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## ARTICLE

PRISMATIC EQUIVALENCE – A NEW CASE OF  
UNDERDETERMINATION:  
GOETHE VS. NEWTON ON THE PRISM EXPERIMENTS

Olaf L. Mueller

Goethe's objections to Newton's theory of light and colours are better than often acknowledged. You can accept the most important elements of these objections without disagreeing with Newton about light and colours. As I will argue, Goethe exposed a crucial weakness of Newton's methodological self-assessment. Newton believed that with the help of his prism experiments, he could prove that sunlight was composed of variously coloured rays of light. Goethe showed that this step from observation to theory is more problematic than Newton wanted to admit. By insisting that the step to theory is not forced upon us by the phenomena, Goethe revealed our own free, creative contribution to theory construction. And Goethe's insight is surprisingly significant, because he correctly claimed that all of the results of Newton's prism experiments fit a theoretical alternative equally well. If this is correct, then by suggesting an alternative to a well-established physical theory, Goethe developed the problem of underdetermination a century before Duhem and Quine's famous arguments.

**KEYWORDS:** underdetermination; colours; light; darkness; Newton; Goethe; Quine; Chang

## 1. INTRODUCTION

Goethe wanted to triumph over Newton's theory of light and colours: over a theory that had been accepted by nearly all physicists of his time and that still makes up a substantial portion of our understanding of light and colours. The famous poet's three-part *Farbenlehre* (*Theory of Colours*) is motivated, propelled, and united by his uncompromising opposition to that well-established scientific theory. From today's point of view, Goethe's assault on Newton's theory seems somewhat strange; historically interesting, perhaps, but not respectable from any sensible, systematic point of view.

Contrary to these appearances, I shall try to defend Goethe's critique of Newton on the methodological grounds recognized by contemporary philosophy of science. If I am right, Goethe discovered a deficiency in Newton's methodological self-assessment. 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 Newton simply had more luck than Goethe. I will only insist that Goethe produced solid methodological work with his critique of Newton.

In contrast to what is often alleged, Goethe understood quite well how empirical sciences work and what they can achieve.<sup>1</sup> He thought these matters through more deeply than his contemporaries and thereby arrived at a result that was ahead of his time. I will argue that Goethe delivered just about everything needed to formulate and substantiate the thesis of the empirical underdetermination of scientific theories.<sup>2</sup> This thesis gained considerable fame more than a century later, through Duhem and Quine, and has been discussed in many different versions over the last decades.<sup>3</sup> The version of the thesis that can be drawn from Goethe is more down-to-earth and matches the history of science more realistically than Quine's classic version, which, famously and boldly, concerns *complete* systems of the (complete) world (Quine, 'On Empirically Equivalent Systems', 313).

In this essay, I do not intend to analyse or evaluate Quine and Duhem's considerations, which are famous enough. My primary aim is to identify and develop Goethe's contribution concerning underdetermination. Drawing on his work, I'll provide a few motives in favour of underdetermination which have not yet been fully appreciated, or even considered at all – due, at least partly, to the fact that they have not been translated into English.<sup>4</sup> I hope that those familiar with the contemporary discussion

<sup>1</sup>The allegation is as old as Goethe's *Farbenlehre* itself (Mollweide, 'Tübingen, b. Cotta. Zur Farbenlehre', 233/4). See also, for example, Helmholtz, 'On Goethe's Scientific Researches', 8/9, 11/2, 13, 16.

<sup>2</sup>In his terminology, Goethe came closest to the thesis in Goethe, *Leopoldina-Ausgabe*, I.8, 182.

<sup>3</sup>Quine, *Word and Object*, 78; 'On Empirically Equivalent Systems of the World'; Laudan, 'Demystifying Underdetermination'; Laudan and Leplin, 'Empirical Equivalence and Underdetermination'; Hoefer and Rosenberg, 'Empirical Equivalence, Underdetermination, and Systems'; Kukla, *Studies in Scientific Realism*; Magnus, 'Underdetermination and the Problem of Identical Rivals'; Okasha, 'The Underdetermination of Theory by Data'; Dawid, 'Underdetermination and Theory Succession'; Bergström, 'Quine, Underdetermination, and Scepticism'; 'Underdetermination of Physical Theory'. Recently, Stanford has developed a fresh perspective, with a new set of examples, see note 26.

<sup>4</sup>Goethe's *Farbenlehre* consists of three volumes and several appendices; the original titles of the three volumes are: *Entwurf einer Farbenlehre*, generally known as the didactic part (Goethe, *Leopoldina-Ausgabe*, I.4); *Enthüllung der Theorie Newtons*, generally known as

about underdetermination will appreciate the significance of Goethe's ideas. In particular, they may welcome a new concrete example from the history of science, which helps both illustrate and support the underdetermination thesis.

## 2. TWO LEVELS OF CONTROVERSY

I just outlined *in abstracto* and in all too modern terms what the controversy between Newtonians and Goethe 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 described 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.<sup>5</sup> The second claim (whose decisive term I have italicized) 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*.<sup>6</sup> From Newton's perspective, the claim on the object level is unequivocally determined by empirical observations and thus (according to Newton, but in modern terms) not an example of underdetermination.

Goethe attacked Newton's proud attitude towards his scientific results, and he was right to do so, as I will try to show.<sup>7</sup> I want to demonstrate that Goethe was led to the following correct view (which may well be of utmost interest for contemporary proponents of underdetermination):

the polemic part (Goethe, *Leopoldina-Ausgabe*, I.5); *Materialien zur Geschichte der Farbenlehre*, generally known as the historical part (Goethe, *Leopoldina-Ausgabe*, I.6). Whereas the main sources of my considerations can be found in the polemic part, only the didactic part has been translated into English (twice, in fact), though not everywhere in the most satisfactory fashion (Goethe, *Goethe's Theory of Colours*; 'Theory of Color: Didactic Section'). 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.

<sup>5</sup>It results from Newton's first two theorems (Newton, *Opticks*, 20, 26).

<sup>6</sup>Turnbull, *The Correspondence of Isaac Newton, Volume 1*, 96–97, 142, 173–175, 177, 209; *The Correspondence of Isaac Newton, Volume 2*, 79–80; Newton, *Opticks*, 1, 158/9; see also 'Draft Comments on Rizzetti' (1722), Cambridge University Library MSS Add 3970, f. 481 v; cited by Shapiro, 'The Gradual Acceptance of Newton's Theory', 119.

<sup>7</sup>Goethe was of course not the first to criticize Newton's methodological self-assessment; in Newton's time, Hooke tried the same – with less success than Goethe, as I'll indicate in note 23.

The prism experiments *do not prove* that sunlight is a heterogeneous mixture of variously coloured light rays (or in Quinean terms, they *do not determine* that theory).

This 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).

Now, Goethe certainly did not want to accept Newton's first claim either. Objections to the heterogeneity of white light can be found throughout Goethe's *Farbenlehre*. As I do not want to question the results of contemporary science, and as I count the heterogeneity of white light as an integral part of its results, I shall downplay Goethe's disagreement with it. In my opinion, we can accept Goethe's fundamental point without thereby adopting a verdict, one way or another, about Newton's claim on the object level.

Admittedly, Goethe often appears to be concerned with the object level. But that can be explained. Goethe did not always sharply distinguish between the two different levels; particularly in the first few years of his research (long before the publication of the *Farbenlehre*), he did not always sharply distinguish between claims about the properties of light and claims about the *status* of these claims. Whenever reasonably possible, I will lift Goethe's formulation onto the higher level, whereby his account becomes more plausible and poignant. This interpretation matches his stated views, as will become clearer when we hear what Goethe had to say about the status of his protests against Newton's results:

We thus do not by any means imagine ourselves to have proven that Newton was wrong.

(Goethe, *Leopoldina-Ausgabe*, I.5, §31)

In this passage, Goethe refers only to Newton's *first* theorem (Newton, *Opticks*, 20). In the context of this passage, however, Goethe explicitly generalizes his considerations. The passage can be understood as an indication of a general restraint that, for the sake of brevity, Goethe does not always repeat. These considerations come under the heading 'Proof through Experiment'. Here is how they begin:

We would not like to scare off our reader straight from the start with some paradox. Nevertheless, we cannot refrain from claiming that nothing can be proven through experience and experiments.

(Goethe, *Leopoldina-Ausgabe*, I.5, §30)

From this you may suspect that Goethe did reject the experimental method of the natural sciences altogether. If this were the case, then no possibility of reconciling Goethe's *Farbenlehre* with the achievements and *methods* of contemporary science would remain. However, the suspicion is baseless, as Goethe continues:

The phenomena can be very precisely observed. The experiments can be performed immaculately, and one can exhibit experience and experiments in a certain order.

(*Leopoldina-Ausgabe*, I.5, §30)

Goethe was serious here. In his *Farbenlehre*, he described an impressive number of experiments that he carried out himself. And he encouraged his readers to do the same. This was no mere lip service. On the one hand, Goethe's friends and acquaintances got roped into his colour lab – Schiller, A. Humboldt, Fichte, Schelling, Hegel, Schopenhauer, and many others spent a lot of time looking through Goethe's various prisms. On the other hand, the *Farbenlehre* contains coloured figures that are not merely *illustrations* of experiments. Rather, their primary purpose is to function as part of one's own experiments.<sup>8</sup> Anyone who looks at these figures with a prism can reproduce the prominent experiences from Goethe's writings on colours.

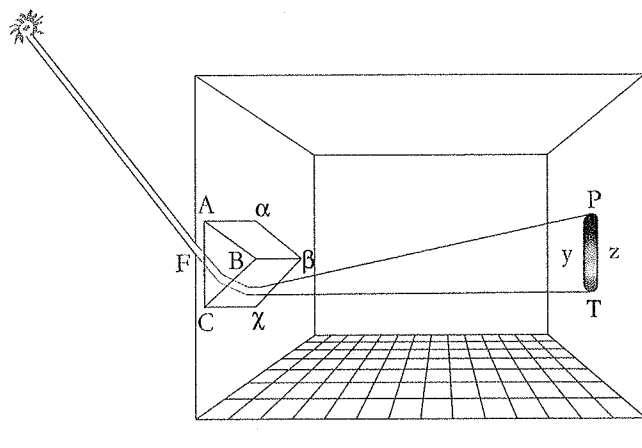
### 3. GOETHE'S VARIATIONS ON NEWTON'S MOST FAMOUS EXPERIMENT

Let us examine the conclusiveness of one of the simplest, and most famous, Newtonian experiments.<sup>9</sup> On a sunny day Newton closes the doors and window shutters of a room facing south, and then turns out 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 board 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 board is not white, but like a multi-coloured rainbow; and it is not round, but five times as long as it is wide. At one end it is red. At the other end it is violet. The coloured band in between is yellow, green, and blue.

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

<sup>8</sup>'[...] we were unable to dispense with plates, but we endeavoured to construct them so that they may be confidently [...] considered as forming part of the [experimental – O.M.] apparatus [...]' (Goethe, *Leopoldina-Ausgabe*, I.4, 9/10, cf. *Goethe's Theory of Colours*, xlix and 'Theory of Color: Didactic Section', 162).

<sup>9</sup>For the following, see Turnbull, *The Correspondence of Isaac Newton, Volume 1*, 92–94. Also see my Figure 1 on the next page.



**Figure 1.** Newton discovers the heterogeneity of light. Light rays are refracted by a prism (left). In the dark chamber on the right, Newton catches his well-known spectrum. The light rays that are redirected from their path the furthest are violet. They can be seen in the upper part of the spectrum. (Redrawn by Ingo Nussbaumer; the original is in Newton's notebook, reprinted in Lohne, 'Isaac Newton: The Rise of a Scientist').

If one now imagines the multi-coloured band as a series of patches of colour (violet, blue, 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 divides the colourless light ray (emerging from the sun) into variously coloured rays of light. It divides that light ray by refracting its violet part more strongly from its path than the blue part; the blue 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.<sup>10</sup>

That is how Newton sees it. Do we want to call Newton's train of thought a proof?<sup>11</sup> Does the experiment sketched above *force* the conclusion on us that white sunlight is a mixture of variously coloured light rays, and that these variously coloured light rays were diversely refracted? It does not, says Goethe. He took Newton's result as a theoretical hypothesis that goes

beyond what can be seen in the experiment; but Newton did not wish to feign hypotheses (Newton, *Opticks*, 369–370).

Of course, Goethe does not challenge the *existence* of the elongated colour band twenty-two feet beyond the prism. He challenges its *conclusiveness* for the hypothesis of the heterogeneity of light. And for this purpose, he is not just being obstinate by insisting that a band of colours on some particular board 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. To put it in his own terms, he 'multiplies' the observations.<sup>12</sup>

In the course of experimenting, Goethe develops the innovative idea of exchanging the roles of light and darkness; he wants to see what prism phenomena appear given a dark spot on a well-illuminated prism.

The first step towards this new experiment can easily be achieved by a simple variation in the circumstances. Just replace the board (that catches the coloured band of light) with the eye's retina. In other words, instead of looking at a board that registers what passes through the prism, we look directly through the prism ourselves. Newton's original prism experiment can be repeated at low cost with this more direct procedure.<sup>13</sup> If, for example, we look through the prism at a tiny white spot against a black background, we see Newton's famous band of colours:

red, yellow, green, blue, violet.

Now Goethe introduces his new experiment. He reverses everything; he looks at a tiny *black* spot on a white background.<sup>14</sup> The result is surprising. Once again, there is a band of colours. And as long as the two spots are the same size and the same prism is used from the same distance, the new band of colours can be seen just as clearly as the original band of colours, and it is also the same size as the original one. However, the new band of colours contains some new colours, and they have an entirely unusual order:

blue, violet, *purple*, red, yellow.<sup>15</sup>

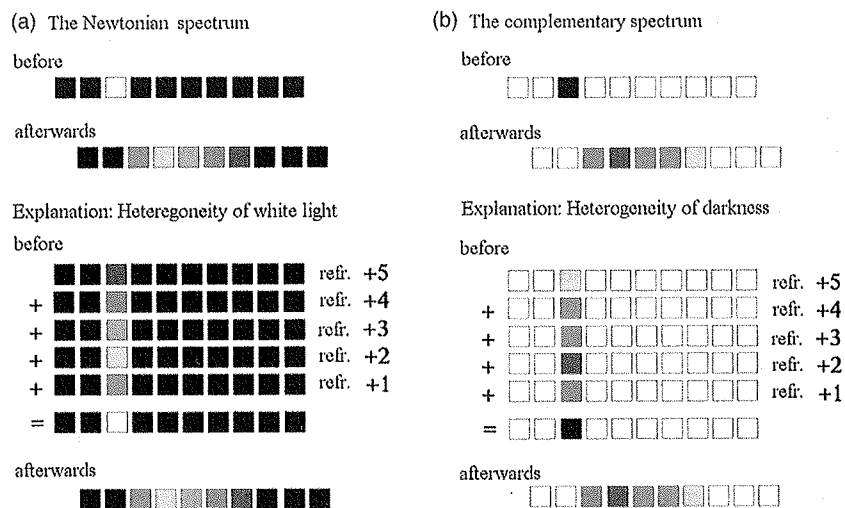
<sup>10</sup>See Figure 2(a) on page 8. – Strictly speaking, it is insufficient to observe just five different colours of light rays. Rather there will be indefinitely many fine gradations between the five colours specified. For the sake of brevity, I shall continue to talk about five different colours.

<sup>11</sup>Newton does not credit the experiment with any conclusiveness in his first publication from 1672; the proof there was to be delivered by the *experimentum crucis* (Turnbull, *The Correspondence of Isaac Newton, Volume 1*, 94/5). For two reasons, however, this fact does not affect my considerations. First, these have an analogous counterpart with respect to the *experimentum crucis*; this counterpart is just a little more complicated (see note 23). And second, in the *Opticks* Newton does indeed credit the simpler experiment with conclusiveness (Newton, *Opticks*, 26–33).

<sup>12</sup>This expression – 'vermannigfachen' – occurs often (e.g. Goethe, *Leopoldina-Ausgabe*, I.5, §56, §168).

<sup>13</sup>For obvious reasons, Goethe calls the first experiments discussed here 'objective experiments' while the experiments in which the experimenter looks through a prism are called 'subjective experiments'. The objective and subjective experiments are strictly related to each other (Goethe, *Leopoldina-Ausgabe*, I.4, §299–305, cf. *Goethe's Theory of Colours*, §299–305 and 'Theory of Color: Didactic Section', §299–305). There are also subjective experiments in Newton's research (not, however, with that name). The very first experiment in the *Opticks* is a subjective experiment (Newton, *Opticks*, 20–23).

<sup>14</sup>See Goethe, *Leopoldina-Ausgabe*, I.4, §215, 1970, §215, 1995, §215. Compare Figure 2(b).



**Figure 2.** (a) (Left). In Newton's experiment, the light rays appear white before they pass through the prism (upper part of the figure). Newton interprets these as the sum of red, yellow, green, blue, and violet light rays (centre of the figure). The violet light rays are refracted the furthest (a whole five units). The red light rays are refracted the least (only one unit). The black boxes symbolize missing light rays, which Newton's explanation ignores as they are taken to be causally inefficacious. Recall that both the number of coloured rays and the five degrees of their refrangibility in my figures are a massive simplification; Newton talked about infinitely many degrees of refrangibility. But of course, more coloured boxes could be added without loss of explanatory power. (b) (Right). In his new experiment, Goethe produces the complementary spectrum. A black spot appears colourful when viewed through a prism (upper part of the figure). In the unorthodox explanation, the black spot is interpreted as a summation of blue, violet, purple, red, and yellow darkness rays (centre of the figure). The yellow darkness rays are refracted the furthest (a whole five units). The blue darkness rays are refracted the least (only one unit). The white boxes symbolize missing darkness rays, which are ignored by this explanation as they are taken to be causally inefficacious.

<sup>15</sup>As I will substantiate in the next footnote, all of the subjective experiments discussed here can be repeated objectively. Even so, in the text I stick to the subjective complements because they appeared earlier. Newton even knew about some early versions. They can be found in two letters from the Jesuit Lucas. Both versions are subjective experiments. The first version is in a letter from 17.5.1776 (Turnbull, *The Correspondence of Isaac Newton, Volume 2*, 8–12, see point 7 on p. 11). The letter was sent to Newton through Oldenburg; Newton answered it with several letters, although he did not mention point 7 in his answers (cf. Turnbull, *The Correspondence of Isaac Newton, Volume 2*, 8). The second version of the relevant experiment is in a letter from Lucas from February 1677/8 (Turnbull, *The Correspondence of Isaac Newton, Volume 2*, 249). The letter went to Newton through Hooke and was answered by Newton on 5.3.1677/8 (Turnbull, *The Correspondence of Isaac Newton, Volume 2*, 254–260). There, Newton reacted to the second version of these novel experiments (257). In the *Opticks*, Newton presents and explains the same (subjective) experiment (Newton, *Opticks*, 165).

To the impartial eye, the two bands of colours are on a par. They are equally luminescent, clear, big, and colourful. There is not the slightest reason to favour one band of colours over the other.<sup>16</sup> Goethe concludes: If Newton were justified in inferring that white light divides into its component colours

red, yellow, green, blue, violet,

when passing through the prism from his original experiment (with a white spot on a dark background), then the following inference would have to be equally justified. Darkness divides into its component colours,

blue, violet, purple, red, yellow,

when passing through the prism in the new experiment (with a dark spot on a white background). This is what I call the heterogeneity of darkness. Goethe does not use that expression (or its German equivalent). He says:

Thus these phenomena seemed completely parallel to me. What was a correct explanation of the one seemed equally applicable to the other, and from that I concluded the following: If the [Newtonian – O.M.] school can claim that the white image on dark background is dissolved, separated, and scattered through refraction, then the school can and must just as well claim that the black image was dissolved, split, and scattered through refraction.

(*Leopoldina-Ausgabe*, I.7, 86)

According to this new idea, darkness and blackness are composite phenomena. They result from the juxtaposition of the colours blue, violet, purple, red, and yellow – they result from the juxtaposition of variously coloured darkness rays, so to speak.

<sup>16</sup>On the basis of parallel experiments with water prisms, Goethe shows that nothing changes by returning to the objective experiments (Goethe, *Leopoldina-Ausgabe*, I.4, §331, cf. *Goethe's Theory of Colours*, §331, 'Theory of Color: Didactic Section', §331). You can observe the result of this objective experiment nicely on Goethe's 'Tafel VI' (Goethe, *Leopoldina-Ausgabe*, I.7, 69; cf. Goethe, 'Theory of Color: Didactic Section', 206–7/VIII, 'Plate VI'). It is worthwhile comparing this colour plate with another plate where Newton's original objective experiment is portrayed. Apart from different colours, both offer exactly the same illustration, see Goethe's 'Tafel V' (Goethe, *Leopoldina-Ausgabe*, I.7, 65; compare Goethe, 'Theory of Color: Didactic Section', 206–7/VII, 'Plate V'). In the first English translation, Goethe's figures have different numbers, see Figure 2 and Figure 1, PLATE IV in Goethe, *Goethe's Theory of Colours*, 192–193. Goethe's observations of the complementary behaviour (in objective experiments) have often been repeated by physicists and other scientists (Holtsmark, 'Newton's Experimentum Crucis Reconsidered'; Rang and Grebe-Ellis, 'Komplementäre Spektren'; Kirschmann, 'Das umgekehrte Spektrum und seine Farben', 197ff; Nussbaumer, *Zur Farbenlehre*, 177/8).

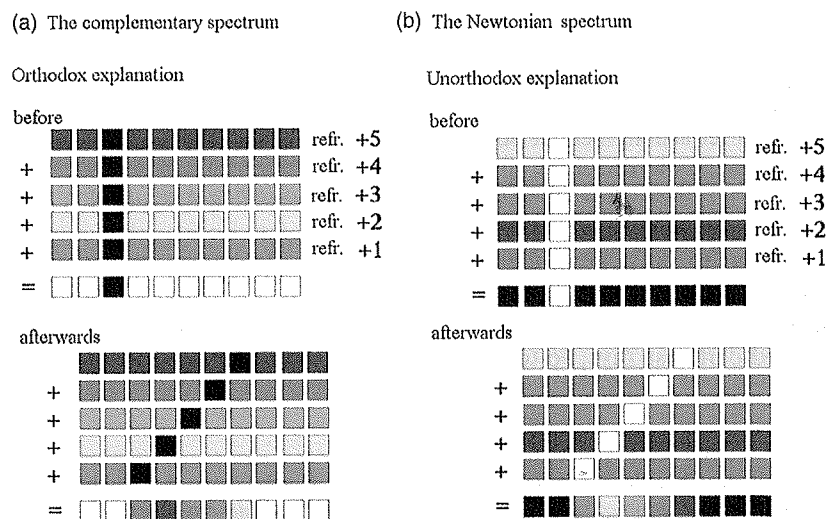
At first glance, this appears to be an extravagant hypothesis that invites a number of severe objections. I will deal with two of them. But before we delve into controversies concerning the heterogeneity of darkness, I would like to repeat that Goethe does not defend this hypothesis *in persona propria*. He merely wants to transform our instinctive resistance against the heterogeneity of darkness into resistance against Newton's heterogeneity of light. According to Goethe, *both* hypotheses are extravagant and equally improbable. The only difference is that we have become accustomed to Newton's heterogeneity of light, while the heterogeneity of darkness is an unusual, new idea.

The first objection to this new idea that I shall consider claims that darkness, as opposed to light, cannot be sent through prisms. Only light rays move through space. If one presupposes the traditional theory of optical phenomena, then that is correct. But talk of light rays is hypothetical and replete with theoretical assumptions. Who has ever seen a ray of light? From what you see, you may infer that light rays are offered to our eyes (Goethe, *Leopoldina-Ausgabe*, I.5, §217). However, you could equally

infer darkness rays from the image offered. Directly you can observe neither.<sup>17</sup> You can only see patches (in at least two dimensions), whether they are purple, yellow, blue, white, or black. These patches *can* (but need not) be theoretically explained with the help of light rays (in which case black patches will be explained as the absence of light rays). However, you could also explain the purple, yellow, blue, and black patches with the help of darkness rays. So the notion of darkness rays is a theoretical concept – just as is the notion of light rays.

But, you may object, we can *interrupt* light rays (thereby producing the dark shadow of an opaque object), whereas darkness rays cannot be interrupted in the same way. Answer: We *can* interrupt darkness rays – thereby producing the *white* shadow of an opaque object. Up to now, not too many people have seen white shadows; but they can be, and have been, demonstrated.<sup>18</sup>

What about the energetic effects of light rays? Since they transport thermic energy, does not this prove their causal efficacy, and thus, their existence? It does not, because the complementary effect exists as well (see Section 7).



**Figure 3.** (a) (Left). Newton can explain Goethe's experiment in orthodox fashion. The absence of light is supposed to have no causal powers. Only the surrounding white light sends colourful composite rays through the prism, which are then variously refracted by the prism according to the known rules (e.g. the violet rays the furthest – five units). When the results are combined, each colour of the complementary spectrum can be explained (lower part of the figure). Purple, for example, is the sum of violet, blue, yellow, and red – that is, the sum of all the colours except green (which in turn is the complement of purple). Purple is the result, so to speak, of removing green from the all-colour-inclusive white. (b) (Right). If we turn Newton's explanation of the complementary spectrum (a) into its colour negative, we arrive at the unorthodox explanation of the Newtonian spectrum. Each of the darkness rays are tracked as they pass through the prism, and then they are summed up.

#### 4. THE NEWTONIAN EXPLANATION OF COMPLEMENTARY COLOUR SPECTRA

The second objection to the heterogeneity of darkness draws our attention to the fact that this hypothesis is superfluous. Newton's heterogeneity of white light suffices to explain the (new) band of colours that appears when one looks through a prism at a black spot. According to Newton's hypothesis, the light rays coming from the whiteness (surrounding the black spot) contain many different colours that will be variously refracted as they pass through the prism. Consequently, many different overlapping colour combinations should meet at different points on our retina, and the juxtaposition ought to result in exactly the observed band of colours:

blue, violet, purple, red, yellow.

The objection is based on a promise – the promise to provide an explanation that has yet to be formulated. Let us examine the first step of this explanation. For example, let us examine the point on our retina where the violet component of a certain white light ray arrives. The light ray must have departed far from the left of the black spot (see the first row of colours in Figure 3(a)). The other coloured components of the ray of light would then be refracted by

<sup>17</sup>See Goethe's translation of Kepler, which Goethe approvingly comments upon (Goethe, *Leopoldina-Ausgabe*, I.6, 157/8).

<sup>18</sup>See Maier, *Optik der Bilder*, 148; cf. Susanne Böttgers's documentation (Kühl, Löbe and Rang, *Experiment Farbe*, 126).



the prism less strongly to the right than our violet component, and would therefore miss the point on the retina under consideration. Nevertheless, additional refracted light rays arrive at this spot on the retina. For example, the blue component of another white light ray that began less far to the left of the black spot, and consequently need not be refracted as strongly by the prism so as to hit the retina at exactly the point under consideration (Figure 3(a), second row). According to Newton, blue light is refracted less strongly than violet light as it passes through a prism.

Now if green light would come from the dark spot viewed through the prism, then this green light would also hit the point on the retina under consideration. Green light would be refracted even less to the right than the more strongly refracted blue and violet light rays (which originate from farther to the left). However, the spot in our experiment is black, and it does not emit green light. It does not emit light at all (Figure 3(a), third row).

Does it follow that only blue and violet light should reach the point on the retina under consideration? No, as until now we have only considered the light coming from the left side of the black spot. The yellow component of a white light ray emitted from directly to the *right* of the black spot is refracted even less strongly than the rays mentioned earlier, and consequently, it also arrives exactly at the point on the retina under consideration. And red light will arrive there from even farther to the right of the black spot (Figure 3(a), fifth row).

That completes the story about the point on the retina under consideration. As they pass through the prism, all other coloured rays of light from around the black spot are either not refracted enough to reach the spot on the retina, or they are refracted so strongly that they pass by. Thus, from Newton's spectrum, all the colours *except green* will reach the point on the retina under consideration. And if light rays with the colours:

red, yellow, —, blue, violet,

all overlap, the result is purple (see Figure 3(a), lowest row, fifth column from the left).

That is the Newtonian explanation of the purple patch in the middle of the band of colours that we see when we look through a prism at a black spot.<sup>19</sup> Similar explanations can be given for each of the other colours observed in

<sup>19</sup>For two reasons it is not obvious whether Newton *himself* would have explained the purple centre of Goethe's spectrum in the way outlined. First, the colour in question appears in his colour circle at a point called 'D', without any extension, like a mere idealized limit as it were; it would have to be the mean colour between violet and red (Newton, *Opticks*, 154–156). Second, this very colour was not explicitly recognized in the complementary spectrum (neither by Newton nor by Lucas). These difficulties, however, do not affect my main point. The German Newtonians of Goethe's days appealed precisely to the mixing rules that I have been invoking, see, for example, the anonymous attack on Goethe, quoted in Goethe, *Leopoldina-Ausgabe*, I.7, 89.

the experiment. So it is clear that the new band of colours does not require some new, extravagant hypothesis. It does not require the heterogeneity of darkness. And that seems to imply that the heterogeneity of darkness is superfluous – says the second objection to the new hypothesis.

Goethe waves aside the objection with grandiose gestures; to him, the Newtonian explanation of the new band of colours appears too contrived to be convincing. Goethe becomes polemic and makes no effort to defeat his opponents with their own weapons:

Future generations will regard such a sample specimen with astonishment, as towards the end of the Eighteenth Century, the natural sciences proceeded in ways of which the darkest monasticism and self-confusing scholasticism would not have to be ashamed.

(*Leopoldina-Ausgabe*, I.7, 89)

I claim that Goethe could have undermined the objection more thoroughly than he found necessary.<sup>20</sup> He repeatedly pointed out that the prismatic colours that appear when looking at a black spot can be handled exactly like Newton's prism colours when looking at a white spot. But with regard to the present situation, he failed to extend the parallel between the two phenomena far enough.

## 5. HOW GOETHE COULD HAVE RESPONDED

In order to meet the objection against the heterogeneity of darkness discussed in the previous section, Goethe could have turned the objection around. He could have used it against Newton's heterogeneity of light. He could have said that Newton's heterogeneity of light is superfluous because the Newtonian spectrum can be explained as a complicated juxtaposition of darkness rays that come from the *black surroundings* of the white spot; according to this unorthodox explanation, darkness rays are differently refrangible (see Figure 3(b), which is isomorphic to Figure 3(a)).

This unorthodox explanation follows exactly the same pattern as the Newtonian explanation of the complementary spectrum. The heterogeneity of darkness (and the unorthodox explanation developed from it) is indeed an exact complement to the Newtonian heterogeneity of white light (and the orthodox explanation developed from it). Newtonians take the colour series

red, yellow, green, blue, violet,

<sup>20</sup>Against misunderstandings: Criticizing Goethe's unnecessary polemics in the present context does not amount to the widespread and notorious critique of the polemic part of the *Farbenlehre*. The philosophical and optical merits of that part are grossly underestimated in the literature, for example in Zehe's accompanying commentary (*Leopoldina-Ausgabe*, II.5A, 269–270 *et passim*).

to be fundamental. From this they infer the heterogeneity of white light, and they claim:

As they pass through a prism, violet light rays will be more strongly refracted than blue rays, blue rays more strongly than green rays, etc. (Figure 2(a))

Given this, and given certain assumptions about the results of juxtaposing variously coloured light rays (see the previous section), Newtonians explain the band of colours:

blue, violet, purple, red, yellow,

which appears when a black spot is viewed through a prism (Figure 3(a)). Their unorthodox opponents proceed exactly the other way around. They consider the latter band of colours to be fundamental, and from this they infer the heterogeneity of darkness. They claim:

As they pass through the prism, yellow darkness rays are refracted more strongly than red darkness rays, red darkness rays more strongly than purple darkness rays, etc. (Figure 2(b))

Given this, and given certain assumptions about the results of juxtaposing variously coloured darkness rays, Newton's opponents explain the band of colours:

red, yellow, green, blue, violet,

which appears when a white spot is viewed through a prism (Figure 3(b)).

In a sense, this is an exact *colour negative* of the Newtonian interpretation; just as the print of a colour photograph transforms all colours of its negative into their complements, the unorthodox interpretation of the prism phenomena transforms the Newtonian interpretation through colour complementation. If we exchange the roles of the colours:

violet with yellow,

blue with red,

green with purple, and

white with black,

and if we exchange talk of light rays with talk of darkness rays, then the Newtonian theory transforms into its unorthodox complement. Both accounts have the same structure (yet, the two accounts cannot both be true).

The upshot is that the two competing accounts do not only fit equally well each observation I have described – in addition, they are equally well off in

terms of elegance, economy, simplicity, and parsimony. With Goethe's help, we have uncovered an example of two competing theories between which an unbiased decision cannot be reached. To be more precise: the prism phenomena of geometrical optics cannot force a decision between the two theories; nor can we reach a decision by trying to draw on the structural properties of the two theories.

## 6. FURTHER EXPERIMENTS AGAINST THE HETEROGENEITY OF DARKNESS?

In the previous section, I ventured the empirical claim that both Goethe's unorthodox heterogeneity of darkness *and* Newton's heterogeneity of white light are on a par because they fit the prism phenomena equally well. Is that true? It is certainly true for the prism experiments that we considered so far. It is true for the experiments in which *either* a little white light and a lot of darkness *or* a lot of white light and a little darkness are sent through a prism – no matter whether the resulting spectra are painted on Newton's white board or on the retina.

However, there are more prismatic experiments than have been hitherto considered. I maintain that we can deliver unorthodox explanations for *every* prism experiment in Newton's *Opticks*. This is less than claiming that Newton's theory about prismatic colours is *empirically* equivalent with its unorthodox complement about darkness rays. Rather the two theories are, as one might say, *prismatically* equivalent. The proof is beyond the scope of my essay; but in recent years, an impressive number of experiments supporting my claim of prismatic equivalence have been described and analysed by physicists (Holtsmark, 'Newton's Experimentum Crucis Reconsidered'; Rang and Grebe-Ellis, 'A Komplementäre Spektren'; Rang, 'Der Hellraum als Bedingung zur Invertierung'; Sällström, *Monochromatische Schattenstrahlen*).

Let me sketch two lines of thought relevant to my claim. On the one hand, the claim would be based on the unorthodox explanation of additional prism phenomena, each of which – up until now – has been explained in terms of Newtonian orthodoxy; and on the other hand, the claim would be based on the complementary multiplication of phenomena. For each phenomenon that appears to support Newton's theory, there would be a complementary phenomenon, which would be its colour negative, as it were, and would therefore support the unorthodox theory as clearly as the original phenomenon would support Newton's theory.

In order to illustrate the two lines of thought roughly, I shall draw on Newton's white synthesis. This is an additional prism experiment that appears to support Newton's heterogeneity of white light. Given our two lines of thought, these appearances will fade away. We will first become acquainted with the colour negative of that experiment (the black synthesis), and then consider the unorthodox explanation of the original experiment.



In the white synthesis experiment, a prism colour spectrum is fanned out in the dark:

red, yellow, green, blue, violet,

and by means of a renewed refraction (in the opposite direction) we obtain a white spot (Turnbull, *The Correspondence of Isaac Newton, Volume 1*, 100/1; Müller, 'Colour Spectral Counterpoints', 156/7). The black synthesis experiment functions exactly the other way around. We produce a black spot by recombining a fanned out complementary colour spectrum

blue, violet, purple, red, yellow,

in an illuminated room.

If the white synthesis supports the heterogeneity of light, then the black synthesis supports the heterogeneity of darkness. But we cannot consider both hypotheses to be true simultaneously. (One hypothesis can only be true if the other one is false. Newton's explanations are based on the assumption that we may ignore black backgrounds. The unorthodox explanations of its competitor are based on the opposite assumption, i.e. that we may ignore white backgrounds. In short, the two hypotheses are mutually exclusive.)

Our new consideration can support the heterogeneity of darkness only if the black synthesis can be successfully demonstrated. This task has recently been achieved.<sup>21</sup>

But my main claim would hold even without this achievement. In the present dialectical situation, we are looking for resources to decide between Newton's theory and its unorthodox counterpart; and in this context we do not need to check whether the experiment results in the desired black spot. Why not? *Because Newton's theory predicts that this will happen.*

In the purple patch at the centre of the juxtaposed complementary spectrum, two groups of light rays collide, which according to Newton, do not belong together and move in very different directions because of refraction. As they pass through the prism, purple-violet light is refracted very far, while purple-red light is much less strongly refracted. This tears a lightless gap, so to speak, in the middle of the image.<sup>22</sup>

If that is correct, then Newton's theory predicts phenomena that can be explained à la Newton, but which speak just as clearly in favour of the heterogeneity of darkness. In addition, we also have the starting point for the

other line of thought with which I can support my claim about the prismatic equivalence of the two theories. Once we transform the Newtonian explanation of the black synthesis word for word into its complementary counterpart, then we obtain the unorthodox explanation of the Newtonian white synthesis experiment!

And that means that we do not necessarily have to tie the white synthesis to Newton's heterogeneity of white light. The white synthesis experiment fits equally well with the heterogeneity of darkness. Both theories remain prismatically equivalent – at least with respect to the two additional experiments we have considered.<sup>23</sup>

## 7. UNDERDETERMINATION

What follows from Goethe's insights for the empirical underdetermination of scientific theories? This question has not been raised often in the literature.<sup>24</sup> Quine's extreme version of the thesis requires that there *always* are equally justifiable alternatives to *every* total theory (matching *all and any* observation). Given the universal quantifiers, it seems

<sup>23</sup>Elsewhere I have shown how this result generalizes even to the *experimentum crucis* (Turnbull, *The Correspondence of Isaac Newton, Volume 1*, 94/5. The experiment appears in more detail in the *Opticks*, but without the label 'experimentum crucis' or its English translation (Newton, *Opticks*, 45–48)). This is particularly relevant because modificationist critics such as Hooke proposed alternative theories which they – wrongly – assumed to be empirically on a par with Newton's (Turnbull, *The Correspondence of Isaac Newton, Volume 1*, 113); they were wrong since their theories do not fit the *experimentum crucis* (Lampert, 'Newton vs. Goethe', 264–275). Now, Goethe was (I claim) the first of Newton's critics who understood that the observations in the *experimentum crucis* are compatible with another theory, to wit, the heterogeneity of darkness (Goethe, *Leopoldina-Ausgabe*, I.5, §132). Goethe understood it intuitively; the proof is new (Müller, *Mehr Licht*, II.5). In addition, Matthias Rang (a physicist) and I have shown: (i) Newton's theory implies that there must be a complementary counterpart to the *experimentum crucis*; (ii) this complementary counterpart to the *experimentum crucis* can be carried out empirically (Rang and Müller, 'Newton in Grönland'). Rang and Grebe-Ellis showed a high-tech version of that complementary counterpart at the workshop *experimentum lucis*, Berlin 2010. Already fifty years ago, in Scandinavia, there were initial experimental successes in this direction. They have not attracted sufficient attention, although their theoretical frame was published in a leading physics journal (Holtsmark, 'Newton's Experimentum Crucis Reconsidered'). Recently these experimental results have been recorded in a spectacular documentary film (Sällström, *Monochromatische Schattenstrahlen*).

<sup>24</sup>As far as I can see, Marcum is the only philosopher who takes Goethe's attack on Newton's *Opticks* to be relevant for issues of underdetermination. But Marcum's claim is much weaker than mine. According to Marcum, the underdetermination of Newton's optical theory disappears as soon as sufficiently many optical phenomena are taken into account; as he is unaware of the symmetries resulting from the heterogeneity of darkness, he wrongly thinks that appropriate *series* of prismatic experiments are able to break the stalemate (Marcum, 'The Nature of Light and Color', 478 *et passim*).

<sup>21</sup>Nussbaumer, *Zur Farbenlehre*, 105, 156, 188; see Müller, 'Colour Spectral Counterpoints', 164.

<sup>22</sup>Such considerations are easy to generalize; Newton's theory predicts that each of his experiments must have a complementary counterpart. Proof: see Müller, *Mehr Licht*, §II.5.22–§II.5.31.

utopian to illustrate or substantiate the thesis with real examples from the history of science.<sup>25</sup>

For that reason, Goethe's considerations fit better with more moderate versions of underdetermination, which appeal only to observations available in a given historical context.<sup>26</sup> One could say that Goethe's considerations suggest the following thesis: From the publication of Newton's first letter concerning colours and light in 1672 (Turnbull, *The Correspondence of Isaac Newton, Volume 1*, 92–102) to that of Goethe's *Farbenlehre* in 1810, there was no prismatic evidence breaking the deadlock between Newton's theory and its complementary counterpart.

You may say that this is not particularly striking; there are always numerous possibilities to reconcile data with theory – if only through *ad hoc* adjustments within the theory. But in the original presentation of his underdetermination thesis, Quine said that we have no reason to suppose that the data

admit of any one systematization that is scientifically *better* or *simpler* than all possible others.

(*Word and Object*, 23, my italics)

Here we have a more interesting version of underdetermination than the one formulated *only* in terms of empirical adequacy: the alternative theories that are tied for first place, according to Quine, have to exhibit theoretical virtues as well; mere empirical (or prismatic) equivalence is not sufficient for Quine's thesis. The thesis is far stronger than often assumed. Nonetheless, the example we have been considering fits the bill; or so I am going to claim.

Bergström takes this to be impossible. According to him, we can *never* decide on neutral grounds whether two theories are equally well off in terms of these theoretical virtues. Why not? Because the virtues cannot be measured, their weight cannot be compared, they are incommensurable, they cannot be fed into an algorithm of theory choice. Therefore, says Bergström, underdetermination is threatened as soon as it is formulated in terms

<sup>25</sup>The contemporary debate lacks convincing examples of underdetermination, as, for example, Stanford complains (Stanford, 'Refusing the Devil's Bargain', 6). That has not bothered everyone (Bergström, 'Quine, Underdetermination, and Scepticism', 336/7, 341).

<sup>26</sup>Such versions are discussed today under the rubric 'scientific underdetermination' (Dawid, 'Underdetermination and Theory Succession', 303), 'weak underdetermination' (Hoyningen-Huene, 'Reconsidering the Miracle Argument', 176), and 'transient underdetermination' (Sklar, 'Methodological Conservatism', 380/1; Stanford, 'Refusing the Devil's Bargain', 7; Hoyningen-Huene, 'Reconsidering the Miracle Argument', 176). Nevertheless, the considerations in favour of underdetermination that I have developed with Goethe's help are not directly related to Stanford's 'problem of unconceived alternatives' ('Refusing the Devil's Bargain'; *Exceeding Our Grasp*). The heterogeneity of darkness has been seriously considered – independently of Goethe – by Reade (*Experimental Outlines*). Worse still, its very conceivability had been in the air since Lucas's letters (see note 15).

of empirical adequacy *plus* theoretical virtues (Bergström, 'Underdetermination of Physical Theory', 98–100).

This seems hasty, as is witnessed by the symmetry between the two theories we have been considering. Due to their isomorphic, symmetric structure, the two theories are equally simple, equally parsimonious, and equally elegant – to name just three prominent theoretical virtues. Quine appears to have had the right intuition, as can be seen in the continuation of the passage quoted above:

It seems likelier, *if only on account of symmetries or dualities*, that countless alternative theories would be tied for first place.

(*Word and Object*, 23; my italics)

Quine might have welcomed my new example of such symmetries and dualities. It helps neutralize Bergström's protests against the passage quoted, which run thus:

As far as I can see, this is not likelier. Rather, it seems very unlikely. Empirical and methodological considerations can never force the scientific community to conclude that two theories are tied for first place.

('Underdetermination of Physical Theory', 100)

Bergström is wrong as long as *intrinsic* properties are at stake, that is, properties which can be determined by investigating the formulation of the theory itself. How about *extrinsic* criteria of theory choice, such as conservatism? I am not sure whether Quine's thesis should be understood in terms of these criteria as well; Quine did not say. The question of whether he should have said it is beyond the scope of my paper; so I can only give a few hints.<sup>27</sup>

As the heterogeneity of darkness is an unusual idea to which we are not accustomed at all, we might want to say that some version of the principle of conservatism urges us to opt against darkness rays. And again, on conservative grounds we are well-advised to continue with Newton's theory (or its contemporary successors). This consideration depends crucially on extrinsic relations between the theory and its accidental place in history. It is not easy to see how it could increase the theory's *rational* value. What would we have to say if the heterogeneity of darkness had been formulated first? Given that neither prismatic data nor intrinsic virtues spoke against the

<sup>27</sup>The issue of conservatism is tricky and cannot be dealt with here in sufficient detail; for extensive discussion see Müller, *Mehr Licht*, IV.5. Sklar explicitly addresses the question as to whether or not it is a good maxim to appeal to conservatism in order to break cases of underdetermination; he rehearses a number of sceptical objections to such uses of conservatism and does not manage to repudiate all of them (Sklar, 'Methodological Conservatism', 388ff). Finally, he argues that there are better, and deeper, reasons which favour conservative maxims in other areas of the methodology of science (Sklar, 'Methodological Conservatism', 395–400).

unorthodox theory, it is but a coincidence that it was not accepted in the days of Newton or Goethe.

Let me illustrate this with three considerations. Firstly, if Newton had been experimenting in a Greenlandian igloo, lit by the arctic sun, he would have come close to the white chamber needed for complementary experiments; in this case he might have formulated the unorthodox theory. The same might have happened, secondly, if he had not been interested in perfecting telescopes (with their troublesome chromatic aberrations of the *white* starlight against *black* background), but in perfecting microscopes, which enlarge little *dark* objects (such as insects) against bright background. Thirdly, if the proponent of the unorthodox heterogeneity of darkness, Joseph Reade, had chanced to live earlier; if he had formulated his theory (Reade, *Experimental Outlines*) earlier and successfully defended it – then what? In all these cases, the heterogeneity of darkness would have been formulated first. Thus conservatism could have equally well spoken against Newton's theory.

To sum up, a merely conservative decision between Newton's theory and its unorthodox alternative seems to be a matter of historical coincidences. Coincidences are the opposite of reason. But Newton wished to 'prove' his theory 'by Reason and Experiments' (*Opticks*, 1).

Could the underdetermination between the two theories be resolved (i) by later theories or (ii) on the basis of subsequent observations? The first possibility has been emphasized by Laudan and Leplin:

Thus one of two empirically equivalent hypotheses or theories can be evidentially supported to the exclusion of the other by being incorporated into an independently supported, more general theory that does not support the other, although it does predict all the empirical consequences of the other.  
(*'Empirical Equivalence and Underdetermination'*, 67)

Typically, however, more general theories emerge later, which prompts the following question: What general theories would we have now, if earlier on we had opted for some alternative theory which, back then, was empirically equivalent (or at least prismatically equivalent) to the one we have chosen?

Indeed, if we knew for sure that physics moves forward along a firm, objective course, then later developments in physics would speak objectively against the heterogeneity of darkness. However, my considerations concerning the prism experiments give rise to serious doubts about scientific objectivity, or at any rate, about the unique determination of physical theories by observation plus theoretical virtues. When the scientific world opted for Newton's theory of light, there should have been no talk of objectivity, or uniqueness. (I am unsure whether this is a rare case or the general rule.) Even if the subsequent history of successes fits well with that choice, this does not prove that another choice would have led to less successful science. Perhaps the theory of the heterogeneity of darkness does not fit well

with contemporary physics just because contemporary physics is based on the *decision* to pursue only Newton's theory. Since this decision has paid off in the meantime, there is no need to retract it. Nevertheless, we would do well not to read more objectivity into the decision than is really sanctioned.

Of course, the situation would change drastically if we could appeal to theory-free observations which *cannot* be accommodated by the unorthodox theory. These observations would have to stem from outside the empirical scope of geometrical optics (which itself has been seen to be structured symmetrically, and thus cannot help). We may, for example, consider non-optical effects of light rays, such as their thermic effects. Indeed, as Herschel (*'Experiments on the Solar, and on the Terrestrial Rays'*) showed, different parts of the Newtonian spectrum are apt to increase the measured temperature, depending on the spectral colour: As compared to the dark chamber's temperature (beyond the elongated edges of the spectrum), his thermometer exhibited the strongest increase of temperature in the red end of the spectrum; and this increase was even surpassed beyond that red end, in what we've come to call 'infra-red' heat radiation.

No one has yet tried to systematically reverse that experiment; this is a project for future research. But the first steps in this direction have been taken, with stunning results: As compared to the white chamber's temperature (beyond the elongated edges of Goethe's spectrum), the temperature *drops* – again depending on the spectral colour. The thermometer exhibits the strongest *decrease* of temperature in the blue end of Goethe's spectrum; and this effect gets even stronger beyond that end, in what one might want to call 'infra-blue' coolness radiation.<sup>28</sup>

Let us suppose that these first results survive further systematic investigation. Then this strengthens my answer to considerations à la Laudan and Lepin: Admittedly, as a matter of historical fact, Newton's theory of spectral light was integrated into a more comprehensive theory of light, colours, and heat (into a theory that even explains all phenomena of the heterogeneity of darkness, but contradicts it). However, the same could have happened to its alternative, to the darkness theory. It could have been conjoined to a theory of radiating *cold*.

Amazingly, that latter theory (of radiating cold) is not a mere possibility, made up in the armchair. No, it was proposed around 1800 by Rumford; at that time it was empirically underdetermined whether heat alone or cold alone are 'real qualities or entities' (Chang, 'Rumford and the Reflection of Radiant Cold', 135 *et passim*). The two cases – Chang's and mine – are closely related and can be combined: As soon as you defend the heterogeneity of darkness, you are likely to focus on the *cooling* effects of darkness rays, and from there it is a small step to say that heat does not belong to the furniture of the universe (whereas Herschel, complementarily, focused on the *warming* effects of Newtonian *light* rays).

<sup>28</sup>Johannes Grebe-Ellis, personal communication on 9 July 2015.

## 8. CONCLUSION

The astonishing symmetry between Newton's colour spectrum and its complementary counterpart was sufficient for Goethe to see that the phenomena do not give unequivocal support for Newton's theory. My examination of the details confirms Goethe's insight. He would have probably protested against the claim that Newton's heterogeneity of white light is equally *good* a hypothesis as is its unorthodox alternative (the heterogeneity of darkness). He would have said that both hypotheses are equally *bad*.<sup>29</sup>

Be that as it may, Goethe did not have anything against the attempt to describe the world with the help of idealized, even abstract, theories. But as he was perhaps the first to see that theory choice is not determined by experiments and reason alone, his recommendation was that we should treat our theories more cautiously:

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 theorise. 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, *Leopoldina-Ausgabe*, I.4, 5, cf. *Goethe's Theory of Colours*, x1–x1i and 'Theory of Color: Didactic Section', 159)

Newton lacked the liberty that Goethe demanded. Newton was unaware of his own free decision in the leap from phenomena to theory. Worse, he was not even aware of the gap between experience and theory that he needed to bridge. Goethe's criticism of this unreflective attitude is still relevant today. The famous poet and minister had quite a talent for philosophy of science.<sup>30</sup>

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<sup>29</sup>More about Goethe's own account of spectral colours (in which he tries to avoid the one-sidedness of both theories) in Müller, 'Goethe contra Newton on Colours, Light, and the Philosophy of Science'.

<sup>30</sup>This is a revised version of talks held at Trondheim, Barcelona, and York. Thanks to Eric Oberheim for translating large portions of the original text into English, to the anonymous referees for helpful comments, and to Emanuel Viebahn for stylistic advice concerning the final version.

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