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ARTICLE

Goethe's Polarity of Light and Darkness

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Abstract Rarely does research in the history and philosophy of science lead to new empirical results, but that is exactly what has happened in one of the essays of this special issue: Rang and Grebe-Ellis have developed new experimental techniques to perform measurements Goethe proposed 217 years ago. These measurements fit neatly with Goethe's idea of polarity—his complementary spectrum is not only an optical, but also a thermodynamical counterpart of Newton's spectrum. I use the new measurements, firstly, to argue against the asymmetries between light and darkness posited by Lyre and Schreiber; and, secondly, to explicate the alternative theory (the heterogeneity of darkness) that Goethe had introduced to urge scientific pluralism. In my replies to exegetical criticism by Böhler, Hampe and Zemplén, I show that the main goal of Goethe's *Farbenlehre* was indeed to expose symmetries between light and darkness. Furthermore, I argue that it is worthwhile to focus on the experiments, arguments and hypotheses of the *Farbenlehre*, and not merely on rhetorical, narrative or stylistical aspects, as Böhler and Hampe would have it. Goethe's criticism of Newton is often dismissed, but it is in fact surprisingly relevant today.

Keywords Darkness · Goethe · HPS · Light · Newton · Optics

1 Introduction

Whereas five essays of this special issue contain challenging remarks about my project of defending Goethe's criticism of Newtonian optics, one of them provides some support from experimental physics: According to my interpretation, Goethe's *Farbenlehre (Theory of Colours)* yields a controversial empirical prediction about certain temperature

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measurements; the prediction has now been confirmed by Matthias Rang and Johannes Grebe-Ellis (2018). As I will argue, this fine piece of optical experimentation, which is published here for the first time, strengthens my replies to the other essays.

Goethe's monumental *Farbenlehre* can be approached from many different angles. No discipline and no method can do justice to it in every respect. My book is an attempt to explicate, defend and expand a Goethean line of thought that is intriguing from the perspective of both physics and philosophy of science.[1] The aim was to formulate a plausible version of his infamous criticism of Newtonian optics—a criticism involving an early proposal of an underdetermination thesis à la Quine. Goethe uses well-designed experiments to show that Newton's heterogeneity of white light has a complementary counterpart that is also compatible with the optical data (available in Newton's and Goethe's days): the heterogeneity of darkness, according to which darkness and blackness are composite phenomena that result from the juxtaposition of variously coloured and refrangible darkness rays. The beginning of Alexander Schreiber's essay (2018) contains an excellent introduction to this theory, so I will not go into it here.[2]

Even if one takes the darkness theory to be mistaken, just as Goethe did, it can be philosophically instructive to ask why it fails and which experiments or arguments speak against it. These questions are surprisingly hard to answer. In the next two sections, I will discuss a tempting diagnosis of why the theory is mistaken. And I will try to show that this diagnosis is repudiated by the experimental results of Rang and Grebe-Ellis.

2 Rays of Darkness do not Transmit Heat (First Objection from Physics)

Holger Lyre's essay is based on an intuition scientifically minded readers of my book are likely to share: entities posited by contemporary physics (e.g. light rays or photons) are taken to transmit *energy*; darkness rays do not transmit energy; and since the concept of energy is a key element of our scientific world view, the heterogeneity of darkness is incompatible with contemporary physics (Lyre 2018, step 5).[3]

To be convincing, this theoretical line of thought would have to be empirically underpinned. In a debate about the underdetermination of scientific theory by data, *theoretical* resources (such as the concept of energy) are insufficient to adjudicate between competing theories—*empirical* results are needed. And since even data can be theory-laden, Lyre's case against my underdetermination-thesis would become particularly strong if it could be established with elementary empirical means.

Let us therefore discuss the objection by going back in time as far as possible: back to the original temperature measurements conducted by Wilhelm Herschel around 1800. Herschel discovered that different parts of the Newtonian spectrum increase the temperature of a blackened thermometer to a different extent. After calibrating the thermometer in the darkness beyond the elongated edges of the spectrum, he found 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 have come to call infrared heat radiation (cf. Herschel 1800). As

[1] The main ideas of my book are outlined in English in Müller (2016, 2017b). For an English review see Lande (2017).

[2] I will explicate the theory in more detail in the last section of this essay.

[3] I will quote Lyre's objection in the next section. An objection along these lines could have been put forward in Goethe's days, as the energetic effects of light were already known then (Falkenburg 2015, 577–8).

Herschel's measurements brought together thermal energy and spectral light for the first time, and as Goethe planned further experiments in the same vein, this case serves best to spell out Lyre's objection.

3 Goethe's Reaction to Herschel: Some Historical Context for the Measurements of Rang and Grebe-Ellis

Goethe learned about Herschel's measurements through Johann Ritter, who visited him on February 25, 1801, to report not only on Herschel's recent results, but also on the experiments he himself had just carried out (Goethe 1887–1919/III.3, 7). With these ground-breaking experiments, Ritter had discovered the effects of ultraviolet light. As they met, Goethe and Ritter performed several experiments; although Goethe had just survived a life-threatening illness (Seidler 2012, 18–9) and was at last able to continue work on his *Faust*, he dedicated a considerable amount of his time to optical matters (Goethe 1887–1919/III.3, 6–7). It was evidently of importance to him that Herschel's investigations were continued and extended: soon after Ritter's visit, Goethe composed a long letter, in which he set out further measurements he wanted Ritter to conduct (Goethe, quoted in Ritter 1808, 724–726).

His instructions were accompanied by two carefully drawn and coloured diagrams (Fig. 1). The upper diagram depicts an experiment known since Newton's days. A ray of sunlight passes through an aperture and hits a prism, which divides its variously refrangible and coloured components, so that they leave the prism in slightly different directions and produce Newton's spectrum at a certain distance (Fig. 1, upper diagram, far right).

Below, there is the experiment's counterpart discovered by Goethe: a shadow is cast through the prism, and again diverging colours appear. These lead to Goethe's spectrum, which features precisely the complementary colours of Newton's spectrum. In his criticism

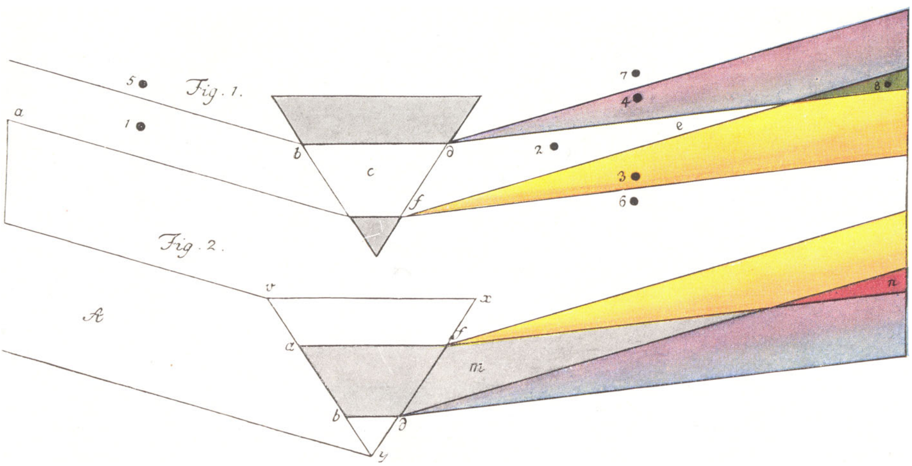

Fig. 1 The predecessors of Plates V and VI from Goethe's *Farbenlehre*. The upper diagram shows how the spectral colours of the prismatically refracted sunlight unfold in the dark chamber; the green centre of Newton's spectrum appears only at a distance of more than one metre. The lower diagram depicts the complementary experiment, in which darkness passes through the prism. (Goethe, letter to Ritter dated March 7, 1801 (Ritter 1808, 759); see Goethe 1947–/I.3, Plate XXII, without page number)

of Newton, Goethe claimed that from this new experiment one could deduce the heterogeneity of darkness in the very same way Newton had deduced the heterogeneity of white light from his original experiment:

> This spectrum brought about with a dark image [a shadow] is just as good a spectrum as that brought about with the bright image [of the sun]; both must always be held next to each other, must be viewed and mentioned in parallel if one is to understand the essential point. If these two plates [my Fig. 1, top and bottom] are placed next to each other, if they are viewed and considered properly […], then they must banish the Newtonian spectre once and for all. (Goethe 1947–/I.7, 68; our translation)

> 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] 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. (Goethe 1947–/I.7, 86; our translation)

To support this bold claim, Goethe tried to invert various Newtonian experiments, each time exchanging the roles of light and darkness (see e.g. Goethe 2016, §132).[4] Thus I felt justified to introduce what I called *Goethe's theorem*, according to which swapping light and darkness converts the observed colours into their complementary counterparts. Can this inversion be extended from optics into thermodynamics?

This question brings us back to the relation between spectral radiation and temperature. Goethe added numbered points to the upper diagram to indicate where the thermometer should be placed (Fig. 1). He did not only propose measurements within the spectrum where Newton would typically have placed the screen (point No. 8), but also closer to the prism (Nos. 4 and 5). And he did not only propose measurements in the darkness beyond the spectrum (Nos. 6 and 7), *but also in the white area behind the prism* (No. 2). Furthermore, he emphasised how much depends on the choice of a base level, from which the *changes* of temperature are to be determined (see Goethe, quoted in Ritter 1808, 724–5). The upper diagram raises the following question: How does the spectral temperature change *in comparison to the temperature of the brightest—white—area of the experiment?*

Here we have reached a crucial point for my interpretation; recall that Goethe's inverted spectrum flourishes in *bright* surroundings. Therefore, the proposed measurement in the bright area also suggests an inversion of Herschel's experiment. And this must have been Goethe's aim—if indeed we may assume that Goethe accepted the theorem I named after him. Why else should he have included the second diagram, which depicts how the inverted spectrum develops between prism and screen, and which results from applying Goethe's theorem to the upper diagram? To be sure, Goethe did not include any measurement points in the lower diagram. But in the letter he asks for a measurement in the purple centre of the inverted spectrum (see Goethe, quoted in Ritter 1808, 727). And it is clear that this is what his symmetrical approach (of systematically swapping light and darkness) would have demanded; he sent Ritter *both* diagrams and said that they must be

[4] A detailed exegetical discussion of this passage and related ones lies beyond the scope of this essay. But I want to mention one fact that has been overlooked by many of Goethe's readers: Goethe used ten of the seventeen plates of the *Farbenlehre* to illustrate his research programme of inverting optical experiments.

viewed and mentioned in parallel in order to "understand the essential point" (Goethe 1947–/I.7, 68).

In my view, this is good evidence that my protagonist accepted what I call *Goethe's theorem*. By ascribing this theorem to Goethe, we can explain why he chose to add two complementary diagrams to his letter. Anyone as busy as Goethe will not draw and colour a second diagram without good reason. Nevertheless, one may wonder why the second diagram is hardly mentioned in the letter. Well, probably because Goethe thought it would speak for itself. At least that seems more plausible than an explanation on which the second diagram was superfluous.

In the light of the two diagrams, we can thus interpret Goethe's letter as follows: Goethe was suggesting the inversion of Herschel's measurements; he wanted Ritter to transfer the measurements from Newton's to Goethe's spectrum.

For more than 200 years, no one seems to have taken up this suggestion. This is where the measurements by Matthias Rang and Johannes Grebe-Ellis (2018) come in: they show that compared to its white surroundings, the temperature *decreases* within Goethe's spectrum. Proponents of the darkness theory, according to which darkness is composed of colourful darkness rays, can thus respond to Lyre's objection, which he sums up as follows:

> Physical bodies get heated by sun light. Darkness rays are seemingly not connected with heat or energy transport (or any other physically substantial transport phenomena). Hence, [the statements of the darkness theory] are in conflict with basic thermodynamical energy conservation (already at Goethe's times). (Lyre 2018, step 5)

Granted, even to an adherent of the darkness theory, the results of the experiment do not suggest that darkness rays transmit *heat*; if anything, they appear to transmit coldness. And of course, current orthodoxy does not count this phenomenon as energy transmission. Almost all contemporary physicists will dismiss the idea of rays of darkness or coldness. They will offer an alternative description of the results in Figure 3 (from Rang and Grebe-Ellis's essay) and point out that the negative values on the y-axis (energy current density or irradiance, measured in nW/mm^2) do not represent negative temperatures or negative energy densities, but rather a reduction in comparison to a predefined *positive* base level.

Rang and Grebe-Ellis describe this base level as *spectral background*. The term covers *all* energetic effects (including disturbances) arriving at the screen when the lamp is switched on but the complementary spectrum is not yet visible (because the reflecting slit aperture is closed). Both theoretically and experimentally, measurements of just the spectral background can be taken to approximate measurements in the bright area beyond Goethe's spectrum (when the lamp is switched on and the aperture is open). These latter measurements appear to be those proposed by Goethe, inverting Herschel's original calibration of the thermometer in the dark area beyond Newton's spectrum. Given the foregoing considerations, and given the historical context, it seems natural to define a value of nought to the spectral background.

Of course, it can still be maintained that measurements in the spectral background should not be assigned a neutral intensity, but rather a large positive value, leading to positive values for all measurements in both experiments [cf. Rang and Grebe-Ellis (2018), Eq. (2)]. However, even if the base level is increased in order to yield positive values on the y-axis, the different colours of Goethe's spectrum correspond to different energy levels, contrary to what Lyre claims. These energy levels form a complementary counterpart to those of Newton's spectrum (Figure 2 from Rang and Grebe-Ellis's essay): an *increase* in energy density in Newton's spectrum, e.g. between blue (at a wavelength of ca. 450 nm or a distance of 100 mm) and red (650 nm or 150 mm), corresponds to a *decrease* in the complementary spectrum, namely between yellow (at a distance of 100 mm) and turquoise (150 mm). The two spectra are thus thermodynamic counterparts: the addition of both curves leads to an almost constant energy level (Figure 4 from Rang and Grebe-Ellis's essay). Since these results are based on the law of thermodynamic energy conservation (Rang and Grebe-Ellis 2018, conclusion 1), it is mistaken to claim that this law is in conflict with the darkness theory.

There is another point that weakens Lyre's reasoning: the law of thermodynamic energy conservation was not known in Goethe's times.[5] Moreover, the nature of coldness was controversial; Lord Rumfeld invoked experiments to argue for coldness rays—without having the optical phenomena in mind that served as our starting point, and without knowing of Goethe's research on colours.[6] There were further physicists who took coldness to be part of physical reality, and even Goethe contemplated similar ideas (Ritter 1806, 85–6 (§4), cf. 1810, §234; Goethe 1988b, §696).[7] If the experiments Goethe planned had been carried out back then, and if they had led to similar results, it would not have been unreasonable to posit darkness rays with a cooling effect in Goethe's spectrum.

Goethe was, it seems, the first to suggest that Herschel's measurements in Newton's spectrum should be extended in a complementary way in order to search for the cold counterpart of the heating effects of invisible infrared light. He may well have anticipated the cooling effects of invisible infra-turquoise darkness (or, to put it in an orthodox manner, the reduced heating effects that result from the absence of infrared radiation). Rang and Grebe-Ellis's discovery of these effects validates Goethe's research programme governed by the idea of polarity, and it shows that the darkness theory cannot be dismissed as easily as Lyre thought. The stock of phenomena that both theories can explain has grown.

4 Polarity and Enhancement

Gábor Zemplén (2018, section 4) emphasises that my research on Newton and Goethe leaves out many historical details.[8] Zemplén is right: while my project falls within the history and philosophy of science (HPS), its aim is to draw philosophical conclusions from the history of science; thus I set aside those details that are merely of historical interest, and instead concentrate on aspects that promise philosophical insights.

Nonetheless, the pursuit of an integrated HPS-approach sometimes demands teasing apart complicated historical developments. For that reason, I will use this section and the next one to provide additional support for my interpretation of Goethe. Those readers who are mainly interested in physical or epistemological aspects of the debate may skip ahead to Sect. 6.[9]

[5] Even our modern concept of energy did not emerge until after 1840 (Fox 1974, 130, 132).

[6] See Chang (2002), who cites original work by Lord Rumford, e.g. Thompson (1804). According to Chang (2002, 135), this episode in the history of science can be aligned with Quine's underdetermination thesis. Rang and Grebe-Ellis's measurements show how closely the two cases are related.

[7] Goethe's ideas were inspired by a thought of Kepler's, which Goethe translated and commented on with approval (Goethe 1947–/I.6, 157–8).

[8] In a similar vein Hampe (2018, section 2) and Böhler (2018, section 3).

[9] In future work, I will offer a much more detailed case in favour of my interpretation. My exegetical considerations will take into account the linguistic turn, the experimental turn, the iconic turn and the rhetorical turn, but of course they will also be based on a close reading of Goethe's texts. See Müller (2019).

My book contains the claim that the polarity of light and darkness is the *most important* element of Goethe's criticism of Newton. The striking congruence of the two diagrams discussed above underpins this claim (Fig. 1). The diagrams are predecessors of the famous Plates V and VI of the *Farbenlehre*, where Goethe did not include any measurement points.[10] Instead, he focused on the colours that emerge from the prism: first for the standard experiment, in which a narrow ray of light passes through the prism (Plate V and top of my Fig. 1), then for the complementary experiment, in which a shadow is cast through the prism (Plate VI and bottom of Fig. 1).

Zemplén holds that a different aspect of these experiments deserves attention—their dynamic morphology. As Zemplén (2018, section 3.1) emphasises, the experiments indicate how the spectra unfold and in a sense progress, i.e. show enhancement ("Steigerung").[11] We thus have two leitmotifs in Goethe's research on colour: polarity, on the one hand, and enhancement, on the other. The idea of polarity I have been highlighting becomes apparent if you vertically move from one diagram to the other, i.e. if you exchange the diagrams. By contrast, the idea of enhancement or progression discussed by Zemplén emerges through horizontal movements within each diagram.

These two leitmotifs are not in conflict with each other; they can be seen as running in parallel. For example, both leitmotifs can be used to illustrate what Goethe had in mind when he time and again demanded the multiplication of phenomena (Goethe 1947–/I.6, 251, 379, 392, 423; 1988b, §355, §830; 2016, §21, §56, §70, §135, §168, §193).

Given the approach guided by polarity, such multiplication should be achieved by looking for the polar opposite of each phenomenon—this procedure was the focus of my project. Many Goethe-scholars (e.g. Steinle 2006), however, focus on the approach guided by enhancement, and thus on a different route to multiplication: the idea is to continuously modify parameters in order to find neighbouring phenomena for each phenomenon, to arrange these phenomena in a series and to look for progression and emerging forms ("Gestaltbildung"). Many scholars highlight this idea of enhancement because it fits well with Goethe's morphological research in biology, which is widely considered a success (Engelhardt 1999; Müller 1999). But although it may be interesting to look for connections between Goethe's optical and biological research, this can distract from *physical* details. And while Goethe's morphological research is important, it does not directly bear on his criticism of Newton.

I chose to set aside the enhancement-aspect of Goethe's scientific research in order not to get sidetracked in the immense literature on that matter, but also because it raises difficult questions to which I do not have an answer: Did Goethe hold that in optics polarity and enhancement depend on each other? Or should these aspects be dealt with separately, perhaps because the enhancement of colours inevitably leads to a breakdown in symmetry? Did Goethe (1947–/II.4, Plate I) have good reasons to place purple at the top of his colour wheel and the complementary opposite (green) at the bottom?

These and similar questions will guide my future work on the *Farbenlehre*. Explicating the idea of enhancement in Goethe's optics will, I suspect, require close attention to his experiments, figures and writings—just as was the case for the idea of polarity. But, as far as I can see, Goethe's *Farbenlehre* places greater weight on polarity than on enhancement. I will use the next section to show why his focus is often overlooked, for example in Michael Böhler's contribution to this issue: while Goethe mentions the main aim of his *Farbenlehre* in the preface and illustrates it with examples of polarity, he does so without explicitly referring to polarity.

[10] In the English translation these are colour plates VII and VIII, following p. 206 in Goethe (1988b).

[11] Similar but more abstract considerations are offered by Hampe (2018, section 2).

5 Polarity or Narration?

So far, we have pursued Goethe's idea of a polarity between light and darkness, and we have seen that it can be extended into the realm of colours. What is more, Rang and Grebe-Ellis have generalised this idea, so that it also applies to spectral heat and coldness. Have they moved too far away from the historical Goethe? I do not think so. Rather, they have congenially carried on his research programme. Goethe persistently pursued this programme for quite diverse phenomena: just as Ritter and Schelling, he held that the symmetry of positive and negative electrical poles is intimately connected with the symmetry between magnetic north and south poles, that both symmetries can be extended into chemistry through electrolysis, and that such symmetries also emerge in optics, thermodynamics, photochemistry, and so on (Goethe 1988b, §696).[12] Instead of dealing with all of these matters at once and in the abstract, I decided to concretely flesh out the most fascinating case—which led me to Goethe's theorem.

Admittedly, the notion of polarity as I have sketched it is highly abstract: it functions as a theoretical concept that has to prove its usefulness in structuring our system of beliefs. Is it a scientific term or does it belong to philosophy? Goethe dreaded philosophical as much as scientific abstraction (see e.g. Goethe 1988b, §716, §719–§721, §752). Arguably, this is one reason for his reluctance to explicitly speak of optical polarity too early in the *Farbenlehre*. He was aware of the dangers that lurk in the careless theoretical use of such notions (see Goethe 1988b, 159).[13]

Nevertheless, Goethe indicates the goals of his *Farbenlehre* with sufficient clarity in the preface; his aim is to transfer the universal terminology of polarity that is familiar from other areas of knowledge and experience into the realm of colours. Since Böhler's interpretation of the preface strongly differs from mine, I will quote Goethe at length:

> Although it is true that colors and light are intimately related to one another, we must consider both as belonging to all nature. Through them nature in its entirety seeks to manifest itself, in this case to the sense of sight, to the eye.
> Similarly, the whole of nature reveals itself to yet another sense. Let us shut our eyes, let us open our ears and sharpen our sense of hearing. From the softest breath to the most savage noise, from the simplest tone to the most sublime harmony, from the fiercest cry of passion to the gentlest word of reason, it is nature alone that speaks, revealing its existence, energy, life, and circumstances […]
> Thus nature also speaks to other senses which lie even deeper, to known, misunderstood, and unknown senses. Thus it converses with itself and with us through a thousand phenomena. No one who is observant will ever find nature dead or silent […]
> No matter how diverse, enigmatic and intricate this language often seems, its elements remain forever the same. With gentle weight and counterweight nature balances the scales as they swing. 'Here and there,' 'up and down,' 'before and after,' are dimensions that emerge in the course of this weighing and serve to make specific the phenomena we meet in space and time.

[12] Several schemata in Goethe's scientific legacy show the importance Goethe and his companions placed on applying the idea of polarity in many different areas (Goethe 1947–/I.3, 354–5, 382–3, 502–3).

[13] Contrary to what Böhler (2018, section 3) says, I did not call theoretical use of language deficient, and neither did I attribute such a claim to Goethe. In passing, another misunderstanding has to be clarified: The notion of a rotten compromise (with its drastic moral implications) does not occur in my book; the accurate English translation of the German expression "fauler Kompromiss" is, of course, "poor compromise".

> We perceive these elements of movement and structure in a variety of ways: as simple attraction and repulsion, as the waxing and waning of light, as the motion of air, as vibration of solid bodies, as oxidation and reduction. All these, however, have the effect of dividing or uniting, of setting existence in motion and lending support to some form of life.
> Observers have found an apparent imbalance in the effect of weight and counterweight and have tried to give expression to this relationship as well. They have noted this principle in all things and given names to it: plus, minus; aggressive, resistant; active, passive; assertive, restraining; force, moderation; male, female. In this process a language, a set of symbols, has arisen which we may apply to like events in a metaphor, a closely related expression, a precisely suited word.
> The main goals of the present volume are to extend the application of these universal terms, this language of nature, to the theory of color; to expand and enrich this language through the theory of color and the diversity of its phenomena; and thereby to help disseminate deeper insights among the friends of nature. (Goethe 1988b, 158–9)

Is Böhler (2018, section 1) right to claim that my approach is incompatible with Goethe's remarks on the language of nature? Not quite; roughly, Goethe begins the passage in the realm of colours, moves on to sounds, touches on a wide range of diverse phenomena and finally returns to the colours. His main point becomes apparent only on a close reading. After bringing colours and sounds in parallel, he introduces the multifaceted notion of a language of nature, which suggests itself in the case of sounds: nature reveals herself through sounds and thereby speaks to us. Then Goethe looks at other modes in which nature reveals herself and observes that the same pattern emerges in all kinds of areas. He evidently wants to expose unity in nature's diversity—an aim shared by many scientists (see e.g. Planck 1993, 1). Next, he uses numerous examples to illustrate the pattern he has in mind: in each case, there are *two* elements that form a polar opposition, e.g. attraction and repulsion (see also Goethe 1988a). At the end of the passage, Goethe announces that he will apply this—polar—terminology, this language of nature, to the theory of colour. As he calls the application and expansion of these ideas the "*main* goals of the present volume", the passage favours my interpretation: Goethe's theorem (about the polarity of darkness and light) is at the core of the *Farbenlehre*.[14]

Böhler's interpretation of this passage is surprisingly different. As he leaves out the long list of polar opposites, Böhler does not pay attention to Goethe's aim of transferring polar terminology (his "set of symbols") into the realm of colours. Instead, he emphasises Goethe's *linguistic* goal (of connecting speech and colour theory), yet without making

[14] Before Goethe turns to the sensory-moral effects of colour at the end of the didactic part (Goethe 1988b, §758–§920), he summarises his scientific considerations with a section entitled "*Concluding* Observation on *Language* and Terminology" (Goethe 1988b, §751–§757; emphasis changed). Here, he once more states the main goal of the *Farbenlehre* and this time explicitly says how the polar terminology from other perceptual areas should be applied to the realm of colours: "Scientists have obviously felt that it would be necessary and suitable to use a figurative language […], for the formula of polarity has been borrowed from magnetism and extended to electricity, etc. The concepts of *plus* and *minus*, which represent this formula, have found suitable application to many a phenomenon […] We, too, have long wished to introduce the term *polarity* into the theory of color, and the present work will show our justification and purpose in doing so" (Goethe 1988b, §756–§757, emphasis there). For considerations pointing in the same direction, also see Goethe (1988b, §453).

clear *which* language is at issue, *what* the language is *about* and how it is to have any *unifying* power.[15]

Since Böhler is concerned only with diversity, not with Goethe's unifying approach, he delves into the *narrative* diversity of the *Farbenlehre*. This diversity cannot be denied, but neither can it have been Goethe's main aim. As the above passage shows, his aim was not merely to apply various forms of "narrative knowledge" to the realm of colours.

Imagine someone had praised Goethe's *Farbenlehre* for its literary qualities, e.g. its splendid narrative forms. Would Goethe have been amused? There is every indication that what he hoped for were successful implementations of his experimental designs, such as the recent temperature measurements in the inverted spectrum, which so neatly fit his idea of polarity. The foregoing considerations suggest a more general lesson for interpreting historical works in physics: in order to reach a charitable interpretation of such texts, it can be helpful to address old experimental questions with modern means and to investigate whether the new results fit with the historical text. In the current case, the new results fit the text perfectly (Sect. 3), which speaks in favour of both Goethe and my interpretation of Goethe.

6 Martial Rhetoric in Revolutionary Times

Böhler (2018, section 3) raises another critical question about my book, which is also brought up by Michael Hampe (2018, section 2): Is it inappropriate to embroil Goethe in a hypothetical dispute with Newton in order to determine which side has the better arguments? Is it misguided to dramatise the dispute by using martial metaphors? And does the rhetoric of my book exhibit certain unfortunate features that are widespread in many areas of philosophy, whether analytical or continental, current or past? I must confess that the literary, rhetorical and narrative criticism of my thoughts and words took me by surprise. I had not anticipated such a negative reaction from Goethe-scholars and literary theorists, and I certainly did not want to provoke them. To the contrary, I naively thought that my optimistic view of Goethe as a physicist would be welcomed in literary theory.

It is true, Böhler's and Hampe's criticism gains plausibility from the following observation: philosophers, but not scientists, present their research as a fight for truth; scientists precisify material constants or discover previously unknown effects, but they do not fight for the truth of a theory (Hampe 2018, section 3). For many periods this observation is correct. While scientists are involved in solving puzzles in what Thomas Kuhn labels *normal science*, major disputes are rare. But when the paradigms (and thus the rules that govern scientific puzzle-solving) are questioned, a less harmonious picture unfolds. Kuhn (1996, 151–2 *et passim*) deliberately employs a bloody metaphor when he speaks of such times as scientific *revolutions*. And this metaphor is well-chosen because physicists become much more combative in times of paradigm change; they form allegiances, adopt an aggressive vocabulary, lose their objectivity and fight for their point of view, sometimes even reckoning with their opponents' death.

Both Newton and Goethe had revolutionary aims: Newton successfully revolutionised optics, whereas Goethe's aims went unfulfilled. Hampe and Böhler claim that my picture

[15] Böhler's interpretation does not accord with the paragraphs in the didactic section quoted in the previous footnote, which have to be read as a summary of what has been achieved so far: on the one hand, Goethe once again talks of language, symbols, etc.; on the other, he makes these leitmotifs concrete by explicitly speaking of *polarity* instead of using polar examples to implicitly gesture at the notion.

of Goethe is too combative. But that claim is mistaken. From the very beginning of his research on colour, Goethe knew what he was letting himself in for:

> Among the matters that interest me the most is a new theory of light, darkness and colour […] If I am not mistaken, it must bring forth quite a few revolutions. (Goethe 1887–1919/IV.9, 264; our translation)

This statement resonates with Kuhn's talk of scientific revolutions. Now, Goethe disliked revolutions (see e.g. Goethe 1887–1919/I.35, 11, 24–26, 47; cf. Sharpe 2002, 5; Eissler 1963, 628 and Boyle 2000, 77, 91, 104 *et passim*). If possible, he avoided the notion, and he hardly ever applied it to his own achievements. Against this background, the above passage is revealing; in my view, it illustrates how reluctantly Goethe manoeuvred himself into a revolutionary role—a role he failed to shake off for the rest of his life.[16] Thus it is no surprise that his research on colour brought out an unusually combative Goethe and that this research has almost universally been perceived as a fight, especially by literary theorists and biographers.[17] My martial account of the matter is not an artefact of bad habits in philosophy.[18]

If Goethe was indeed fighting for a new paradigm in optics, it is natural to hold, as Hampe (2018, section 2) does, that there is no competition between Newton (playing hockey) and Goethe (playing chess). After all, one of Kuhn's points is that certain terminological and methodological resources of competing paradigms can be incommensurable, just as the rules of different sporting disciplines.

However, the notion of incommensurability should not be given too much weight, or else it distracts from another fact that shapes our understanding of the natural sciences: even in the course of scientific revolutions, scientists want to show that they are right, and they want to convince their opponents as well as the public (cf. Kuhn 1996, 152–154 *et passim*). Competing theories are not always concerned with the same empirical domain—part of the dispute is about *which* observations, experiments and results are relevant, as

[16] Ten years after publishing the *Farbenlehre*, Goethe regretfully spoke of the battle in the sciences (Goethe 1947–/I.8, 62). But he did not retreat from his position, and 2 years later he published a list of his "adversaries" (Goethe 1947–/I.8, 202–204). Furthermore, there are several passages in which Goethe comes across as veritably pugnacious, particularly in his *Tame Invectives* [see e.g. *V. Zahme Xenie* (Goethe 1947–/I.3, 342)].

[17] See e.g. Richard Friedenthal's use of "fight" and similar expressions (Friedenthal 2010, 285, 286, 287, 290, 291). Even before the first world war, Albert Bielschowsky's biography featured "mines" that Goethe was "prepared to explode" and a "war" that Goethe was "determined and compelled" to have (Bielschowsky 1907, 204, 207). And Emil Ludwig used expressions such as "campaign against Newton", "to wrestle", "colour-antagonists" (Ludwig 1928, 291, 454). While the foregoing references stem from works first published in German, martial vocabulary appears in the Anglophone literature on Goethe, too. For example, the introduction of the *Cambridge Companion to Goethe* mentions that "he battled against Newtonian optics" (Sharpe 2002, 5). And the section on Goethe as a poet states that "he was also capable of expressing his most deeply held convictions (or prejudices) in the most coarse and *brutal* language" (Williams 2002, 58; my italics). Last but not least, Nicholas Boyle speaks of Goethe's "hostility to Newton" (Boyle 2000, 100).

[18] Nonetheless, Kuhn's terminology may well help to explain why combative rhetoric is more common among philosophers than among scientists: in philosophy, any assumption can be doubted, which is why there are few (if any) universally accepted paradigms; many philosophers thus live, so to speak, in a permanent revolution. I think that the lack of undisputed paradigms is a good reason not to treat philosophy as a scientific discipline. See Müller (2017a, Section I).

Zemplén (2018, section 3.4) rightly points out.[19] Nonetheless, their empirical domains overlap, which is why a dispute can arise in the first place.

Admittedly, Goethe's far-reaching research on colour, light and darkness covers some phenomena that fall outside the domain of Newtonian optics. There is nothing wrong in focussing on these aspects (as Zemplén proposes). In my view, however, other parts of Goethe's research deserve more attention, namely those parts that are in clear opposition to Newton's optics. And here we see Goethe experimenting with sunlight, dark chambers, apertures, prisms, etc., and producing work that is no less exact, quantitative or astute than that of Newton and his followers—or so I argued. Given this subject matter, is it far-fetched to ask who has the better experiments and arguments on his side?

7 Metameric Darkness? (Second Objection from Physics)

Physicists have complained that I have given no precise account of the darkness theory. My quick answer is that it works just as Newton's theory, but with inverted parameters and terminology. The essays by Zemplén (2018, section 1) and Schreiber (2018, section 5) show that this answer will not do—it is far from clear how *Newton's* theory works!

In my book, I made two moves to circumvent this problem. On the one hand, I concentrated on the most comprehensible and (from today's perspective) successful part of the *Opticks*: on its first book. This book contains the well-known and widely-taught experiments featuring apertures, lenses and prisms, which are nowadays placed in geometrical optics. Zemplén is right that the other books of the *Opticks* deal with some phenomena that do not fall within this area (e.g. diffraction). Nevertheless, the narrow focus I have chosen seems warranted, as Newton struggled to explain those phenomena and as he was aware of his difficulties in capturing them.

On the other hand, I ignored a problem Newton failed to solve: Newton never managed to establish quantitative dispersion laws for different kinds of light in *arbitrary* optical media. It took almost until the end of Goethe's life for this problem to be solved by physicists.[20] For my purposes it was legitimate to bracket Newton's difficulties, as this

[19] Zemplén invokes Otto Neurath, whose views align just as well with Goethe's philosophical insights as Quine's views do. Quine was arguably influenced by Neurath.

[20] An important component of the solution is the wavelength λ, which is a successor of the notion Newton called *refrangibility* but was unable to quantitatively employ. To measure it, Newton could have deposited a prototype prism in the Tower of London (analogously to the prototype metre in the Louvre): then he could have sent a homogenous ray of light through the prototype prism in a standardised geometrical setting and measured the result on a standardised screen; the outgoing angle could have been used as a measure for the refrangibility of the ray of light. Such a procedure was in the air in Newton's times, but eventually unsuccessful because the results could not be transferred onto prisms of other materials. Shapiro shows where Newton got stuck in his attempt to mathematise the laws of refraction (Shapiro 1979, 127–8 *et passim*; also see Lohne 1961). Since Goethe's year of death, Cauchy's equation can be used to calculate arbitrary refractions, given the wavelength of the refracted light and the material constants of the optical medium (Smith et al. 2001, 3883–4). This calculation does not presuppose any non-classical physics. For the sake of simplicity, I will use neither wavelengths nor Newtonian refrangibilities, but rather the colours of light rays. I will further simplify matters by pretending that any ray of light is either blue (B), turquoise (T), green (G), yellow (Y) or red (R). A further law Newton could only specify qualitatively concerns the question of how much light is reflected at the boundary of two media and how much passes through the new medium (Newton 1964, 36–7). This law was also discovered in Goethe's times (by Fresnel). In order to determine the relation of reflection and transmission, Newton would have had to measure not only wavelengths, but also intensities of light, which he did not. For our purposes, however, it seems appropriate to equip Newton with the notions of wavelenght and intensity.

made the task of defending Goethe harder. If Goethe's theorem can challenge not only the qualitative theory Newton de facto formulated, but also an improved quantitative version from Goethe's times, then that is an achievement of even greater significance.

According to Schreiber, however, my improvement of Newton's theory is not innocuous. He argues that, without measurement devices, and relying solely on visual perception, Newton and Goethe could only *qualitatively* define undisturbed darkness. If this is correct, Schreiber has uncovered an asymmetry between light and darkness that already holds in the optics of Newton's and Goethe's times: while the human eye can perceive only *one* kind of darkest darkness, it can perceive several different kinds of whiteness, i.e. several white metamers (Schreiber 2018).[21]

Indeed, unless we want to blind ourselves, there are several ways of creating maximally bright whiteness: we can either create such whiteness by mixing the entire continuum of visible wavelengths, or by mixing just a few wavelengths (of greater intensity, to make up for the brightness of the wavelengths we have left out). In certain prismatic experiments, these different kinds of whiteness lead to different observations. By contrast, replacing one kind of maximal (visual) darkness with another cannot lead to different observations in any experiment. Schreiber thus concludes that there is an asymmetry between light and darkness, and that darkness is not an optical causal factor (Schreiber 2018, end of section 3).

8 Measuring the Intensity of Light Rays and Darkness Rays

In arguing for this asymmetry, Schreiber relies on the peculiarities of visual perception. To counter the argument, I have to equip Goethe and his contemporaries with means to measure quantities of light and darkness. How can the intensity of blindingly strong or imperceptibly weak rays be measured? Schreiber (2018, section 4) rightly notes that in the current dialectical situation I cannot employ optical metrology that presupposes modern physics. After all, modern physics is (as I have argued) a descendant of Newton's view, and therefore non-neutral.

Contrary to what Schreiber claims, however, it is possible to measure the brightness or intensity of spectral components of light without relying on photoelectron spectroscopy, and thus without leaving the realms of classical physics. Measurement techniques of invisible radiation were making great strides in Goethe's times, and the methods of both Herschel, who used a thermometer, and Ritter, who employed photochemistry, are in principal suited to determine the intensity of any kind of homogenous light. These methods can even be used to measure the intensity of invisible light, regardless of whether it is invisible because of its wavelength (such as Herschel's infrared or Ritter's ultraviolet) or because it is too strong or too weak to be seen.

Let me illustrate the possibility of such measurements by taking a closer look at Herschel's method. True, Herschel was unable to measure temperature increases in the blue range, but this was merely due to the poor quality of his thermometers. In what follows, I will assume that Herschel's thermometers had been continuously improved and perfected—a process that was well underway in Herschel's days and that does not require any

[21] Similar considerations are offered by Zemplén (2018, section 2.1).

use of non-classical physics.[22] Of course, the thermometers we use today are the result of centuries of technological innovation, but they are still thermometers.[23]

With improved thermometers, even Herschel and Goethe could have measured the intensity of light without employing their eyes as measurement devices. Let us use magnitude I_P for these hypothetical measurements—a predecessor of today's magnitude of light intensity I.[24] Given this, we can provide a Newtonian description of the optical occurrences between two points a and b, specifying e.g. the amount of red light:

$$R(a,\ b) = \text{Measured result of magnitude } I_P \text{ for red rays travelling from a to b.}$$

In the same way, we can specify the intensity of the blue component B(a, b), the green component G(a, b), and so on. In principle, such measurements can provide an exhaustive description of the optical occurrences in any Newtonian experiment. For example, Figure 2 from Rang and Grebe-Ellis (2018) depicts the values for an elementary experiment concerning the refraction of white light.

After these preparatory remarks, I want to return to Schreiber's objection. First, consider a *white* mixture No. 1 containing light of all colours with an overall intensity that just falls short of blinding our eyes:

$$R_1(a,\ b) = Y_1(a,\ b) = G_1(a,\ b) = T_1(a,\ b) = B_1(a,\ b) = I_P.$$

Exactly the same impression of whiteness can be produced with a metameric mixture of light No. 2, which consists only (or almost only) of blue and yellow light (and thus of two spectral compensation colours). The other three colours will never be eliminated completely, but they will only enter at a fraction μ of their original intensity—too weak to be visible, but still detectable with highly sensitive thermometers. In order to compensate for the missing brightness, the blue and yellow rays of light have to be amplified, let us say by factors β (for the blue rays) and γ (for the yellow rays):

[22] Only a few years after Herschel's discoveries, Wünsch managed to measure temperature increases in all visible areas of the spectrum; he seems to have used more sensitive thermometers (see e.g. Wünsch 1808, 606). From our current perspective, he was right to conclude from his measurements that light and heat cannot be separated from each other (Wünsch 1808, 629).

[23] This point has to be taken with a grain of salt. In order to cover distant ranges of temperature and different demands of precision, we have to use quite diverse measurement devices, which are counted as "thermometers" because their results partially overlap, so that the ensuing patchwork can be consolidated in a single scale. The measurements of Rang and Grebe-Ellis illustrate this point: their measurement device is a pyroelectric radiation power meter. The calculated power densities (nW/mm^2) can be depicted as a location-sensitive (and thus in a Newtonian spectrum: wavelength-dependent) curve, which is closely and monotonously tied to Herschel's temperature curve. Just as with a traditional thermometer, measurements of the pyroelectric sensor are based on the fact that pyroelectric matter changes temperature as it absorbs radiation, which in turn changes the electrical charge on the electrodes. Because the sensor reacts to the most minute changes of temperature, the relevant spectral signals have to be filtered out of the random background radiation. Analysing the data thus requires computing power that has only become available in the past 50 years.

[24] The hypothetical magnitude I_P can be converted (*one-by-one* for each wavelength) into the standard magnitude I through suitable monotonous and continuous transformations. Newton's theory does not require comparing the intensities of differently coloured homogenous light rays; because Newton held that the essence of a homogenous light ray never changes, one intensity function is enough for each kind of light. From today's perspective, the energy transmitted by homogenous light per unit of time depends on the number of photons per unit of time and on their wavelength (and thus their refrangibility or colour); both components have an effect on temperature measurements. If the thermal output and wavelength of a homogenous light ray are known, its light intensity can be calculated via a transformation that takes into account the properties of the human eye (or any other detector).

$$Y_2(a, b) = \gamma\, I_P \text{ with } \gamma > 1$$
$$B_2(a, b) = \beta\, I_P \text{ with } \beta > 1$$
$$G_2(a, b) = T_2(a, b) = R_2(a, b) = \mu\, I_P \text{ with } \mu \approx 0, \text{ but } \mu > 0.$$

Now, Schreiber contends that the *darkest* possible exposures do not have metameric counterparts. But in fact we can emulate the metameric mixture of whiteness analogously for darkness. Let us begin with darkness containing light rays of all colours at an equally weak intensity—the corresponding values are infinitesimally small, but greater than nought:

$$R_3(a, b) = Y_3(a, b) = G_3(a, b) = T_3(a, b) = B_3(a, b) = \mu\, I_P \text{ with } \mu \approx 0, \text{ but } \mu > 0.$$

If we then reduce the intensity of, say, the red, green and turquoise light even further (e.g. by again multiplying it with μ), we can increase the intensity of the blue and the yellow rays by suitable factors β' and γ' without changing the overall impression:

$$Y_4(a, b) = \gamma'\, \mu\, I_P \text{ with } \gamma' > 1$$
$$B_4(a, b) = \beta'\, \mu\, I_P \text{ with } \beta' > 1$$
$$G_4(a, b) = T_4(a, b) = R_4(a, b) = \mu^2 I_P \text{ with } \mu \approx 0, \text{ but } \mu > \mu^2 > 0.$$

The resulting dark mixture No. 4 looks exactly the same as the equally dark mixture No. 3. Schreiber is right to claim that it makes no observable difference in prismatic experiments whether we use No. 3 or No. 4. But by using highly sensitive thermometers or photochemical means we can measure the invisible: mixture No. 3 contains all colours at an equally weak intensity, while mixture No. 4 does not. (My argument rests on the well-established fact that we will never attain perfect darkness, i.e. an *absolute* absence of electromagnetic radiation).

9 Explicating the Darkness Theory

According to the orthodox theory of light, different mixtures of light rays travel through space; they can be prismatically decomposed into their homogenous components (of various intensities). Analogously, the darkness theory entails that different mixtures of darkness rays travel through space, and that their homogenous components can be prismatically decomposed and measured (albeit not in dark, but in light surroundings).

In the Newtonian descriptions of the previous section, I simplified matters by focussing on the five functions B, T, G, Y and R, which specify the intensity I_P of any homogenous blue, turquoise, green, yellow or red light rays travelling between the points a and b. (Of course, Newton's theory entails that there are more than five such functions, and in fact infinitely many ones; my simplification makes no difference to the considerations of this essay).

Let us now turn to the darkness theory, which posits five complementary functions Y*, R*, P*, B* and T*. These functions specify the intensity of the yellow, red, purple, blue and turquoise *darkness* rays travelling from a to b; the darker and cooler the rays, the greater their intensity. This cooling darkness can be quantified in the same way as the warming light in Newton's paradigm, but with inverted parameters.

Rang and Grebe-Ellis's essay provides a description of the required measurement procedure for elements of Goethe's spectrum (which according to the darkness theory are homogenous rays): a lamp ("lum. area") emits light that is directed by two mirrors to a reflecting slit aperture in the middle of the diagram (their Figure 1). The aperture reflects most of the light to the right, but a small proportion passes through the slit in the aperture and is lost. It thus looks as if a—heterogeneous—ray of darkness is travelling from left to right through the aperture, arriving in the bright surroundings created by the aperture's mirror. Now we want to determine the unorthodox intensities I* of the components of this ray of darkness. After passing through the aperture, the ray travels alongside the reflected light, meets a parabolic mirror and is reflected onto a prism. It is spectrally decomposed and captured on a screen, where Goethe's spectrum appears (shown at the bottom of Figure 3). The unorthodox intensities of each component are measured in the usual way and plotted as a curve, with each negative value standing for the intensity of a component of darkness (top of Figure 3). Lower values stand for a greater intensity of darkness or coldness radiation (in unorthodox terms). The greatest intensity is measured in the infra-turquoise component to the right of the visible part of the spectrum.

So far, I have merely given an unorthodox interpretation of Rang and Grebe-Ellis's experimental set-up. But let us now suppose that we want to measure an arbitrary ray of darkness, say, a homogenous ray of purple. How the ray has been generated is unimportant; let us assume that we come upon such a ray and want to unorthodoxically measure it. What do we have to do? First, we have to use several mirrors to direct the ray from behind (and thus in Figure 1 from left to right) through the reflecting slit aperture. As in the previous set-up, the lamp is switched on, so now the ray of purple travels alongside the reflected light (where previously there was a heterogeneous ray of darkness) through the right-hand side of the experimental set up. This ray meets the prism.[25] And it is diverted from its original path—to the same extent as a green ray of light would be diverted in dark surroundings. Accordingly, it is assigned the same unorthodox refrangibility as is assigned to homogenous green in the orthodox theory. On the screen, the purple ray is measured in the same way as the heterogeneous ray was measured in Rang and Grebe-Ellis's experiment. The homogenous nature of the ray is confirmed by the fact that there is only one point on the screen at which the measurement device detects a (negative) intensity. This value gives us the unorthodox intensity I* of the purple ray.

Thus it is straightforward to formulate an unorthodox counterpart to the quantitative laws of refraction Newton aimed for (but did not achieve): what holds for the refraction of homogenous green light G in dark surroundings according to the Newtonian law of refraction, also holds for the refraction of homogenous purple darkness P* in bright surroundings according to the unorthodox law of refraction; in the same way, the Newtonian law of refraction for turquoise light T is matched by an unorthodox law of refraction for red darkness R*, and so on.[26] Obviously, this procedure works for all pairs of Newtonian rays of light and their complementary rays of darkness. And as it makes no difference how the details of the underlying law of refraction are spelt out, it does not matter that Newton was in fact unable to produce an adequate quantitative law of refraction.

I admit that by now we have moved beyond what Goethe himself would have said about these matters. I have tried to use modern means to *expand* Goethe's criticism of Newton's methods. Goethe produced pioneering work that we can build on even today. The

[25] Were it to meet the prism in dark surroundings, it would be decomposed into its orthodox components, and thus in light rays of all colours but green.

[26] Goethe anticipated this. See Goethe (2016, §132).

alternative theory he put forward for the sake of argument is in better empirical and theoretical shape than one might have expected. Of course, it does not fit with contemporary physics. But it is unclear what physics would look like today if the alternative theory had been taken seriously back then (see Müller 2016, 341–2). Goethe was pleading for scientific tolerance, for pluralism and against Newton's claim of having found, and proven, *the* right theory (Goethe 1947–/I.8, 182). I am concerned merely with one of his steps towards pluralism, which relies on the duplication of theories. As I have tried to show, this step is based on meticulous empirical research, on rigorous arguments and on original philosophical insights—there is much to build and expand on.

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