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Marcos Silva *Editor*

# How Colours Matter to Philosophy

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# How Colours Matter to Philosophy

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# Goethe *contra* Newton on Colours, Light, and the Philosophy of Science

**Olaf L. Müller**

> *It is sometimes bizarrely demanded by people, who do not themselves attend to such demands, that experiences be described without any theoretical connections [ . . . ]. Surely the mere inspection of some object can profit us but little. Every act of seeing leads to consideration, every consideration to reflection, every reflection to combination, and thus it may be said that in every attentive look at nature we already theorize. Let us engage in it with consciousness, with self-awareness, with freedom, and to use a bold word, with irony: all of this is needed if the abstraction we fear is to be harmless, and the empirical result we hope for is to be quite lively and useful*
>
> (Goethe [LA]/I.4:5, compare Goethe [GTC]:x1–x1i and Goethe [ToC]:159)

## 1 Introduction

In his *Farbenlehre* (*Theory of Colours*) of 1810, Johann Wolfgang Goethe challenged one of the most well-established scientific theories of his days, launching a fierce attack on Newton's *Opticks* (1704). In the first book of this publication, Newton had unfolded his seminal theory of light and colours. This very theory still makes up a substantial portion of our understanding of light and colours today. Thus the question arises: Do we have to abandon the achievements and methods of modern natural science if we do not want to dismiss Goethe's protest against Newton as merely the erring ways of an ingenious poet?

If you prefer a conciliatory response, that is, if you respect both our science *and* Goethe, then you might begin by extracting those passages from Goethe's writings on colours that anticipate results of current research. But it would not do justice

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to Goethe to praise him only for anticipating the neural coding of complementary colours or the invention of colour television.[1] Goethe strove for more than just a few isolated scientific successes. Goethe's *Farbenlehre* is motivated, propelled, and united by his uncompromising opposition to that well-established scientific theory.[2] Thus, there seems to be little room for reconciling Goethe's *Farbenlehre* with contemporary science and its methods.

Nevertheless, I shall try to defend Goethe's critique of Newton on the methodological grounds recognized by contemporary philosophy of science. If I am right, then Goethe discovered a deficiency in Newton's methodological self-assessment that must be an uncomfortable eyesore to anyone familiar with scientific method. By that I do not mean to suggest that Newton's results are wrong and must therefore be discarded. With a little luck, you can attain useful results even when they are based on a deficient conception of your method's powers. On the other hand, given bad luck, even the best methodological self-assessment can lead to a dead end. I will not address the question as to whether or not Newton simply had more luck than Goethe. I will only insist that Goethe produced solid methodological work with his critique of Newton, as well as in his own theory of colours.

In contrast to what is often claimed, Goethe understood well how empirical sciences work and what they can achieve. He thought it through more deeply than Newton. This is where I locate Goethe's lasting contribution. With the help of his critique of Newton, we can analyse and criticize an exemplary case of excessive confidence of the natural sciences; the goal is to transform it into a more appropriate self-conception. Thus, the results and methods of the natural sciences are not at issue. The issue is the uncritical attitude toward these results and methods – the attitude of scientism that can be traced back to Newton and his peers, and that is still widespread today. Of course, the scientists' adequate methodological self-conception does not have to play a large role for scientific practice – just as the bird does not need to understand aerodynamics in order to fly, or as the tango dancer does not need to know the geometry of her steps. Nevertheless, Goethe's methodological reflections serve an important purpose. They help us better understand ourselves in a world increasingly shaped by science.

[1] See Mausfeld [WANS]:23/4 on the neural coding of complementary colours. The reference to colour television can be found without further explanation in Hegge [ToSi]:202.

[2] Goethe's *Farbenlehre* consists of three parts and several appendices; the original titles of the three parts are: *Entwurf einer Farbenlehre* ([LA]/I.4, generally known as the didactic part); *Enthüllung der Theorie Newtons* ([LA]/I.5, generally known as the polemic part); *Materialien zur Geschichte der Farbenlehre* ([LA]/I.6, generally known as the historical part). Whereas the main sources of my considerations can be found in the second part, only the first part has been translated into English (twice, in fact), though not everywhere in the most satisfactory fashion (Goethe [GTC], [CoT]). Thus, all English quotations from Goethe's *Farbenlehre* presented here have been translated anew. For the reader's convenience, however, references to the existing published English translations will be provided wherever possible. In the meantime, there is also a translations of the polemicae part, published by M. Petry and M. Duck, which occured too late to be incorporated here.

## 2 Two Levels of Controversy

I just outlined *in abstracto* what the controversy is about. In order to present it more concretely, let us move to the heart of the controversy and consider the properties of (white) sunlight. Newton's position is more or less as follows:

> The prism experiments (which Newton describes in detail and to which we shall return) *prove* that sunlight is a heterogeneous mixture of variously coloured light rays.

To be precise, Newton's position contains two claims. The first claim concerns the properties of light; it states Newton's conclusion (which we still accept today). This first claim is on the object level, so to speak.[3] The second claim (whose decisive term I have italicised) is made at a higher level. It concerns the status of the first claim. According to Newton, the heterogeneity of white light is an *experimentally proven fact*. For example, the first official sentence of *The Opticks* (in the first part of the first book, directly after the preface) reads:

> My design in this Book is not to explain the Properties of Light by Hypotheses, but to propose and *prove them by reason and experiments* (Newton [O]:5, my italics).

A brief look at the first book of *The Opticks* reveals that Newton was serious about this ambition. The book contains theorems and *proofs* (as well as definitions and axioms). Whenever Newton formulates a theorem, he provides an experimental proof. Thus, in the passage relevant here, he says:

> THEOR. II. *The Light of the Sun consists of rays differently Refrangible*.
> The Proof by Experiments. *Exper. 3*. [ . . . ] (Newton [O]:21, italicised in the original).

Goethe attacked Newton's uncritical attitude toward his scientific results, and he was right to do so, as I will try to show. I want to demonstrate that Goethe was led to the following correct view:

> The prism experiments *do not prove* that sunlight is a heterogeneous mixture of variously coloured light rays.

That sounds like the complete opposite of the orthodox position as set out above. But it only contradicts Newton's second claim (on the higher level). Someone who denies that the gardener has been convincingly incriminated (given the burden of proof) can still think that the gardener was the murderer. And someone who denies that the prism experiments prove the heterogeneity of white light can still believe in its heterogeneity, and thus agree with Newton's first claim (on the object level). That is the position that I would like to offer to sympathisers of Goethe who do not wish to disagree with contemporary natural science.

[3]It results from Newton's first two theorems (Newton [O]:17, 21).

## 3 Newton's First Experiment Revisited and Revised

In Goethe's view, careful observation of the phenomena has an educational function. By making yourself familiar with the phenomena, you are protected from hasty conclusions, and you are guarded against the dangers of confounding complex hypotheses with what you see with your own eyes. According to Goethe, most of Newton's readers succumb to these dangers, and this not by accident. Goethe repeatedly accuses Newton of presenting his experiments hermetically and abstrusely, so that it is difficult for the reader to repeat and test them.[4] Regardless of whether Newton intentionally muddled his descriptions (which Goethe insinuates and which I doubt), it cannot be disputed that Goethe's descriptions of the experiments are better than Newton's. They are superior in clarity, comprehensibility, and intelligibility. I emphasize this not so much because I wish to indicate whose writing style was better. Rather, I emphasize it so as to expose which of the two took experiments and observations deeper to heart.

The contrast between Goethe and Newton's styles mirrors a more thorough methodological contrast. Goethe noticed that Newton draws only on a small number of possible prism experiments, and worse still, on exactly those that appear to favour his theory. To overstate the point – Goethe had to object to Newton, *just because* he took the experimental method of the natural sciences more seriously than Newton.

Let us examine the conclusiveness of the most famous of these experiments: Newton's prismatic analysis of white light (Fig. 1).[5] On a sunny day Newton closes the doors and window shutters of a room facing south, and then turns off all the lights. He drills a tiny, round hole in one of the sun-splashed window shutters; and he places his famous prism to catch the light immediately after it passes through the hole. Twenty-two feet away, he puts a white screen in a suitable location (as the light changes direction according to the optical law of refraction), so that all of the sunlight coming through the hole hits it. Newton observes two things: The light hitting the screen is not white, but like a multi-coloured rainbow; and the image is not round, but five times as long as it is wide. At one end it is red. At the other end it is blue (with a tint of violet). The coloured band in between is yellow, green, and turquoise (i.e., cyan). These spectral colours form the so-called Newtonian spectrum, abbreviated $S_N$, see Fig. 2.[6]

Through careful measurements and calculations, Newton discovers that the width of the band of colours corresponds to his expectations, given the sun's size, the tininess of the hole in the window shutter, the prism's orientation, the distance from

[4]See, for example, Goethe's discussion of the first Newtonian experiment ([LA]/I.5:§35, §37, §39, §41).

[5]For the following, see Newton [NTaL]:3076–3078.

[6]Whether the observed patches of colour are seen arranged horizontally or vertically depends on the orientation of the prism. In my representation, I have chosen the second possibility. Goethe and Newton often had the first possibility in mind (see e.g. Newton's sketch in Fig. 1). For the sake of uniformity, I will often adapt their considerations to my representation, without noting this in each case.

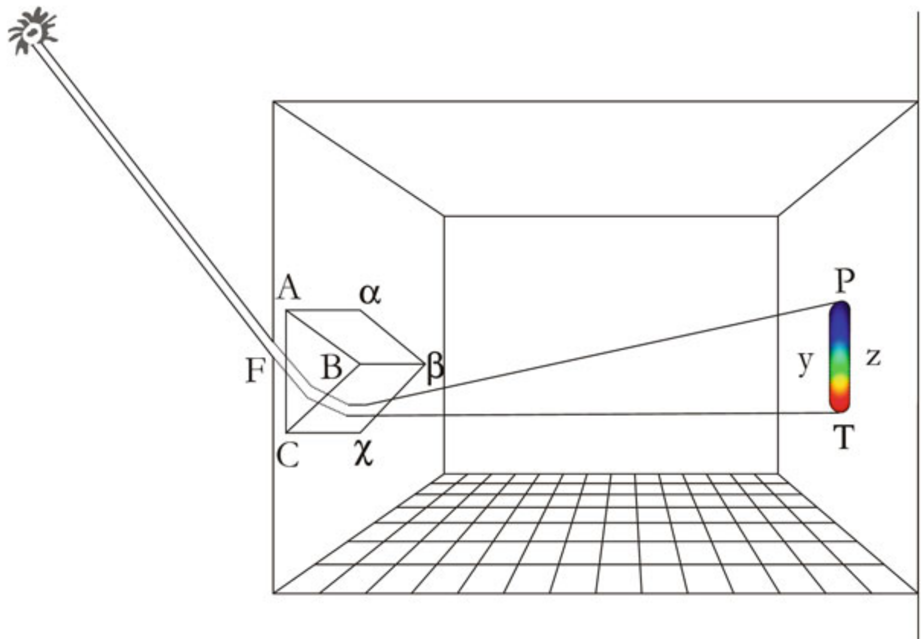
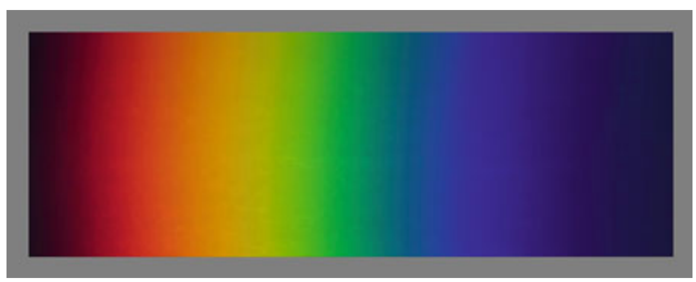



**Fig. 1** Newton discovers the heterogeneity of light. Lights rays are refracted by a prism ABCαβχ (*left*). In the dark chamber on the right, Newton catches his well-known spectrum $S_N$ between the two poles P and T. The light rays that are redirected from their path the furthest are *blue*. They can be seen in the upper part of the spectrum (Redrawn by Ingo Nussbaumer; the original is in Newton's notebook, reprinted in Newton [UFVo]:3)

**Fig. 2** Newton's spectrum $S_N$ (Photographed by Ingo Nussbaumer)



the prism to the white screen, etc. What is surprising is the length of the band of colours – and the fact that it is colourful.

If one now imagines the multi-coloured band as a series of patches of colour (blue, turquoise, green, yellow, and red), then the suspicion arises that variously coloured light rays must have left the prism in slightly different directions. The prism thus divided the colourless light ray (emerging from the hole) into variously coloured rays of light. It divided that light ray by refracting its blue part more strongly from its path than the turquoise part; the turquoise more strongly than the green; and so on. In short, white sunlight is a mixture of variously coloured rays that are variously refracted as they pass through the prism. (Strictly speaking, it is insufficient to observe just five different colours of light rays. Rather there will be indefinitely many fine gradations between the five colours specified. Nevertheless, I shall continue talking about five different colours in order to avoid unnecessary complications).

Now that I have unfolded Newton's reasoning I wish to ask: Do we want to call it a proof? Does the experiment sketched above force the conclusion upon us that white light from the sun is a mixture of variously coloured light rays, and that these variously coloured light rays were diversely refracted? Goethe challenges these claims. He takes Newton's result as a theoretical hypothesis that goes beyond what can be seen in the experiment.

Notice that Goethe does not challenge the *existence* of the elongated colour band twenty-two feet behind the prism. He challenges its *conclusiveness* for the hypothesis of the heterogeneity of white light. And for this purpose, he is not just being obstinate by insisting that a band of colours on some particular screen does not imply anything about the composition of light that passes through a hole in a window shutter far away. Goethe does not act like the notorious sceptic who sees non-sequiturs wherever there are arguments. Rather, he takes matters into his own hands and repeats Newton's experiment under varying conditions; he "multiplies" the phenomena.[7]

He moves the screen nearer to the prism, increases the size of the hole in the window shutter, changes the angle of the prism, and meticulously records all his observations. No doubt, if one of the two were obsessed with the experimental method, then it was Goethe.

Goethe's series of experiments delivers staggering results. Newton's colour spectrum $S_N$ is an extreme case and quite special at that:

> The Newtonian theory that reigned for over a century was, however, based on a *limited* case, and it neglected the rights of all of the remaining phenomena; it is these rights that we have tried to restore with our proposal [Goethe is referring to the first – didactic –part of the *Farbenlehre* – O.M.]. This was necessary, as we want to bring the hypothetical distortion of so many wonderful and pleasing natural phenomena back into balance (Goethe [LA]/I.7:7; my italics).

In this paper I want to concentrate on just one group of phenomena which Goethe brought back into optical research. There are more, and some of them are of great importance; for the sake of brevity they have to be set aside here.[8] Even when we restrict our attention, Goethe's insights are surprising enough. For the sequence of colours $S_N$:

> red, yellow, green, turquoise, blue (Fig. 2),

only appears when you coordinate the distance between screen and prism precisely with the radius of the sun's disk. Once you move the screen too close to the prism (or if you, alternatively but impossibly, increased the size of the sun as it appears in the sky) the green patch at the middle of Newton's colour spectrum disappears. In its place you see a colourless gap bordering the yellow patch on the one side and the turquoise patch on the other. The sequence is:

> red, yellow, *white*, turquoise, blue (Fig. 3).

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[7]This expression – "vermannigfaltigen" – occurs often, see e.g. [LA]/I.5:§56, §168.

[8]For details about another important group of these phenomena and their significance see O.M. [PE].

**Fig. 3** Greenless spectrum $S_G$ (with a white *centre*), as it appears at closer distance to the screen. For Newton's explanation see Fig. 4. Notice that the *yellow* stripe in the *left* part of the spectrum $S_G$ is cleaner and more luminescent than the *yellow* part in Newton's spectrum $S_N$. Furthermore, the left half of $S_G$ is complementary to its right half (Photographed by Ingo Nussbaumer)

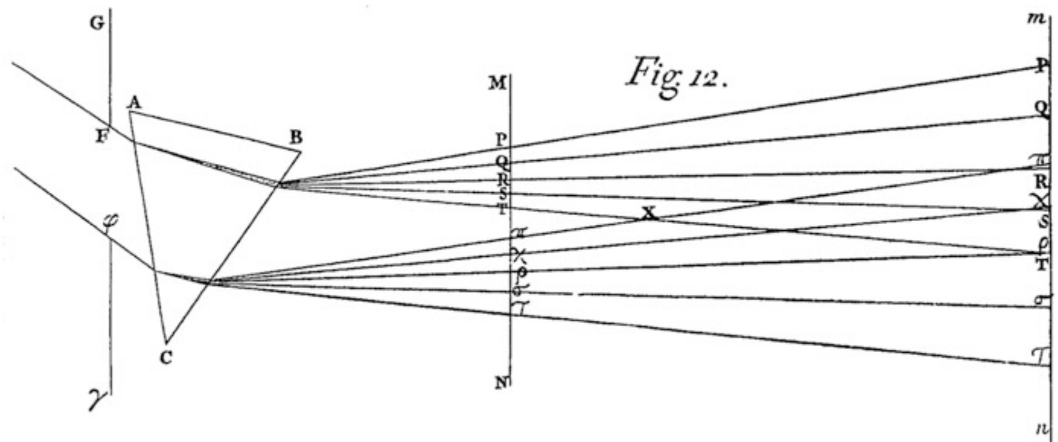


**Fig. 4** Newton's explanation of the greenless spectrum $S_G$. A broad white bundle of rays of white light passes through the hole in the window shutter Fφ and enters prism ABC. Where it leaves ABC, five broad and diversely coloured bundles of rays appear, which continue in slightly different directions: the (blue) bundle of rays PPππ is refracted the most, the (red) bundle of rays TTττ is refracted the least; the other three bundles of rays lie somewhere in between. In the centre of the nearby screen NM all of these bundles of rays are superimposed and add up to a white appearance (between T and π); neither the red bundle nor the yellow bundle reaches the area above the centre, which explains its bluish appearance; accordingly for the area below the white centre (In Newton's writings this figure is called "Fig. 12" (Newton [O]:Lib. I Par. II Table III). Mirrored rendering by Matthias Herder)

And the white gap in the middle of this new spectrum $S_G$ becomes increasingly larger (in relation to the coloured part of the sequence), the nearer you move the screen to the prism. When confronted with these observations, how should we react to Newton's claim that sunlight contains (among others) green light rays? Why doesn't Newton's green light appear directly behind the prism?

It is important to see that Newton's theory is equipped with an immediate answer (Fig. 4). The white gap in the coloured band $S_G$ directly behind the prism can be interpreted as an overlay of multi-coloured rays of light that arrive at the prism from the sun's disk in parallel, but (despite different directions of refraction through the prism) are not yet far enough from each other to appear separately on the screen.[9]

[9]It is remarkable how casually Newton treats the topic. See Newton [O]:102.

As opposed to what is often claimed, Goethe was aware of this response.[10] Nevertheless, he remained discontent. And the reason for this was not that he did not understand Newton's theory. Goethe does not need to deny that the white gap (in the coloured band $S_G$ directly behind the prism) can be integrated into Newton's heterogeneity of white light. As we have seen in Sect. 2, Goethe does not have to prove that Newton's theory is wrong.[11] The observation of the white gap in $S_G$ does not serve him as an experimental refutation of Newton's theory. Goethe argues on a higher level and correctly directs the phenomenon of the white gap against Newton's claim to have experimentally *proven* that white light is heterogeneous. According to Goethe, the white gap exposes Newton's heterogeneity of white light as mere hypothesis. And this rebuke is justified, as I shall demonstrate in the next section.

## 4 The Gap in Newton's Proof

*hypotheses non fingo*: That was Newton's proud campaign slogan.[12] A hypothesis is less than a proof. The hypothesis may be more or less in accordance with the phenomena. But even in the more favourable case, it does not inevitably follow from the phenomena alone. The hypothesis cannot simply be read off of them. With this in mind, I want to ask: Is it a proven fact or just a hypothesis when Newton claims that white light is a heterogeneous mixture that contains some green light?

After Goethe multiplied the experiments, we have two groups of phenomena that are on a par. We have prism experiments with a green patch in the coloured band $S_N$, and we have prism experiments without a green patch in the coloured band $S_G$. Do these phenomena dictate a decision about the composition of white light? In particular, do they force the claim upon us that white light contains some green rays?

They don't. As long as there is no reason to favour one group of phenomena over the other, we have a choice. We can *decide* to start from the prism experiment with a green patch. In this case, we travel Newton's path and explain the greenless experimental results according to assumptions based on experimental results exhibiting green (Fig. 4). But that is not the only possibility. We could just as well decide to start from the greenless experiments, and then consult these results in order to explain the results that produce a green patch in the middle of the coloured band on the screen. According to this view, the green centre in the more distant spectrum $S_N$ arises as a juxtaposition of the yellow and turquoise colour patches that occur near

[10] See Goethe [LA]/I.7:72/3, 79–83; the claim that the response was not borne in mind by Goethe can be found for example in Helbig [NO]:122.

[11] Goethe: "We thus do not by any means imagine ourselves to have proven that Newton was wrong" ([LA]/I.5:§31).

[12] The slogan can be found in a prominent place in the *Principia*, namely in the penultimate paragraph right at the end of the monumental work (in the "SCHOLIUM GENERALE" that appears for the first time in the second edition, see Newton [PNPM]:174). Newton also applied the slogan to optics, see Sect. 2 and note 14.

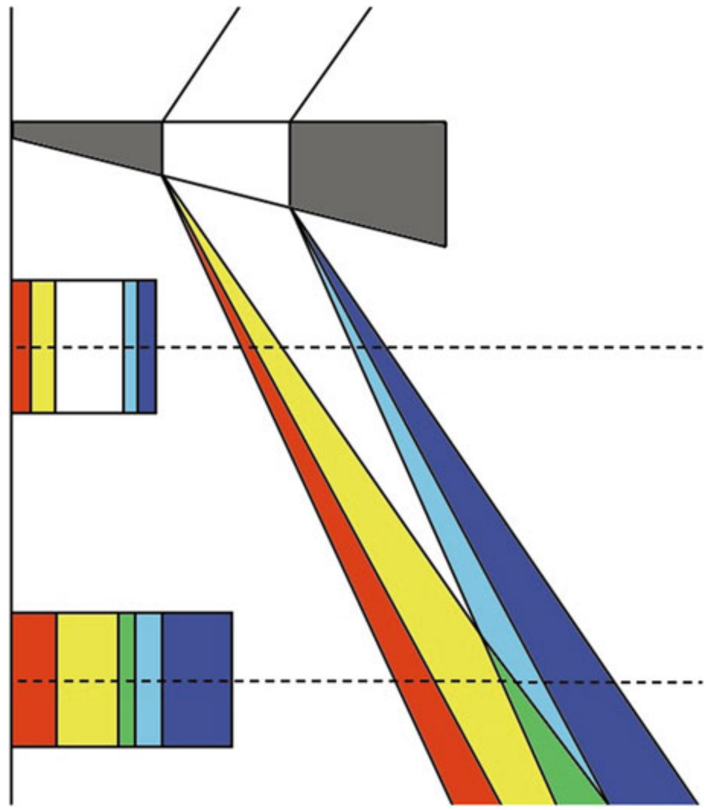

**Fig. 5** According to Goethe's explanation of Newton's spectrum (Fig. 2), the two complementary parts of the greenless spectrum $S_G$, which emerge in close vicinity to the prism ($S_W$ and $S_C$, see Figs. 7 and 9), are the basic phenomena of optics. The greater the distance between screen and prism, the smaller the white centre of $S_G$, and thus the smaller the distance between the yellow stripe and the turquoise stripe. Where they meet and finally overlap, the green centre of $S_N$ (Fig. 2) emerges (Cut out and redrawn from Goethe's 5th colour plate, see "Plate V" in Goethe [ToC]:206–7/VII; in the first English translation, Goethe's figures have different numbers, see Fig. 1, PLATE IV in Goethe [GTC]:192–193. The German original is in Goethe [LA]/I.7:63–65)

the prism (Fig. 5). These emerge directly behind the prism, so to speak, but do not yet overlap there, and therefore can only mix somewhat further away.[13]

Given the symmetry of the situation, Goethe has two piercing criticisms of Newton. First, in selecting the phenomena that he does, Newton makes a decision without ever identifying it as a decision. And second, he fails to justify his decision. In short, there is a gap in Newton's proof. We do not need to judge whether Newton was aware of this gap. I find the following questions more instructive: Could Newton have closed the gap? Could he justify his choice to base the proof just on those prism experiments where a green patch can be observed in the centre of the coloured band?

Perhaps Newton could again draw our attention to the fact that his results are consistent with the greenless experimental results. But in order to exploit this point in favour of his proof, Newton would have to show more. He would have to show that, taken as a whole, the reversed procedure is less successful. That is, he

[13]Goethe follows the second option in his own account of the prism experiments, see Goethe [LA]/I.4:§330, §214, §216, compare [GTC]:§330, §214, §216, [ToC]:§330, §214, §216.

would have to *compare* the success of his suggestion with the success of competing suggestions – and that is exactly what Newton does not want to do, since he does not want to sell his heterogeneity of white light as a more or less successful hypothesis: In his eyes, it is an experimentally proven truth.[14]

If Newton wants to live up to these high aspirations, then he must provide stronger reasons for favouring the green-patched experimental result $S_N$. Or he must try to downplay the greenless result $S_G$ as a degenerate, special case. At first glance, the prospects seem poor. His own choice of the distance between the prism and the white screen appears arbitrary. Why does Newton put the screen precisely 22 ft from the prism, and not three inches or fifty feet away? When Goethe moved the screen closer to the prism, he did not do this aimlessly, that is, merely to multiply phenomena. Rather, he wanted to see what happens directly behind the prism where the formerly white light allegedly divides into colours. If you want to prove that white light contains a green component that the prism separates out, then you must locate the green component exactly where this transpires, not at an arbitrary distance of 22 ft.

This clearly speaks against Newton's experimental set-up. But it does not end the present strand of my considerations. Newton could try to divert our attention from the distance between the prism and the screen. He could point out that another parameter of his prism experiment is crucial – the radius of the sun's disk as it appears in the sky. If we, say, increased the distance between us and the sun (or if we diminished the size of the sun itself), that is, if the sun's disk filled a smaller angle from our perspective, then we could move the screen closer to the prism, without losing the desired green patch in the middle of the coloured band on the screen.[15] Given this, it might serve Newton's purposes to grant a privileged status to those prism phenomena that would appear if the sun were infinitesimally small, or infinitely far away from us.

What could Newton say in favour of varying those astronomic parameters? He could say that he wants to examine light rays that are not disturbed by neighbouring light rays. The smaller the sun, or the further away, the fewer disturbances from other light rays. That sounds tempting. But it is exactly this tempting idea against which Goethe warned. First of all, we are unable to produce variations of the sun's size or of its distance from the earth; such variations, which would have to be tremendous, are science fiction. Second, and worse, shrinking the size of the sun's disk renders the entire observation more difficult – with an infinitesimally small sun, we would see nothing at all. Third, in any possible experiment, even with a smaller (but not disappearing) sun, we cannot observe a green patch in the band of colours *directly* behind the prism. As long as we neglect this greenless phenomenon, we are still making a decision that is not imposed upon us by mere observation of phenomena.

[14]Newton was serious about this ambition, as can be seen in many places throughout the *Opticks*. See for example the summary of his results directly after formulation of "PROPOSITION VII. THEOREM V" ([O]:100).

[15]See Goethe [LA]/I.5:§115–118 as well as Newton [O]:43/4.

These points raise the suspicion that Newton's appeal to single rays of white light (and to an infinitely small sun's disk) had nothing to do with real experiments. Perhaps Newton wanted to say that *if* we could make the sun so small that only a single ray of white light could travel from it to us, then this light ray would be cleanly divided by the prism into its variously coloured components – so cleanly indeed that we could attain a complete colour spectrum $S_N$ directly behind the prism (which, however, would be much too weak to be seen by human eyes).

In a certain respect, the constellation so described is entitled to a special status as compared to all other phenomena that appear with larger appearances of the sun in the sky, and with various distances from the prism. However, this special constellation does not belong to the realm of phenomena that can be directly observed. It is the result of idealization, and it contains an abstract hypothesis: that light rays are infinitely thin. But the observable phenomena do not force us to idealize towards the direction of Newton's hypothesis. Goethe says rightly:

> One never finds rays, one just explains the phenomena with rays [ . . . ] That Newton and his school believe to see with their eyes what they theorized into the phenomena – that is precisely what one complains about ([LA]/I.5:§217; see also Goethe [LA]/I.4:§310, compare [GTC]:§310, [ToC]:§310).

In the terms of contemporary philosophy of science, this amounts to naming the danger of theory-laden observation.[16] Of course, it is not forbidden to idealize and hypothesize.[17] Modern natural science is replete with idealizations and hypotheses. Newton did not want to admit this, and he believed that he could build on more solid ground. If Goethe reminds him of the fact that his alleged proof contains hypothetical elements, then one should not accuse Goethe of having misjudged the idealized, hypothetical character of modern natural science. Rather, one should give credit to Goethe for having seen an inconsistency between the methodological self-conception of leading scientists and their actual practices.

What should we think about this inconsistency? According to my interpretation, Goethe wants to adjust the self-conception of the natural sciences. His attack does not aim at the practices of idealization and hypothesizing. As we shall see in the next sections, Goethe can accept mathematical idealizations of the prism phenomena without abandoning his main point. He can insist that the prismatic results thus achieved fail to be objective.

[16] Goethe was perhaps the first commentator of modern physics who (against Newtonian naïvety) emphasized that in principle each observation is theory-laden (Goethe [LA]/I.4:5, Goethe [GTC]:x1-x1i and Goethe [ToC]:159). See the quote at the very beginning of my essay.

[17] Goethe provides a brilliant discussion of abstract geometrical aids that are used in textbooks to clarify the law of refraction, see his eleventh table (Goethe [LA]/I.7:93–95). Unfortunately, its description missing in the English translation.

## 5 Idealization, Mathematics, and Objectivity

In the previous section, I claimed that the prism experiments do not force us to idealize towards Newton's hypothesis. In a trivial sense, this is obvious. The phenomena do not force us to any idealization. If we decide to stick closely to the observed phenomena, then of course the phenomena cannot force us to idealize at all. (How should they do that?)

Now, it is difficult to imagine how science should manage without idealizations. It would be a natural science without mathematics, or at least a natural science in which mathematics would play a role completely different to the one with which we are accustomed. Speculation in this direction may have some philosophical attraction, but we had better not draw on Goethe in this regard. True, there are no mathematical calculations in Goethe's *Farbenlehre*. But that is no reason to praise or condemn Goethe for envisaging natural sciences without mathematics. The lack of mathematics in Goethe's *Farbenlehre* is due to two reasons. On the one hand, Goethe does not trust himself to be capable of profitably using mathematical methods.[18] He kept his project open to the assistance of mathematicians (alas, to no avail):

> [ . . . ] the mathematician will gladly join our endeavour, especially concerning the physical part of the *Farbenlehre* ([LA]/I.4:23, [GTC]:lx, [ToC]:167; see also [LA]/I.4:§727, [GTC]:§727, [ToC]:§727).

On the other hand, Goethe believed (in my opinion, for the most part correctly) that he did not need mathematics to achieve the principal purposes of the *Farbenlehre*.

You might ask: At what point should Goethe have benefitted from the mathematicians he unsuccessfully invited to contribute to his project? Goethe did not say. However, in my opinion, the answer to the question is obvious. Mathematicians might, for example, carry out a series of measurements aimed at developing a formula: This formula would predict at what minimum distance from the prism we would observe a green patch in the middle of the coloured band on the screen (as a function of material, angle, and position of the prism as well as of the size of the sun's disk, or more generally, of the size of the light source).[19] Such a formula would be based on idealizations. As soon as you want to draw a mathematically respectable curve through a series of points acquired by real measurements, you have to embellish the measurements. Goethe cannot protest against this since he often emphasizes the significance of aesthetic considerations for natural science.

Let us go a step further. Our formula would not only provide information about cases that we have observed or have not yet observed. Purely formally, it also treats

[18] See Goethe [LA]/I.4:§723, compare [GTC]:§723, [ToC]:§723.

[19] Perhaps no tools from the region of higher mathematics are necessary for the specification of such a formula. (Given the prism's optical parameters, it might be just a little trigonometry, see Fig. 5). But what harm does that do? The mathematics in Newton's *Opticks* is also rather down to earth in comparison to the mathematics in the *Principia*.

extreme cases that we *cannot* observe in principle. What happens, for example, if we let the parameter for the size of the sun's disk (or of the light source) approach zero? Even if the formula gives us an answer – if for example it says (to Newton's benefit) that when the size of the sun's disk approaches zero, the green patch appears directly behind the prism – even then we should not and ought not claim to have observed a single ray of white light, or to have experimentally proven that the prism decomposed such a single ray into the complete spectrum of colours.

Observed phenomena do not live up to the mathematically extreme case. The mathematically extreme case belongs to the realm of hypotheses. The phenomena belong to the realm of facts. As long as we do not confound hypotheses (won through idealization) with the observed facts, Goethe would have no fundamental objection against idealizations.

A misunderstanding threatens to trivialize Goethe's point. Trying to downplay the dispute, you could ask: Is it a dispute just about words? Perhaps Goethe speaks more strictly than Newton, and always banishes, purely verbally, scientific results to the uncertain realm of hypotheses? Couldn't we instead simply say that we want to call a scientific result a proven fact when the result in question follows from idealized observations? This suggestion is in accordance with the self-conception of many natural scientists who may well be aware that they are idealizing, without being inclined or forced to abandon talk of scientifically proven facts. Unfortunately, the suggestion conceals a crucial problem that Goethe saw with admirable clarity – a problem that remained hidden from Newton.

The problem is that the phenomena can be idealized in completely different directions. Even when we have opted for idealization (and thus for exact natural sciences), even then the phenomena do not dictate which way we have to go. We are repeatedly confronted with a choice between different theoretical options. Which of these options we pursue does not depend on observation and mathematical rigor alone, but also on considerations based on *our* preferences. It depends, for example, on considerations of elegance, simplicity, parsimony, generality, fertility, and on overall coherence with the theories we already accept.[20] Considerations such as these do not always point in the same direction. It could happen, for example, that we do not favour an ontologically parsimonious theoretical option of high generality because it becomes too complex. This indicates that even the most careful weighing of the pros and cons does not have to lead to a unique result. Our criteria for theory choice do not form an algorithm that, after having been fed the available observations, spits out *the* single best theory.[21] Thus there may still remain several theoretical alternatives on the table – even if all data are given, and if in addition all

[20] See e.g. Quine et al. [WoB]:66–80.

[21] According to Kuhn, there is "no neutral algorithm for theory-choice, no systematic decision procedure which, properly applied, must lead each individual in the group to the same decision" (Kuhn [SoSR]:200). Cf. Duhem [ASoP]:218.

extra-empirical criteria for theory choice have been considered. This is what Quine called the underdetermination of scientific theory.[22]

What I outlined in the last paragraph can be considered a minimal consensus among many philosophers of science in the twentieth century. Goethe anticipated the consensus, if not in all of its details, and not exactly in the terminology used today.[23] At the same time, he addressed a question that is forced upon us once we take seriously the position that I sketched above: Are there genuine examples of persuasive alternatives to our well-established theories, or is this merely an abstract possibility – that is, a possibility that only occurs in philosophical discussions?

With Goethe's help it can be shown (I claim) that there are several alternatives to Newton's *Opticks* which exemplify Quine's underdetermination thesis. For example, Goethe's own account of prismatic colours may well be considered to fit the bill. It is beyond the scope of this paper to discuss that theory in detail or to develop the other alternatives that emerge from Goethe's research about colours.[24] So let me conclude my paper with a few sketchy remarks about Goethe's account and its merits as compared to those of Newton's theory.

## 6 Border Spectra

As indicated in Sect. 4, Goethe claimed that the green centre in Newton's spectrum $S_N$ arises as a juxtaposition of the yellow and turquoise colour patches that occur near the prism (Fig. 5). Let us take a closer look at this. Given the orthodox point of view, we send (idealized) light rays through the prism: the rays have active, optical powers, and their dark surroundings (in Newton's dark chamber) provide the neutral stage where the rays exhibit their optical play.

In this situation, Goethe introduces a *gestalt switch*; he invites us to see the same configuration under a different aspect: Now it is *borders* between light and darkness which exercise active, optical powers. What (in the orthodox theory) constituted the neutral background, or frame, suddenly becomes an *integral part* of the optical play. (Notice that this profound move does not force us to ban the idealized tools of

[22] See Quine [oEES]. In the twin paper to the present one (see note 34), I propose a more rigorous reasoning in favour of underdetermination à la Quine, which derives from another Goethean variation of Newton's experiments; see O.M. [PE].

[23] He talks, for example, of "prejudices" instead of theoretical preferences, see [LA]/I.5:§30. In his terminology, Goethe came closest to the underdetermination thesis in Goethe [LA]/I.8:182.

[24] Arguably Goethe's strongest example is what I call the theory of the heterogeneity of *darkness* (without that name in Goethe [LA]/I.7:86). Unlike Goethe's own account of prismatic colours sketched in the main text, the heterogeneity of darkness is introduced by Goethe merely for the sake of argument. He wants to demonstrate, and can demonstrate, that all things considered, this theory is just as good (or bad) as Newton's. (For many details about this see O.M. [PE]; a comprehensive account is given in O.M. [ML]).

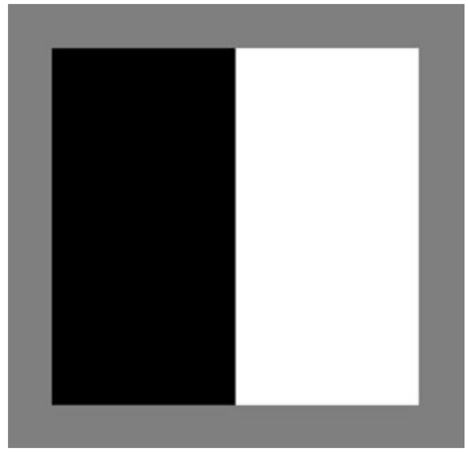

**Fig. 6** Black contrast, which – when observed with the prism – produces the warm border spectrum $S_W$ (Fig. 7). The black half of this contrast is (according to Goethe) not to be considered as neutral (and causally inefficacious) part of the frame of what is seen; rather it belongs to the image as much as its white half (Image by Benjamin Marschall)

**Fig. 7** Warm border spectrum $S_W$. The *gestalt* switch, which Goethe wants us to undertake, leads to observing *four* colours: *black*, *red*, *yellow*, *white* – rather than just two. Accordingly, *black* and *white* do not constitute the frame of the phenomenon, but an integral part of it (Photographed by Ingo Nussbaumer)

geometry from our optical enterprise; a border between black and white is as sharp as you could wish. Isn't it even sharper than a light ray?)

Given this, Newton's spectrum $S_N$ is to be split in two; the first part results from an optical border between darkness (left) and brightness (right) – the second part from a border which is turned the other way around: a border between brightness (left) and darkness (right). Let us consider these two optical plays separately. If you send a contrast.

black, white (Fig. 6),

through the prism, you obtain what I call the warm border spectrum $S_W$:

black, red, yellow, white (Fig. 7).

Notice that now both colours black and white are part of the experiment's result. If you switch the orientation of the contrast to be sent through the prism, i.e., if you work with this contrast:

white, black (Fig. 8),

then you obtain what I call the cool border spectrum $S_C$:

white, turquoise, blue, black (Fig. 9).

According to Goethe, the basis of all colour phenomena does not lie in the Newtonian spectrum $S_N$ (as Newton would have it), but rather in the border spectra

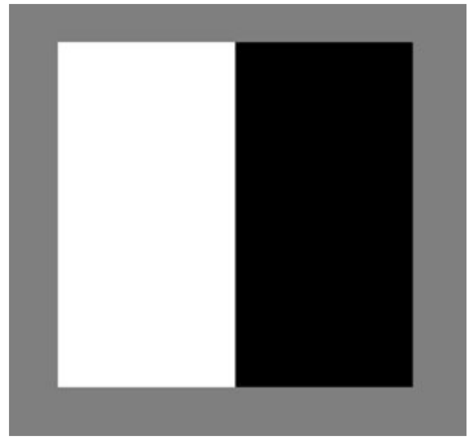

**Fig. 8** *White* contrast, which – when observed with the prism – produces the cool border spectrum $S_C$ (Fig. 9) (Image by Benjamin Marschall)

**Fig. 9** Cool border spectrum $S_C$. For a Newtonian explanation see Fig. 4, upper half (Photographed by Ingo Nussbaumer)

$S_C$ and $S_W$. As shown above, the green centre of Newton's spectrum can well be explained as the overlap of these two spectra.

Nowadays we believe that the full Newtonian spectrum $S_N$ is fundamental and that the border spectra $S_W$ and $S_C$ are not; from the current point of view Goethe has lost the dispute.[25] Nevertheless I want to highlight two aspects in favour of Goethe's point of view. They have to do with how we perceive colours: with the phenomenology of colours.[26]

First, the colours of the border spectra look more convincing than those of the full spectrum $S_N$. This is particularly obvious in the case of yellow.[27] Newton's spectrum $S_N$ does contain a small stripe of yellow between green and red, but it is brownish and dark. The yellow in border spectrum $S_W$, however, shines brightly and looks as clean as a ripe lemon. If the aim is to construct an optical theory of *colour*

[25]Here is roughly what current physics says about the matter: white light consists of different types of photons, whose frequencies correspond to the various spectral colours (as long as enough photons of the same frequency reach a white screen); in particular, there are photons of a certain frequency that produce light of green appearance – so there is such a thing as unmixed, pure spectral green (speaking loosely). On Goethe's view, however, green can only be composed of different colours, namely of the turquoise section in border spectrum $S_C$ and of the yellow section in $S_W$, see Goethe [LA]/I.4:§245/6, [GTC]:§245/6, [ToC]:§245/6.

[26]The next paragraphs comprise considerations and formulations that were first published in a different – art historical – context, see O.M. [BSiS]:133–135.

[27]Bjerke [NBzG]:42. The Viennese painter and colour researcher Ingo Nussbaumer voiced similar criticism of Newton's yellow in his lecture "Paradigma, Urphänomen, Hypothese und Prinzip" (philosophy of science colloquium at the Humboldt University Berlin on 21 June 2007).

**Table 1** Pairs of complementary colours

| Cool border spectrum $S_C$ | Warm border spectrum $S_W$ |
|---|---|
| Black | White |
| Blue (with a tint of violet) | Yellow |
| Turquoise (i.e., cyan) | Red |
| White | Black |

(as it was for both Newton and Goethe) and not merely an optical theory of *light*, this consideration ought to have some weight. It gives us an additional reason to favour Goethe's theory. Indeed, the colours of the border spectra are *aesthetically* prior to those of the full spectrum $S_N$.

Let us turn to the second aspect in favour of Goethe's account. There is no clear organising principle in Newton's spectrum $S_N$; but the two border spectra are *exact* counterparts to each other (Table 1).

The spectra are counterparts because each section of the cool border spectrum $S_C$ contains the precise complementary colour of the warm border spectrum $S_W$: Blue is the colour complement to yellow, turquoise the complement to red. (The same holds for the intermediate colours as well as for black and white). So if you were to stare at any part of one border spectrum and then turn your eyes to a grey or white surface, you would see an afterimage which matches the colour of the corresponding part in the other border spectrum.

This symmetry (or "polarity", as Goethe called it) between the two border spectra was a clear sign for Goethe: In his view, it indicated that he had discovered a general principle. In all of his scientific work, whether theoretical or experimental, Goethe would actively search for symmetries – just as the physicists of our time do.[28] Here we have another – aesthetical – aspect that supports Goethe's theory. As indicated above, criteria such us elegance, symmetry, and simplicity matter for theory choice.[29] Since the significance of symmetry for physics had not been acknowledged in Goethe's days, it is not surprising that his optical research was dismissed as a fancy baublery of an amateur with a sense of beauty out of control. Nowadays we should know better.[30] Even in his days, however, a few physicists did appreciate Goethe's principle of polarity. As I have argued elsewhere, it has led Johann Ritter, the ingenious physicist and chemist, to detect what we now call ultraviolet radiation; Goethe was probably the second person who saw Ritter's brilliant experiment.[31]

To sum up: Although nowadays the Newtonian spectrum is seen as more fundamental than the border spectra and although the latter can be explained in Newtonian terms, it is also possible to explain things the other way around. Which

[28]Goethe's systematic search for symmetry is discussed in O.M. [GPmS] and O.M. [ML], part II; symmetries in science are the subject of O.M. [ZSUF], O.M. [CSC].

[29]They also matter when experiments are chosen, canonized, or published. (See O.M. [CSC]).

[30]See Doncel et al. (eds) [SiP].

[31]O.M. [GPmS]: 164–167.

theory has to be preferred? The empirical data that had been collected in Goethe and Newton's days do not settle the issue. So we may introduce further criteria for theory choice, such as beauty, symmetry, simplicity. According Goethe's view, the border spectra appear to provide us with a more attractive (because more beautiful and symmetric) starting point for doing optics. It may be difficult to judge whether these considerations would have been decisive in Newton and Goethe's days; suffice it to say that it is not obvious that, back then, Goethe's theory should have or would have lost the competion, given rational criteria of theory choice.

## 7 A Double Error in Max Born's Objection

Against the considerations of the foregoing section, a strong objection can be raised. It was first voiced by Nobel prize winner Max Born and runs thus:

> GOETHE took the border spectra to be a fundamental phenomenon created by the interplay of light and dark. Now, anthroposophical colour researchers and others claim not only that GOETHE'S observations were correct (which hardly anyone would doubt), but also that his border spectra are fully on a par with NEWTON's spectra. They thus must hold that the border spectra could just as well serve as starting point for the physical analysis of colour. I take this claim to be false. One has to keep in mind the concept of separating something into its elementary components that NEWTON employs. Merely separating the components is not enough; one also has to show that they can be recombined into the original (Born [BzF]:37; translation mine).

Indeed, Newton had proudly announced what one might call a white synthesis – the reversion of the white analysis from his first experiment:

> But the most surprising and wonderful composition was that of Whiteness. [ . . . ] I have often with Admiration beheld, that all the Colours of the Prism being made to converge, and thereby to be again mixed [ . . . ] reproduced light, intirely and perfectly white (Newton [NTaL]:3083; emphasis omitted).

Given this, Max Born claimed that the colours of Goethe's border spectra cannot be recombined so as to regain the original contrasts from which they were derived. Here the Nobel prize winner made an empirical mistake, which I'll correct at the end of this section. But he made a theoretical mistake as well; he overlooked that all optical events are symmetric with respect to time.

To exhibit his mistakes, I'll first explicate the very idea of time symmetry in optics; then I'll show how this idea has been implemented in the Newtonian white synthesis; finally I'll transfer the idea to Goethe's border spectra in order to demonstrate that Born was wrong not only theoretically, but also empirically.

Let us first return to the Newtonian spectrum $S_N$ on the screen in the dark room (Fig. 1) and consider the following thought experiment.[32] We change the direction

[32] In the following paragraphs I have incorporated some formulations that have been published before, see O.M. [CSC], Sect. 6.

of time for the entire set-up; putting it into rewind as it were. Then the red, yellow, green, turquoise, and blue light rays would travel from the screen back to the prism, and would be refracted by both surfaces (into the prism and out of it) exactly along the same trajectories they came from. Each ray would be refracted more or less strongly, according to its refrangibility. (At both surfaces, the red rays will be refracted the least, the blue rays the most).

Where do these rays go after they return through the prism? The answer is simple. They meet right back on the sun's surface. At this point, rays of all different colours are superimposed so that they lose their colour. We end up exactly as we started in the original experiment, with a white solar disk on a dark background.

In my thought experiment, I assumed that optical processes can be reversed through time. Can this be proven? It would be nice to have an optical experiment that exhibits such time symmetry to the naked eye; for example, in form of a symmetry between white analysis and white *synthesis*. To see how this might work, consider the following question: How come we actually see a coloured image on the screen in Newton's first experiment? How does this image get to our eyes? Here is too simple an answer: All of the different colours of rays arriving at the screen are reflected straight into our pupils. To our pupils? Recall that every one of us can see each colour on the illuminated screen; so these light rays have to travel to all of our pupils. They have to travel everywhere. This means that light rays are reflected from the screen in every direction. They disperse everywhere throughout the room.

So far this is trivial. Less trivial is the following special case. If the light rays are reflected from the screen in every direction, then some of them must return from the screen precisely along the same path they came from.

This is the idea that Newton's ally Desaguliers exploited for the white synthesis.[33] The coloured rays travelling backwards (from our earlier thought experiment involving reversed time) already occur in the original experiment itself.

Of course, not every light ray is reflected from the screen exactly back along the path by which it came. Most of the rays are reflected somewhere else, for example, to your pupils. But even so, a fair, though paler part of the light reflected goes straight back where it came from. Not only did we not think of this, we didn't see it either.

Now watch. If already in the original experiment the light rays travel the distance between the screen and the prism twice (first forwards and second backwards), then the original prism from Newton's analysis also serves the purpose of the synthesis. One just leaves the prism where it already was.

Figure 10 shows Desaguliers' white synthesis. Desaguliers takes a long prism so that there is enough space for him to look through it right along the same path as the rays of sunlight. He looks through the prism at the screen, which exhibits, from other angles (without the prism in the way of our eyes), a wide, variously coloured Newtonian spectrum $S_N$. When looking through the prism, however, we do not see the wide multi-coloured spectrum, but a narrow white circle of light; this is the superposition of different zones of the coloured spectrum $S_N$.

[33] For the following see Desaguliers [AoSE]:442 (= Experiment V).

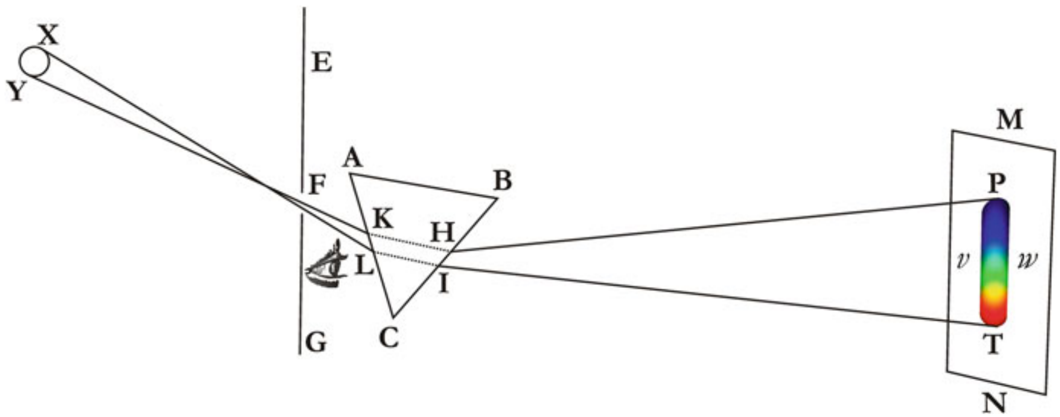


**Fig. 10** Newton's white synthesis in the style of his ally Desaguliers – here the experimenter looks *through prism ABC* at the spectrum PT. He sees a white image of the solar disk (Illustration by Ingo Nussbaumer, reproduced with his kind permission from Nussbaumer [RvI]:157; original drawing in Desaguliers [AoSE], Fig. 15)

Obviously, the same thing can be done with the two border spectra. You look through the very same prism by which e.g. the warm border spectrum $S_W$ (Fig. 7) was unfolded on the screen, and what you see is the contrast from which that spectrum has been generated – the contrast between black and white (Fig. 6). The same method can be applied to the cold border spectrum $S_C$. The synthesis of both contrasts (black/white and white/black) from the two spectra is documented in Fig. 11. Given time symmetry in optics, this experiment is not surprising. What is surprising is that Max Born thought that it cannot succeed. Once again, Goethe's cards are stronger than famous physicists realize.

Of course, Goethe's theory is not in accordance with contemporary physics. But what does that prove? If we knew for sure that physics moves forward along a firm, objective course, then later developments in physics would speak objectively against Goethe's theory of colours. However, my considerations concerning the prism experiments give rise to serious doubts about scientific objectivity.[34]

[34]This is a revised translation, elaboration, and correction of 50% of a paper published in German with quite some mistakes ten years ago (O.M. [GPUb]). The other half of the paper is translated (and again, corrected) in O.M. [PE]. For the sake of clarity, the two English papers have a certain overlap (particularly in sections II and III of the present paper). However the main arguments in these two papers are independent of one another: In the other paper I have employed sharp mathematical means to radicalize one line of Goethean thought (perhaps far beyond of what he would have liked). In the present paper, by contrast, I have tried to be closer to Goethe's spirit in colour research. Many thanks to Eric Oberheim for translating large portions of the original text into English, and to Emanuel Viebahn for both philosophical and stylistic advice concerning the final version. Last but not least, I wish to express my gratitude to Ingo Nussbaumer for years and years of conversations about spectral colours as well as for carrying out and documenting the ultimate experiment of the present paper.

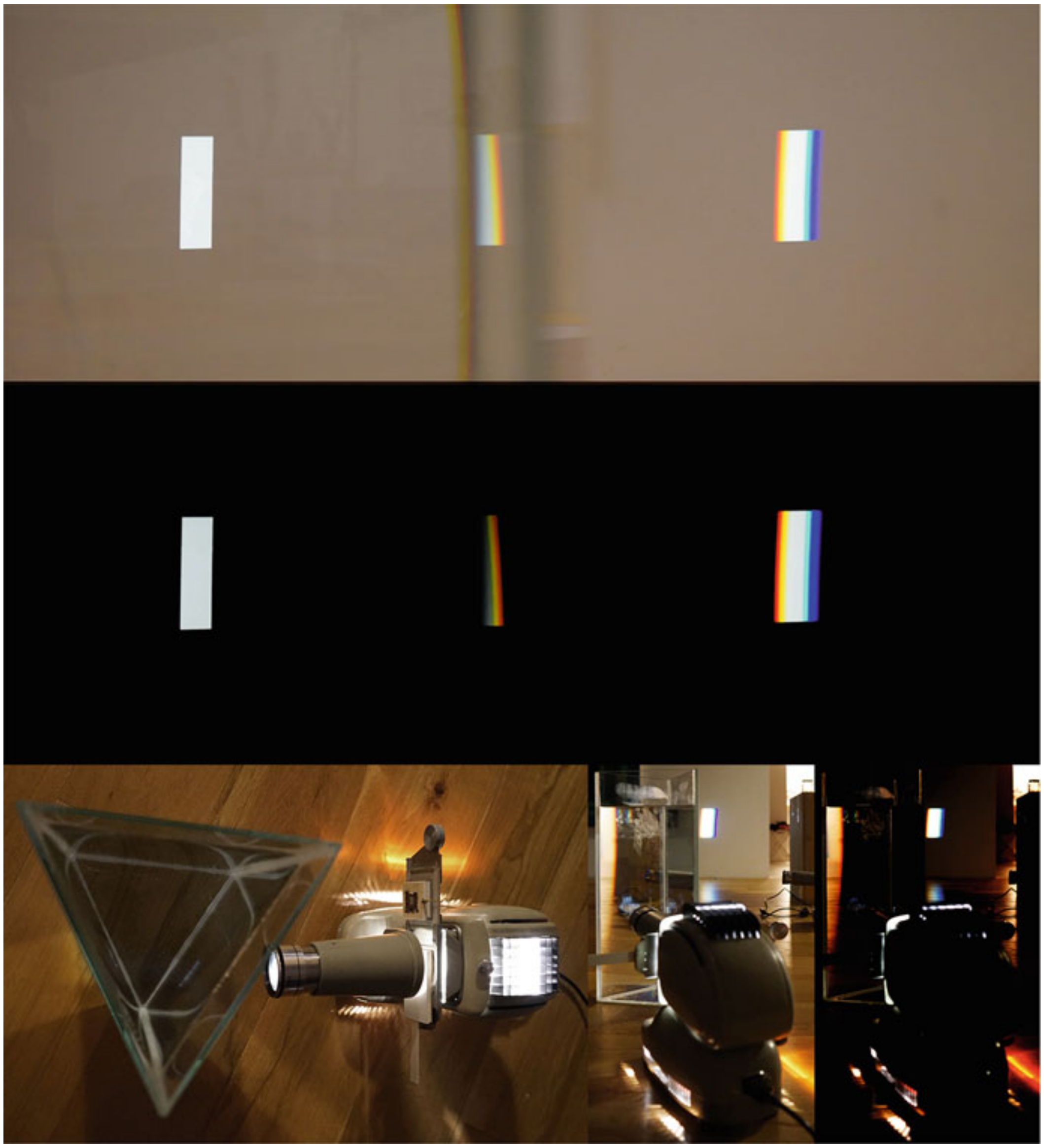

**Fig. 11** If we apply Desaguliers' technique for synthesizing colours (Fig. 10) to the border spectra $S_W$ and $S_C$ (Figs. 7 and 9), the original contrasts between black and white (Fig. 6, Fig. 8) reappear. **Bottom row**, *left*: The slide projector sends its light through the water prism. **Bottom row**, *centre*: Above the projector, the photo camera (not shown) is placed to take a picture past the prism as well as through it: On the screen in the distance, the two border spectra emerge, which are photographed simultaneously both past the prism and through it. **Bottom row**, *right*: The same constellation, just with the lights turned off. **Middle row**: The photograph taken in the constellation just described and shown. **Middle row**, *right*: The two border spectra $S_W$ (*left*) and $S_C$ (*right*), divided by the white centre (see Fig. 3), as photographed past the water prism. **Middle row**, *left*: The two border spectra as photographed through the water prism – their colours disappear, and you see the black/white contrast as well as its white/black counterpart. **Middle row**, *centre*: As the two images described before belong to one and the same photograph, they are divided by the prism's edge, next to which a mirror image (an experimental artefact) is visible. **Top row**: The same photograph, just with the lights turned on so that the water prism's sides in the centre are better visible. With the lights on, the synthesized black/white/black contrasts appear of course brighter, and thus look greyish (Photographed by Ingo Nussbaumer)

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