. 2d shows this effect.

Figs. 1a-d and 2a-d were generated with MS PowerPoint by creating two screens. One of them with two horizontal rectangles filling the entire screen with black but leaving a horizontal white stripe between them. On the other screen, only a horizontal black rectangle was inserted in the middle of the white screen. The axis of the prism must be kept horizontal. With this, it is possible to vary the height of the white rectangle on the first screen, and of the black rectangle on the second, and observe the situations described for the sheets of paper.

Using MS PowerPoint, one can do some very interesting experiments. For example, instead of black rectangles, fill them with shades of gray. One should observe that the same dispersion of light or darkness in the colors described will still be seen but these colors will be a little faded, precisely as described by Goethe. In the first screen, instead of a white stripe between the black rectangles, one can create another rectangle to represent the stripe. Using the three rectangles, these can be filled with various colors, and one will notice that there will always be some dispersion of colors on the border between two different colors, as observed by Goethe, noting that these two colors influence the intensity of the colors obtained through the prism.

The following figure shows the situation of the second screen (a black stripe, corresponding to a beam of darkness immersed in light) in a photo taken with a cell phone almost touching a prism with 60º angles; the curvature was produced by the lens. Unfortunately, the colors are distorted; for example, in the lower part, the transition from yellow to red passing through orange is not clearly visible.

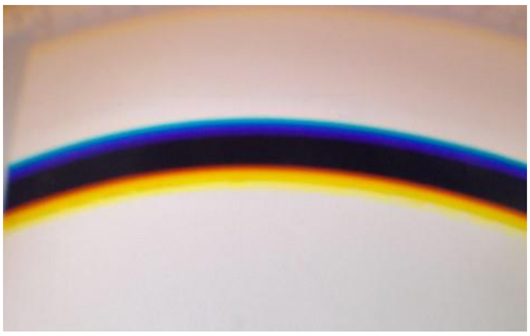

Fig. 3

Fig. 4, copied from PehrSall's excellent video, shows the transition situations from dark to light presented in the figure on the left, and on the right the result as produced by a prism, including, below, the result with very thin beams.

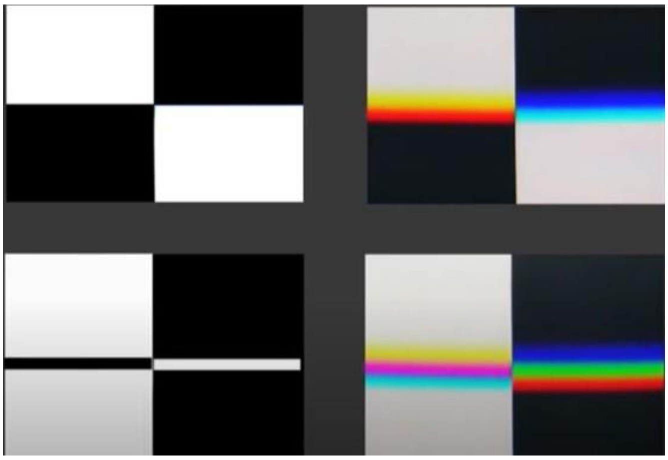

Fig. 4

It is important to note that on a video screen the color resulting from the mixture of red, green and cyan colors of light (each with maximum intensity, 255 in the code of intensities from 0 to 255 represented in the computer in one byte for each of the three colors) is not really white, having a shade of light gray.

Using a screen produced in Power Point, it is possible to obtain an almost continuous variation in the heights of the stripes, noting in the first case what happens when progressively decreasing the height of the white stripe, and in the second case that of the black stripe.

6. An application of Goethe's theory

An interesting application of Goethe's theory is the colors used in video monitors and printers. On video monitor screens, RGB is used as the basic colors, and on printers, CMY is used as the complementary colors. Goethe's theory helps us understand why these colors are used. In the case of screens, there are colors that are light on a dark background, the screen without light – black is produced by the absence of the three RGB colors (0 value for the three *bytes* of these colors). In the case of printers, there is a dual situation: colors that are dark in relation to white paper. Using the basic colors in each case results in a better effect.

Note, however, that mixing the seven "colors of light" of the rainbow does not produce white, but rather a light gray shade, as can be seen in computer screens. The composition of the RGB light colors also produces a slightly grayish tone. The

CMY color composition should produce black, but the result is somewhat grayish. For this reason, a black ink cartridge is used in addition to CMY ink cartridges, also bearing in mind that black ink cartridges cost less than color ink ones.

On the pages of the newspaper "O Estado de São Paulo," one of the most important ones in Brazil, on the left side of each double page, four small adjacent squares appear, from top to bottom, in the colors light blue, magenta, yellow and black respectively. Now the reader can understand the mystery of these squares. Probably during printing someone (or an automatic system) checks whether these colors are adequate, because otherwise the colored photos and letters would not look good.

7. Light-Newton and Dark-Newton

From what has been seen, if Newton had used a beam of darkness immersed in light, instead of a beam of light immersed in darkness, he would have done his entire theory, but with complementary colors according to Goethe's theory of colors. In section 3, Holtsmark [1970] was quoted as saying that Newton used the images of the spectrum to derive a particular physical model of light. If he had used a dark beam, he would have had another physical model of light.

It is worth noting that all the experiments reported in *Opticks* can be done with dual situations, using beams of darkness immersed in light, obtaining the complementary colors.

André Bjerke's interesting book [1961] contains a table, showing dual situations, with two columns, called "*Licht-Newtons 'Optik'* [Light-Newton's optics]" and "*Dunkel-Newtons 'Opakik'* [Dark-Newton's opacity]", where he shows in the first column 10 examples from Newton's book and, next to it, in the second column, the same formulation by Newton but exchanging light for darkness, and the colors for their complementaries [pp. 86-88]. It is worth citing the first line of this table, as an example (the translation is from Bjerke's book, which summarizes the corresponding passage from *Opticks*):

First theorem

Light-Newton *(Opticks)*	Dark-Newton (*opacity*)
"Lights, which are different in color, also show different refractions, with gradual transitions." Red is the least refracted, violet the most.	"Shadows, which are different in color, also show different refractions, with gradual transitions." Light blue is the least refracted color, yellow the most refracted.

One of these dualities brings the *experimentum crucis* (see section 3 above), in which Newton used two prisms with orthogonal axes, showing that in the second there was no dispersion of the beam of light reduced to one of the colors of the spectrum, wanting to prove that these colors were not composed of others. For a long time, this experiment was a headache for the Goetheans who researched the theory of colors, because with a beam of darkness falling on the first prism, the second prism decomposed the complementary colors.

André Bjerke [1961] reports that the problem arose because the beam of darkness falling on the first prism used a bright environment, while on the second prism the isolated color was immersed in darkness, mixing Goethe's situation in the first prism with Newton's in the second prism. The problem was solved by immersing in light each color produced by the beam of darkness after passing through the first prism, and then it did not decompose. That is, Goethe's theory is coherent if the same conditions are preserved throughout all the experiments.

In the table described above, Bjerke presents the *experimentum crucis* and its dual:

Sixth experiment: *"Experimentum crucis."*

Light-Newton (*Opticks*)	Dark-Newton (*Opacity)*
Objective experiment: a small *clear image* with a *dark background* is refracted by a prism. A thin colored beam of the light spectrum is selected by means of a small hole in a screen, which is placed in the path of the light, in front of the prism. The colored beam passes through a new small hole in screen No. 2, then through prism No. 2 – placed parallel to the first – and is projected onto a third screen. With this arrangement it is possible to "capture" a beam of colored light – between two points of the darkroom (two "holes in the darkness"). The beam that falls on prism No. 2 has a certain angle of incidence. Now, by rotating prism No. 1 on its axis, different monochromatic beams are projected onto prism No. 2 and refracted by it, always with the same angle of incidence. On the final screen, the different colored beams appear in different positions: the green	Objective experiment: a small *dark* image with a *light* background is refracted by a prism. A thin colored beam of the darkness spectrum is selected, while with the help of two projectors (white light) the remaining part of the spectrum is blocked. The colored beam passes through a prism No. 2 – placed parallel to the first – and is projected onto a screen. With this arrangement it is possible to "keep" a beam of colored light – between two points of the clear chamber (two "holes in the light"). The beam that falls on prism No. 2 has a certain angle of incidence. Now by rotating prism No. 1 on its axis, different monochromatic beams are projected – on prism No. 2 and refracted in it – always with the same angle of incidence. On the final screen the different colored beams appear in different positions: the magenta beam

beam is refracted more than the red, the violet more than the green.	is refracted more than the light blue, the yellow more than the magenta

It is worth mentioning a quote from T. Holtsmark's paper [1970]: "In principle, Newton could have arrived at the same physical models if he had worked systematically with inverted apertures, i.e., under a lit room but in that case he would have arrived at a different color terminology."

At the end of section 2, it was mentioned that Newton considered colorless light or white as composed of the colors of the rainbow. Considering the experiment with the dispersion of a beam of darkness by a prism, it would be necessary to conclude, analogously, that darkness is composed of the colors complementary to those of the rainbow. This contradicts the theories that light sometimes behaves like a particle (for example, the light of a star being attracted by stars of great mass), and sometimes like an electromagnetic wave. Regarding this second aspect, it should be noted that "wave" is a concept of classical, Newtonian mechanics. It should not be applied either to atomic phenomena, where the classical theory does not apply, or to light. In particular, a wave propagates by attraction and repulsion of molecules, as in a rope fixed at one end and swung at the other, or in the waves of a lake where a stone is thrown. However, electromagnetic "waves" propagate in a vacuum, where there are theoretically no particles to attract or repel each other. The correct terminology would be to use the term "electromagnetic radiation", not "electromagnetic wave".

An electromagnetic radiation behaves like a wave when it interacts with matter, as is the case of the "double-slit" experiment, carried out in 1801 by Thomas Young (1773-1829) – see *Double - slit experiment* on Wikipedia. In this experiment, stating, as is usual, that light behaves as a wave *before* the two slits is not a scientific fact, it is at most a scientific assumption – in fact, nothing should be said about the nature of light before its interaction with the slits. It is interesting to note that light is invisible; it becomes visible when it interacts with matter.

8. The color circle

Goethe created a "color circle," in which each color is placed in a circular sector. Opposite colors (with the same diameter) are what he called complementary colors. The following figure is one of the color circles in the *Farbenlehre*. Note the complementary colors in the diameters.

Fig. 5

Complementary colors are often used by painters to represent contrasts. In fact, Goethe's interest in colors came from his interest in painting, prior to the prism case reported in section 4.

9. The "Newton Disk" fallacy

A very common experiment carried out in schools is the "Newton disk," where the 7 colors of the rainbow are painted as circular sectors on a wooden disk. A slit on the edge of this circle, held by an axle, allows a string to pass through it and another disk with a crank. Thus, the disk with the colors can be rotated, and the triumphant teacher says something like: "See how Newton was right: the superposition of all the colors gives white!" First of all, the result seen by the students is not really white, but light gray – and the teacher usually gives the excuse that the colors are not pure. Second, there was no superposition of the colors on the disk. What happened is an effect produced by the retina: it is what superimposes the colors.

10. The colored shadows

Another phenomenon studied by Goethe and which, according to Israel Pedrosa in his excellent book [1982], had already been examined by Leonardo da Vinci (1452-1519), is that of colored shadows, which are very common but generally go unnoticed by those who are not familiar with them. Ott and Proskauer [1979] dedicated an entire book to them. To experience them, one can use two light sources, for example with two table lamps (bedside lamps), or just one and use ambient light, as long as it produces shadows on objects, or, better yet, daylight coming from an opening, such as a window, without the sun shining on the experiment. One of the lamps should be covered with a colored transparent cellophane, and the other, to balance the brightness, should not be too bright (hence the interest in using the light of a cloudy day, or closing the window sufficiently).

Place an object in front of the lamps so that it produces two shadows, one from each source. By adjusting the intensity of the lamps (for example, moving them closer or further apart), the shadow produced by the colored light source (and illuminated a little by the other light source) will become colored, but with the complementary color to that of the colored source. That is, if the latter is green, the shadow will be magenta, and vice versa. If the colored lamp is blue, the shadow will be yellowish or orange, and vice versa, and so on. This phenomenon can be observed at dusk or dawn when streetlights are on. If the streetlights are bluish, one sees a shadow of an object colored with a yellowish or orange color. If the streetlights are yellowish, one sees a bluish shadow. If the lamp with colored light is yellowish, the weak daylight will produce a bluish shadow, and so on.

One might think that this phenomenon is subjective, produced by each person's visual system. However, by taking a photo, the colored shadow is seen clearly. In the following figures, taken with a Panasonic Lumix DMC-ZS30 camera, a bedside lamp (with a slightly yellowish light) was used on the left side of the object, covered with transparent colored paper.

As a second, colorless source, daylight from behind the object was used, entering through a window, adjusting the blinds to give the best effect of the colored shadow. In fig. 6a, the lamp was covered with yellow cellophane paper, in 6b with green paper, and in 6c with blue paper, as can be seen from the colors around the objects (but not behind the light from the lamp). Note the shadows of the object, colored respectively with blue, magenta and yellow, the complementary colors to the colored light from the lamp, according to Goethe's theory. The colors were somewhat distorted by the camera and are certainly distorted by the screen where this text is displayed.

Fig. 6a

Fig. 6b

Fig. 6c

Note that almost vertically, below the object, the color produced by the colored light source is more intense than in the rest (to the left of the object). This is because to the left of the object the daylight slightly erased the color produced by the colored light source.

11. The afterimage

It is interesting to note that Goethe's *Farbenlehre* begins with what he called "physiological colors," such as the afterimage, that is, he introduces the observer to his theory, which is thus a humanist theory. Regarding the afterimage, by staring at a well-lit colored figure for some time, and then covering it with a white sheet, or removing it and leaving white in its place, dimly lit, without moving the eyes, one sees the complementary colors according to Goethe (a way of discovering, given a color, what its complementary color is). On the internet, search for *after image*, with several suggestions for experiments. The next figure shows the Brazilian flag in complementary colors. It was aligned to the left so that one could look at it very closely at one of its points (especially in the center) for several seconds, and then look to the right of it, seeing the flag in its normal colors (obviously, the colors depend on the screen resolution).

Fig. 7

This is a subjective-objective experience. Clearly the afterimages are created by the visual system of each person who has a healthy vision system (some people have difficulty seeing the afterimages), but all people report "seeing" the same colors.

12. The origin of colors according to Goethe

In his poetic vein, Goethe stated that colors appear in the *struggle* between light and darkness. For him, darkness had a quality of its own. Briefly, he observed that if a turbid medium with a dark background is illuminated from the side, the medium appears bluish. If a turbid medium is illuminated from behind by a light source, the medium appears yellowish, tending towards red as the turbidity increases. This can be seen with cigarette smoke and a side light source and a dark background, or with the light source behind the smoke.

This is how we can understand why the sky is blue – the atmosphere, the opaque medium, is illuminated by the Sun and the background is completely dark. At sunrise or sunset, the Sun is behind the atmosphere, as if it were denser, and the

Sun acquires colors from yellow to red as it approaches the horizon. The astronauts said that the Earth was blue. No, this is the color assumed by the atmosphere illuminated from the side by the Sun, with the dark background of the land or seas behind it. There are explanations for these phenomena using reflection, refraction and diffraction of light in the particles of the atmosphere: violet and blue would be more dispersed, spreading out more, predominating over the other colors; at sunrise and sunset the path of light in the atmosphere is greater, reducing the blue light, leaving more light from yellow to red. But these are much more complex theoretical explanations, which cannot be experienced as in the case of smoke, and because they require the abstract concept of particles in the atmosphere. In Goethe's theory, there is no need to understand a theory: the experience itself is the explanation.

Another example from the *Farbenlehre*: the flame of a candle has a bluish section at its bottom. The gas near the candle, emitted by wax or paraffin, forms an opaque medium, and is illuminated by the yellow flame above. By placing a black paper or object behind the candle, the blue becomes intense. By placing a white paper behind it, the blue becomes weak. These effects do not occur in a bluish flame (complete combustion) of a gas stove, showing that in this case blue is the color of the flame itself.

Another phenomenon examined by Goethe which can be experienced is the fact that mountains in the distance appear bluish. Again, there is a dark background behind the atmosphere illuminated from the side by the Sun or by daylight.

These are examples of the "struggle" between light and darkness. It has already been demonstrated that within a prism, due to refraction, the same effect of light overlapping with darkness occurs in an opaque medium (the prism glass), hence the dispersion of colors. The edges of a beam of light immersed in darkness produce colors within a prism as Goethe described them, in terms of an opaque medium with light on the side (darkness predominating), or with light behind the medium (light predominating) [Proskauer 1991]. In fact, when a wide beam of light (as in Figs. 1a and 1b) enters a prism, it is important to consider that the dark part around the beam also "penetrates" the prism. which plays the role of the dark background, and the prism material acts as the opaque medium, which is illuminated by the luminous part of the beam, producing the appearance of "cold", bluish colors. On the other edge of the beam, the latter moves away from the dark part, producing the effect of the opaque medium of the prism being illuminated from behind, with the appearance of "warm" colors, from yellow to red.

The essence of this theory is that there must be a boundary between light and darkness, including between lighter and darker colors. Whenever there is such a transition, the colors will appear due to their dispersion in a prism. However, in the case of "pure" colors, such as those used by Newton in his *experimentum crucis* (cf. sections 3 and 7 above), also extended to a color immersed in darkness (see section 7, Dark-Newton), there is dispersion in the second prism, since in it there is the interaction of the beam of light with darkness, or the beam of darkness with light. However, Goethe realized that in this case the color of the colored beam or of the colored environment predominated over the others, which became almost imperceptible. He also explained the increase in the image size of the colored beam, due to the natural dispersion added to the color of the beam itself – or the dual in the case of a beam of darkness. This corresponds to the refraction theory.

It is interesting to note that Goethe's theory also serves to explain the spectra of substances, as shown by Gerhard Ott [1970] in the case of the spectral lines of mercury and helium.

About the nature of light, this article could not fail to cite the extraordinary book *Catching the Light*, by Arthur G. Zajonc [1993], containing several considerations on Goethe's theory of colors.

13. Primordial phenomena

Another aspect of Goethe's method is that some phenomena are considered primordial (*Urphänomene*) and cannot be reduced. For him, light and darkness are examples of such phenomena. Bjerke [1961] formulates it as follows, in free translation: "Reduced to a short formula, Goethe's law for primordial phenomena can be expressed as follows: Light, modified by darkness, produces the warm colors [red, orange and yellow]; darkness modified by light, produces the cold colors." Recall what was described above for the experiment with cigarette smoke, the effects on the atmosphere and what happens inside a prism.

14. Final considerations

As seen above, Newton's case is extremely particular. But it is this setting that is used in experiments with colors, spectra, etc., with prisms or reticles: beams of white or bright light in a dark environment, such as the stars – just according to Newton's taste, who was an astronomer. He made the mistake of stating in *Opticks* (Prop, VII, Theor. VI) that lenses always produce chromatic aberration (a convex lens acts as two prisms in contact with one of its sides; a concave lens acts as two prisms joined by an edge), which delayed the appearance of achromatic lenses by 50 years: the first patent for these lenses dates back to 1758.

In fact, Newton invented the telescope that bears his name by replacing the objective lens (the one that points at objects) with a parabolic mirror at the bottom of the telescope. This mirror concentrates the light onto a small mirror which then reflects it to the ocular lens, on the side of the telescope, close to the observer's eye. In this way, he eliminated the chromatic aberration produced by the objective lens.

Although Newton's theory is derived from a very special case (a thin beam of bright light immersed in darkness), if one stays in that situation, it is coherent, and that is why it is used. But it does not reflect the general reality. In my opinion, Goethe's theory, much more extensive than what is being presented here, is also coherent, and has not been satisfactorily refuted to date, at least in the many publications I have studied. Dennis L. Sepper [2002] wrote an interesting book comparing the two theories.

It should be noted that Newton's theory is reductionist, starting from an extremely particular case, a method typical of current science. One of Goethe's scientific methods [Steiner 1984, 2016; Zajonc 1976] is to always start from the most general case and explain a particular case having the general case as a background.

It is interesting to note that Goethe's method is qualitative, unlike Newton's method, which used refraction indices. Arthur G. Zajonc [1976] quotes a well-known passage by Lord Kelvin (the one about Kelvin temperature degrees), from 1891, saying that one only knows something when one can measure it and express it in numbers; otherwise, one has no science but, at most, a “beginning of knowledge”; see also this quote in Kelvin's biography on Wikipedia, in the references.

When human beings experience the general, and science is qualitative, it becomes human, that is, human beings can relate to it more deeply. Otherwise, it becomes merely intellectual, abstract, at least when it comes to understanding, although it can have practical applications.

Goethe considered his theory of colors to be his most important work. However, because he developed a different scientific method than usual, he did not receive due attention as a scientist but was always highly admired as a poet and writer. On Goethe's scientific work, see the book by Rudolf Steiner [1984], who was precisely the editor of this work for the Deutsche Nationalliteratur [German National Literature], a complete edition of Goethe's works.

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