Theo Smeets /
Wilhelm Lindemann (eds)

ThinkingJewellery

// Two

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Wilhelm Lindemann / Theo Smeets (eds.)

Trier University of Applied Sciences,
Campus for Gemstones and Jewellery, Idar-Oberstein
in cooperation with
Jakob Bengel Foundation, Idar-Oberstein

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Content

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Preface

„May the lecture not be directly related to jewellery."

With this sentence the speakers of the symposium ThinkingJewellery are invited to give a lecture. Critical voices said: „and when are we going to make jewellery?", thus masking the fact that the attempt at a transfer between science and art is probably very exhausting. We have already held our symposium eleven times. This publication is a follow-up to the book „SchmuckDenken" published in 2011, in which we collected lectures from the first six editions, and at the same time it is a prelude to something new. Since the Symsposium will now take place bi-annually, the Idar-Oberstein University in cooperation with the Jakob Bengelstiftung and the city of Idar-Oberstein will publish a series of publications in the „interim years" that will collect and expand part of the contributions to SchmuckDenken.

In addition to the essays by the lecturers from 2017, Regine Prange, Olaf Müller und Wilhelm Lindemann, we took the opportunity to introduce to you our new colleague in our department, Prof. Dr. Susanne Bennewitz, she has the chair for *Social and Cultural Studies in the Context of Material Culture* in our Faculty.

I wish you lots of joy and new insights with ThinkingJewellery 2!

Theo Smeets
Head of Dept. Gemstones and Jewellery

Olaf Müller

A Brief History of Polarity in Physics[1]

Introduction

During the second half of the eighteenth century, the conception of polarity spread rapidly among scientists in diverse fields. Though it proved fruitful, it has since fallen into obscurity.[2] To date there is no accurate account of how the conception of polarity emerged, how it should be understood and why it is valuable. I will address this lacuna by introducing some highlights from polarity in the history of physics. My aim is to give a rational reconstruction of some ideas which appear outdated but are interesting enough to warrant reconsideration. I'll challenge some established views of current physics in the spirit of what Hasok Chang calls complementary science.[3]

To preempt a potential misunderstanding, I am not interested in the history of the word 'polarity' and its transliterations in other languages – after all one can express thoughts involving polarity without knowing any technical term. Rather I am interested in thoughts of a certain form which may but need not be expressed with the word. A theorist who describes polar structures without labelling them 'polar' can still implicitly have the concept of polarity at their disposal.

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[1] This essay is based on my talk 'Goethe on Colours – a Vindication', given on 14 October 2017 at the conference 'ThinkingJewellery XI', Trier Universit of Applied Sciences, Campus Idar-Oberstein. I would like to thank the audience for interesting questions and constructive criticism. Many thanks to Emanuel Viebahn and Troy Vine for valuable support with the translation of the written version.

[2] Nevertheless even modern physics shows traces of the idea of polarity (e.g., in the symmetry between particles and anti-particles (Henley et al. 2007, pp. 108–12).

[3] See (as applied to the history of chemistry) Chang 2013.

The conception of polarity can operate at different levels of generality. A local use of the conception may help capture certain symmetrical structures in a particular field of investigation – for example, magnetism; this is where my account of polarity will get off the ground. At the other end of the scale, the conception of polarity can be used with *unrestrained generality*. Such uses cover the most diverse fields and are often conjoined with the claim that nature as a whole is constituted by polar structures.[4] According to this claim a comprehensive network of polarities connects every occurrence with every other. I can only briefly touch on this bold idea here, which obviously can hardly be propounded without using technical terms such as 'polar' and its derivatives.

Amber and magnets

The concept of polarity probably emerged in early observations of magnetism; Petrus Peregrinus spoke of a magnet having two poles as early as the thirteenth century.[5] Although at that time there was no abstract expression (e.g., 'polarity') for the structural characteristics of magnets, such structures came to light with sufficient clarity; here we can assume an implicit use of polarity.[6]

Illustration 1 shows a case that exemplifies the structures at issue: the red end of a bar magnet attracts the green end of another bar magnet; if we rotate one of the two magnets such that their green ends face each another, the opposite happens – they repel. In short: reversing the spatial orientation of a magnet and thus reversing its poles causes an *inversion* of the forces.

From the very beginning of systematic research into magnetism, scientists suspected that electrostatic phenomena were another case of magnetism. This conjecture was repudiated by William Gilbert, who demonstrated that the forces of attraction of electrostatically charged amber are not magnetic forces.[7] Still it remained a popular view that electricity must be governed by the same (or at least analogous) laws as magnetism – that is, by polar laws. What exactly does that mean? Polarity in the relevant sense is meant to apply to two regions or elements of an experimental setup, the two

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[4] See e.g. Schelling 1857, p. 476.

[5] See Steinle 2012, pp. 109–10 with references to the original literature.

[6] To my knowledge there is no account of when words such as 'polarity' were first used in the sense at issue here.

[7] Gilbert 1893, pp. 74–98; Gilbert 1600, pp. 47–61 (= Liber II, Cap. II–III).

poles, which create a specific kind of symmetry. The structure of this symmetry is such that interchanging the two poles reverses a particular effect, leaving everything else unchanged. Does the phenomenon of electricity display this symmetry too? It does, but it took a long time before it was empirically verified, as I will show in the next section.

Aepin and the tourmaline

For two years from 1755, Franz Ulrich Theodosius Aepin was director of the Berlin Observatory. Although he was employed as an astronomer, he researched a wide field of topics within physics and mathematics. Aepin was convinced of the simplicity of nature and applied this principle to electricity and magnetism: 'Among those who are familiar with this habit of nature, there have been scholars who thought that magnetic and electrical forces, these wonders of nature little known to the ancients, have the same or similar origins. And it has to be said that these scholars deserve applause rather than apology. For while it must be admitted that those who had the idea of the similarity of these two forces have so far expressed conjectures rather than knowledge, we should not blame them for showing us the proper path towards knowledge of nature.'[8]

Aepin faced great difficulties in bringing electricity and magnetism under uniform laws, until a coincidence played into his hands: '*Many years ago I had similar thoughts and searched for the path to these secrets of nature. But the path was so arduous that I became tired and could not pursue the investigations any further. However, recently nature became more inclined to me and encouraged me to go on. A certain stone fell into my hands which is not only endowed with electrical powers but also shines with other wonderful qualities; I deemed it worthy of further observation as it seemed to have powers that were very similar to those of magnets.*'[9]

Aepin was referring to tourmaline fig. 2, a beautiful gemstone that had recently arrived from Ceylon and Brazil. When heated, the stone attracted fine ash particles and could thus be used to clean tobacco pipes – a miracle of electrical powers, as it turned out.

It had been known for some time that there are two kinds of

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[8] Aepin 1760, pp. 4–5; footnote omitted, our translation.

[9] Ibid., pp. 5–6, our translation.

electricity, which were described as positive and negative.[10] Aepin's experiments with his tourmaline provided the first good reason to speak of negative and positive poles of electricity – in analogy to the north and south poles of the magnet: '*One side of the heated tourmaline is always electrically positive, the other always negative. It thus has both kinds of electricity at the same time, like the magnet has twofold magnetism. Furthermore it is not only similar to the magnet in that it has two poles: in both repelling and attracting, it also observes rules that are identical to those governing the behaviour of magnets.*'[11]

Aepin seized the opportunity and immediately tried to generalise the discovery he had made with tourmaline. His attempts were successful: he managed to create pairs of positive and negative poles on many other objects.[12]

It might seem surprising that the structural analogy between magnetism and electricity had not been noticed before. This may have to do with the fact that the two kinds of electricity had not often been observed on one and the same body. Aepin had learned from Benjamin Franklin's writings that both kinds of electricity are present on a charged Leyden jar (an early capacitor).[13] But in this case, one kind of electricity is on the inside of the jar, while its counterpart is on the outside. Thus the geometrical situation differs from that of the magnet: inside and outside fit less to the idea of two poles than opposite sides of an object. In short: the tourmaline was needed to show the analogy between electricity and magnetism.

Kant's negative magnitudes

Shortly after his groundbreaking research on the electrical properties of tourmaline, Aepin was appointed to a chair in St. Petersburg. The journey there would normally have taken him via Königsberg, and so he may well have met Immanuel Kant. Regardless of whether the two scholars did meet on this occasion, Kant swiftly reacted to Aepin's results and generalised his research method. In 1763 he published a small booklet with the following title: *Versuch den Begriff der negativen Größen in die Weltweisheit einzuführen* (Attempt to

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[10] Ibid., pp. 9–13. Also see Steinle 2013, pp. 54–60.

[11] Aepin 1760, pp. 16–7, italics mine, our translation; cf. ibid., p. 32.

[12] Ibid., pp. 20–1, esp. second footnote.

[13] Ibid., p. 20, first footnote.

Introduce the Concept of Negative Magnitudes into Philosophy).[14] Kant had recognised the potential of the idea of confronting a given magnitude with its negative counterpart. In his view this move always requires the same conceptual procedure, regardless of the area to which it is applied.[15] As Kant wanted to show the analogous role of pairs of opposites in diverse areas, he took great pains to explicate the conception of negative magnitudes.[16] In particular he contrasted cases of polarity with cases where we find only one factor in play; in the latter cases we do not posit a second, contrary factor but rather speak of the presence or absence of the one factor.

We are acquainted with both kinds of cases. For magnetism and electricity, not only the north or plus pole is taken to be effective but also the south or minus pole. Such cases of true polarity involve what Kant calls real opposition and will be my focus here.[17] There are also cases in physics where the idea of polarity is not evoked, such as thermodynamics and optics. While in everyday discourse we speak of heat and coldness or of brightness and darkness, their apparent polarity goes against well-established physical theories: coldness does not really exist; it is nothing more than the absence of heat – similarly darkness is nothing more than the absence of light.

In Kant's time it was far from clear which areas of physics were governed by polarities – that is, by real oppositions. Concerning heat Kant wrote: 'There is, for example, the well-known question whether coolness requires a positive cause, or whether as a lack it is to be attributed simply to the absence of the cause of heat. I should like to consider this matter a little, at least as far as it is relevant to my purposes. Doubtless, coldness itself is simply the negation of warmth, and it can easily be seen that it is possible in itself, even in the absence of any positive cause. But it can with equal ease be seen that it can also be the effect of a positive cause, and that

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[15] According to Adickes this 'drive to synopsis and synthesis' is distinctive of Kant's general way of thinking (Adickes 1924, pp. 51, 53, 308 et passim).

[16] Kant 2002, Section I/Kant 1912, first section.

[17] Kant used several different expressions to describe the same relation: 'Realrepugnanz' (real repugnancy), 'Realopposition' (real opposition), 'reale Entgegensetzung' or 'wirkliche Entgegensetzung' (real or actual juxtaposition), 'Realentgegensetzung' (real juxtaposition); see Kant 1912, pp. 172, 175, 174, 176, 177; compare the slightly different translations in Kant 2002, pp. 212, 214, 215, 217. He had the *concept* of polarity but not the *word*. Of course the word itself is unimportant, and the variety of expressions Kant uses is less a sign of conceptual unclarity than of his inability to coin a catchy expression. At the same time his vocabulary has the advantage of being sufficiently remote from magnetism, making it better suited than 'polarity' for universal application.

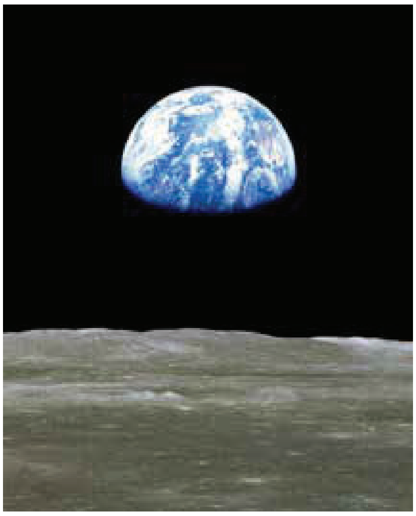
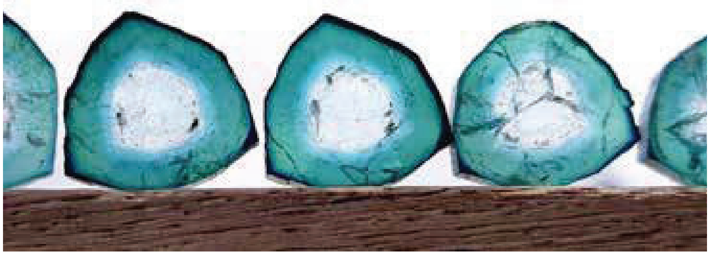


fig. 1

The earth seen from the moon. The beauty of the earth's colours competes with that of tourmaline. Furthermore both the earth and tourmaline can be characterised with the help of poles. The earth has two magnetic poles; a charged tourmaline has two electrical poles.

fig. 2

Tourmaline.
Tourmalines can be found in many different colours. We have chosen a stone that shows colours similar to those of our planet. If a tourmaline is heated, a positive electrical pole forms at one end and a negative pole at the other.



it does actually on occasion arise from such a cause – and all this can be understood independently of what opinion one may entertain concerning the origin of warmth. Absolute coldness is unknown in nature, and if it is discussed, then it is understood only in a comparative sense.'[18]

After reporting on Aepin's results, Kant boldly transferred them to the current case: '*Now, my contention is this: whenever the temperature is raised or lowered, in other words, whenever the degree of heat or coldness is changed, and in particular changed rapidly, and whenever that change occurs at one end of a continuous intervening space, or at one end of an elongated body what happens is this. There are always two poles, so to speak, of warmth to be found: one of them is positive, that is to say, its temperature is higher than the previous temperature of the body in question, while the other pole is negative, its temperature, namely, being lower than the previous temperature of the body; in other words, it is cold.*'[19]

Kant supported his claim with experiments and observations which in his eyes bolstered the analogy between magnetic or electrical poles on the one hand and poles of heat versus coldness on the other; furthermore he speculated about experiments that were yet to be carried out and would (he hoped) support his claim.[20]

The earth, a giant tourmaline? fig. 1

The boldest (and perhaps most dubious) thought Kant expressed in his work on negative magnitudes was the idea that coldness exists in itself. Surprisingly this thought was soon developed further in research on tourmalines. Kant had known of the initial stages of this research but had gone far beyond it in his speculations. In 1766 Swedish chemist Torbern Bergman published a two-volume monograph describing and expanding the very latest insights about our planet: *Physick Beskrifning Ofver Jordklotet* (Physical Description of the Earth).[21]

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[18] Kant 2002, p. 223, endnote omitted/Kant 1912, p. 184.

[19] Kant 2002, p. 224/Kant 1912, p. 186.

[20] Kant 2002, pp. 225–6/Kant 1912, pp. 186–7 (esp. footnote). At first sight the experimental results Kant counted upon appear implausible; according to Adickes the most important experiment Kant mentioned was bound to fail (Adickes 1924, p. 7 with reference to Kant 2002, pp. 225–6n/Kant 1912, pp. 186–7n). However, Lord Rumford shortly afterwards conducted further experiments which fit Kant's general thesis of a real opposition between heat and coldness surprisingly well (Chang 2002).

[21] Bergman 1773, Bergman 1774. For the German version see Bergman 1780a, Bergman 1780b.

In a chapter about lightning and similar phenomena (such as ball lightning), Bergman took up the idea of coldness as a force in itself, radicalising it and connecting it to electrical polarity. This culminated in the following speculation: '*Might coldness generate positive electricity and heat negative electricity? Might the force of the antipodes be opposed to the force we can detect? In a tourmaline both kinds of force can only be generated by changing the temperature in the surrounding medium […]. Perhaps certain mountains and places on the globe are of the same nature as a tourmaline.*'[22]

This thought may have been based on the idea that the coldness at the magnetic north pole of the earth is related to the generation of certain forms of electricity; if this were indeed the case, then different climate zones should correlate with specific electricity distributions. Such considerations were advanced by physicist Georg Christoph Lichtenberg in 1778: '*Might not the globe be a giant tourmaline whose poles roughly coincide with those of the earth: the positive pole with the north pole and the negative pole with the south pole? As this may seem too bold to some, I want to explicate my notion of this tourmaline. I do not take it to be a gemstone of enormous size hidden under the surface of the earth. Rather I take it to be the sum of all objects scattered across the earth, including the air, which is electrified by the heat of the earth or the sun and which can transmit its electricity to all objects.*'[23]

Note that Lichtenberg wasn't a romantic enthusiast but the first German professor of experimental physics and firmly rooted in the tradition of the Enlightenment. He used the idea of the earth as a giant tourmaline for far-reaching theoretical aims.[24] As an accomplished writer he must have been aware of the suggestive power of the picture he had drawn. Given photographs of our blue planet, Lichtenberg's picture seems surprisingly fitting. Doesn't the earth really look like a tourmaline?

To summarize, we have seen how scientists and scientifically minded philosophers expanded the concept of polarity to ever new fields of investigation: starting from magnetism the concept was transferred to electricity and then to the opposition of coldness and

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[22] Bergman 1780b, p. 65, our translation.

[23] Lichtenberg 1956, p. 44, our translation.

[24] This was first pointed out by Wiesenfeldt and Breidbach, who also connected Lichtenberg's formulations with earlier work on tourmalines and who suggested that the Enlightenment's concept of polarity as applied to tourmalines is closely related to the concept of polarity in romantic physics and Naturphilosophie (Wiesenfeldt and Breidbach 2012).

heat, which was finally connected with other polar phenomena. All this was normal science, neither amateurish nor esoteric. On the contrary it was advanced research carried out by leading scientists of the time.

They actively sought out phenomena that could be systematised with the help of polar structures. In Kant's terminology the concept of polarity functioned as a 'regulative idea' – that is, as a guiding principle for research.[25] From today's perspective the strategy was successful in some cases and unsuccessful in others. But the current perspective doesn't always give an accurate idea of how researchers reasoned in earlier times. It is helpful to bear in mind that around 1800 the search for polarities was a successful research programme that had many adherents.

How Newton drove polarity out of optics

Before Newton revolutionised optics with the publication of his prismatic experiments in 1672 fig.3, it was thought that colours emerged from the interplay of light and darkness.[26] The pre-Newtonian theories of colour differ in detail, but they all entail a symmetrical opposition of light and darkness. Newton denounced this consensus by conceptualising darkness as the absence of light rather than an active factor in its own right.[27]

According to his conception of optics, only rays of light are optically effective. He not only defended this claim on a theoretical level but also presupposed it in his empirical work. That Newton's experiments are based on a monistic conception of optics is reflected by the fact that they are conducted in dark surroundings, in the famous camera obscura. Indeed some of his experiments only work in this setting. With respect to one of the most difficult experiments, he wrote, ' *[…] 'tis requisite that the Room be made very dark, least any scattering light, mixing with the colour, disturb*

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[25] See in particular Kant 1976 A, pp. 642–68 and B, pp. 670–96. Kant was not explicitly concerned with the regulative idea of polarity but rather with that of homogeneity (for further discussion of this topic, see Müller 2013a, Sections 2.5 and 3). While Kant did not use the notion of a regulative idea in his pre-critical writings, he came close to it on several occasions, in particular when discussing polarity (Kant 2002, pp. 225–6n/Kant 1912, pp. 186–7n). This may have been an echo of a similar thought by Aepin (1760, p. 5, see above, last sentence of the first quote in Section III).

[26] On this and the following, see e.g. Zemplén 2001, Nakajima 1984.

[27] Newton 1671/2, p. 3085 et passim.

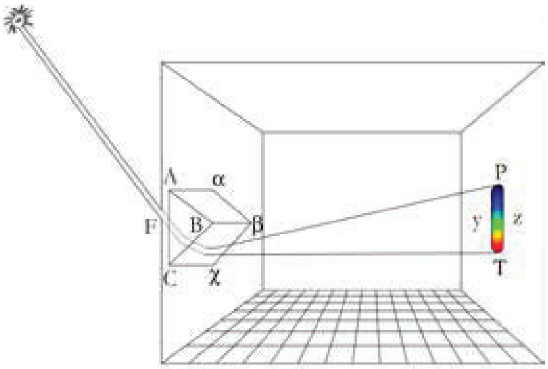

fig. 3

Newton's decomposition of sunlight (1672).
A ray of sunlight shines through the hole in the window shutter F onto a prism, where it is refracted and decomposed into its coloured components

(Illustration by Matthias Herder and Ingo Nussbaumer following a black and white drawing from Newton's lecture notes, see ill. 2 in Newton 1973, p. 3; source: Müller 2015, colour plate 1).

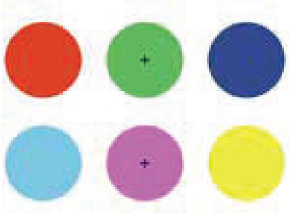

fig. 4

Complementary colours.
Three colours from Newton's prismatic experiments (red, green, blue) are placed above their complements (turquoise, magenta, yellow). To elicit coloured afterimages, cover one of the two rows with white paper and stare at the black cross for about ten seconds. Then look at the white paper without moving your eyes.

(Illustration by Sarah Schalk and Olaf Müller)

and allay it.'[28]

Newton was convinced that darkness is required to minimise disturbing factors and produce clear results. It is easy to see that this approach leaves no room for darkness as an independent causal factor; Newton used darkness as a neutral background for optical experimentation.

It took several decades for the new theory to assert itself.[29] But once Newton's Opticks (1704) had spread across Europe, views giving darkness an independent causal role disappeared. When Goethe entered the debate a century later and suggested returning to a polar conception of optics, he certainly went against the prevailing orthodoxy. This does not mean, however, that his approach was unheard of or unscientific.[30] Goethe had witnessed how new ideas quickly became established in fields such as chemistry, and he knew of the successful polar research programme outlined in Sections II–V above. Against this background Goethe's systematic search for polarities in the realm of colours was far from outlandish.

Goethe's polar research programme in optics

Goethe made clear that he wanted to transfer the terminology of polarity from fields such as magnetism and electricity to optics: '*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.*'[31]

Interpreters have not taken this programmatic statement seriously, perhaps because they have not associated it with those experiments that show how it is to be understood.[32] It might therefore be helpful to present some of the optical experiments in which

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[28] Ibid., p. 3087, italics mine.

[29] Shapiro 1996.

[30] Pace Duck 2016, pp. xxii, xxviii et passim; more on this topic in Müller 2018b, Sections 1–2.

[31] Goethe 1988, §§756–7. Similar remarks are to be found in ibid., §453 and pp. 158–9. The latter passage merely implicitly describes the polar strategy through a host of examples but does not feature the corresponding expression; it is discussed in detail in Müller 2018a, Section 5.

[32] See e.g. Böhler 2018, Section 3, Eckle 2015, p. 235, Kötter 2017, p. 157.

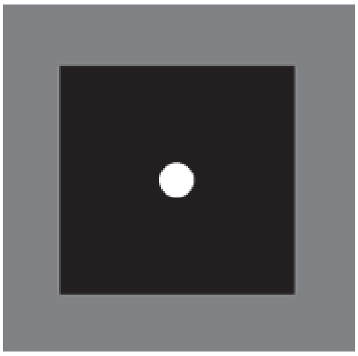

fig. 5

Template to generate Newton's spectrum. In a well-lit environment, place a glass prism on the template with its three edges parallel to the bottom of the page. Look at the white dot through the prism, slowly moving the prism towards your eye. Its upper and lower edges gradually become coloured. If you rotate the prism about its axis at the right distance, you'll see Newton's spectrum of red/yellow/green/turquoise/blue ill. 1. If the distance is varied, different stages of Newton's spectrum (with fewer colours) will be seen.

(Illustration by Benjamin Marschall; source: Müller 2015, p. 69)

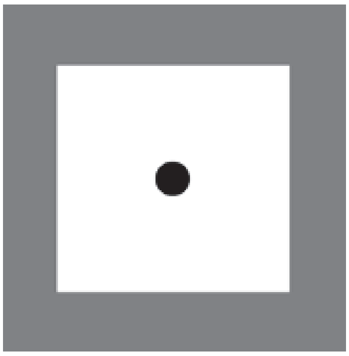

fig. 6

Inverted template to generate Goethe's spectrum. Goethe's spectrum can be generated in the same way as Newton's ill. 7, using an inversion of the previous template.

(Illustration by Benjamin Marschall; source: Müller 2015, p. 146)

Goethe employed polarity as a guiding principle.

He managed to show that each colour has a polar opposite, its complementary colour, shown by the colour's afterimage [fig. 4][33]. This phenomenon is nowadays known as successive contrast. Complementary colours feature not only in physiological experiments but also in physics. If, for example, one looks through a prism at a white circle in black surroundings [fig. 5], the resulting spectrum [fig. 7] can be transformed into its complement [fig. 8] by inverting the contrast – that is, by looking at a black circle in white surroundings [fig 6]. In Goethe's words: '*I had fixed a white disc onto a black background. If viewed through a prism from a certain distance, the disc led to the familiar spectrum and thus replicated Newton's main experiment in his camera obscura. However, a black disc on a white background also created a colourful and indeed more splendid spectre.*'[34]

Goethe systematised these so-called subjective experiments, which were already known in his time [fig. 10]. Furthermore he was the first to display their polarity on a screen in a so-called objective experiment.[35] Whereas Newton sent a narrow ray of light through a darkened prism and captured its decomposition into blue/turquoise/green/yellow/red on a screen [fig. 3 and 9 left], Goethe directed a narrow shadow through an illuminated prism and captured the complementary spectrum of the colours yellow/red/magenta/blue/turquoise [fig. 9 right][36].

In those days it was a challenge to show this effect in sufficient clarity. Small glass prisms were not suited for the purpose, so Goethe had a large water prism made [fig. 11] and proudly recounted his eventual success: '*My aim was to repeat all the results of the subjective experiments [that is, those viewed through the prism] in objective experiments [with the spectra captured on a screen]. The small size of prisms was a problem. I had a larger prism made […] and placed cardboard apertures next to it in order to create all the effects that a view through a prism had made visible on my templates.*'[37]

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[33] See Goethe 1988, §§47–60.

[34] Goethe 1957a, p. 420, our translation. Goethe used the German expression for ghost (*Gespenst*) to play on the ambiguity of 'spectre'.

[35] It is easy to see why Goethe calls the former experiments subjective and the latter ones objective (see next quotation). Newton also relied on subjective experiments but without that name; for instance, the first experiment in his Opticks is a subjective experiment (Newton 1964, pp. 17–8).

[36] On the subjective or objective production of these experiments, see Goethe 1988, §§215, 331.

[37] Goethe 1957a, p. 422, our translation.

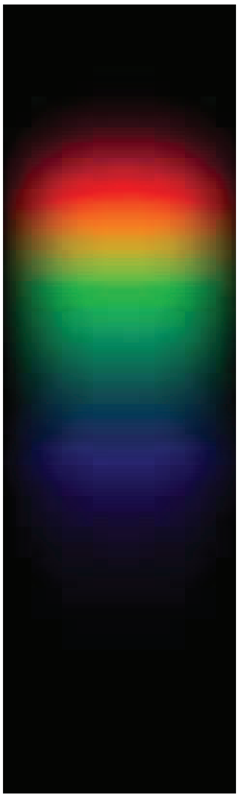

fig. 7

Newton's spectrum. Result of observing ill. 7 through a prism. Both order and orientation of the colours red/yellow/green/turquoise/blue depend on the orientation of the prism.

(Image by Olaf Müller)

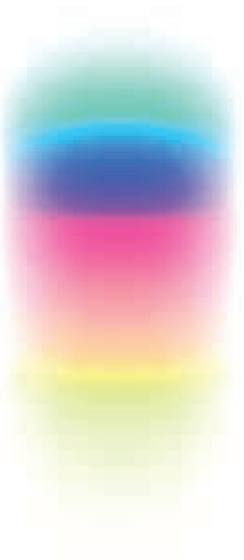

fig. 8

Inversion of Newton's spectrum. Result of observing ill. 8 through a prism. ill. 9 and 10 are related via a symmetry operation (similar to the example of magnetism, ill. 1). If the poles of light and darkness in the experimental set up of ill. 7 and 8 are exchanged, the visible colours will be inverted.

(Image by Olaf Müller)

> *'Objective experiments often use the luminous form of the sun, but seldom a dark form. We have found a convenient way to arrange such an experiment. Let us place our large water prism in the sunlight and glue a round cardboard disc to its outer or inner face.'*[38]

Goethe had presented an optical experiment par excellence: exact, objective, replicable and no less physical than its Newtonian predecessor. The size of the prism meant that the experiment required considerable technical effort. Goethe didn't shy away from such efforts and experimented in a laboratory that was more suitable than Newton's.[39]

Not content with one pair of complementary spectra fig. 9, Goethe varied the distance between prism and screen.[40] It turned out that such variation changed not only the size of Newton's spectrum but also its colours – and exactly the same was the case with Goethe's complementary spectrum and its colours.[41] Goethe had to take precise measurements to demonstrate this. He presented the twofold series of experiments in a pair of carefully drawn and coloured illustrations figs. 12 and 13.

Where Goethe's research programme was held up and how it should carry on

To sum up my account of Goethe's research in optics, he managed to demonstrate experimentally the polarity between light and darkness as well as between complementary colours. How does the polarity of light and darkness relate to the polarities in electricity and magnetism? In all three of these fields, exchanging two poles leads to an inversion of certain effects: in electricity and magnetism, forces are inverted, in optics, colours. Goethe's polarity in optics is thus structurally analogous to established theories in other fields.

Goethe knew that the experimental support for Newton's theory was not confined to the small number of experiments I have mentioned so far.[42] In propagating his polar research agenda in optics, Goethe had to claim that other experiments of Newton's also have polar opposites, namely all of the replicable experiments

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[38] Goethe 1988, §331.

[39] For many helpful details on this point, see Klinger and Müller 2008.

[40] See Goethe 1988, §§324–31.

[41] Ibid., §§204–17 on the subjective spectra and Goethe, and §§317–34 on the objective spectra.

[42] Goethe 2016.

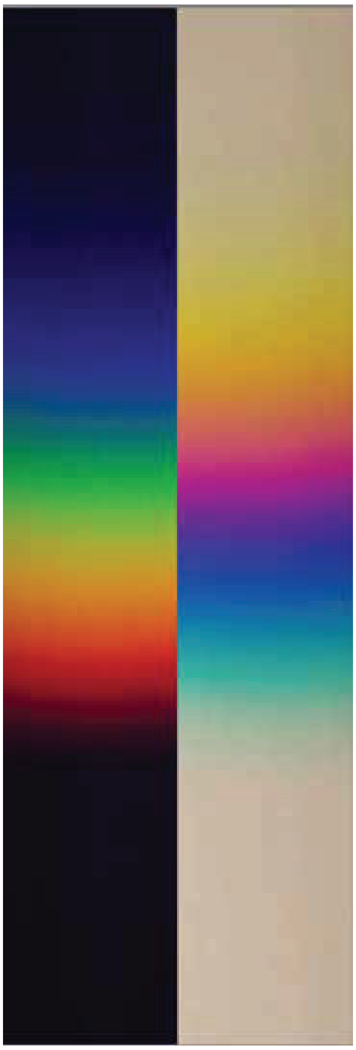

fig. 9

Newton's and Goethe's spectrum compared. Each colour in one spectrum is adjacent to its complement in the other. The spectra shown here appear more orderly than those in ill. 9 and ill. 10, as they have been created using a rectangular light source instead of a circular one.

[Illustration by Ingo Nussbaumer, edited by Matthias Herder; source: Müller 2015, colour plate 6]

in the Opticks on which Newton based his theory. This claim I'll call 'Goethe's theorem'.[43] Though he was unable to invert all of Newton's experiments, this was due to the experimental limitations of his time and not due to the theorem itself. For in order to systematically exchange light and darkness in these experiments, Newton's dark chamber has to be inverted (by constructing a light chamber which is uniformly illuminated). That was impossible for Goethe, as the electric light was not invented until some decades after his death.

How does Goethe's theorem fare from today's point of view, now that it is possible to construct such light chambers? Surprisingly Goethe's theorem holds up both experimentally and theoretically.[44] Indeed Newton's most important experiments have been successfully inverted. For example, in Newton's white synthesis the colours of his spectrum are recombined to create white; if the colours of Goethe's spectrum are recombined in the same manner, darkness results.[45] And whereas in the experimentum crucis an isolated spectral colour does not decompose when projected through a second prism, in its inversion an isolated colour from Goethe's spectrum does not decompose either when projected through a second prism in light surroundings.[46]

Similarly for the remaining experiments. Interestingly Newton's own theory predicts that all of his experiments can be inverted.[47] On the one hand this means that the inverted experiments cannot refute Newton's theory. On the other the overarching polarity of light and darkness in the realm of Newton's experiments spells bad news for his followers: Newton's theory is not the only theory that

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[43] See Müller 2018a, Section 3. Goethe's theorem not only concerns those experiments Newton described but must include all experiments that can be conducted in what is now known as geometrical optics (Müller 2015, §II.5.22). Neither Newton nor Goethe had a clear conception of this modern discipline, but including its experiments in the theorem is natural from a systematic point of view.

[44] Bjerke was the first to carry out research in this vein (Bjerke 1963, pp. 32, 65–6, 85–8 *et passim*).

[45] As demonstrated e.g. by Nussbaumer 2008, pp. 105, 158, 188. See fig.20, images 1 and 2 as well as Müller 2016, Section 6 and Müller 2010, Sections VII (white synthesis) and XV (black synthesis).

[46] The idea of this inversion is due to Goethe, although he was unable to realise it empirically (Goethe 2016, §132). For early theoretical advances, see Holtsmark 1970. The first empirical results were achieved by Sällström 2010. See Müller 2016, p. 339, n. 23 for a brief summary (in English) as well as Rang and Müller 2009 for more details (in German). The fullest account is given in Rang 2015.

[47] For proof see Müller 2015, pp. 209–16; an English sketch of the proof is offered in Müller 2016, Section 6.

fig. 10

Goethe's template for prismatic experiments. In many of Goethe's experiments, a template is observed through a prism. He designed these templates to ensure that the relevant optical situation is reversed.

(Photo: Universitätsbibliothek der Humboldt-Universität zu Berlin, Historische Sammlungen: 2942:tafe:'a':F8)

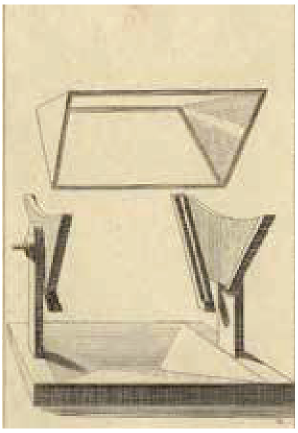

fig. 11

Goethe's water prism. Plate XVI of Goethe's Farbenlehre shows the construction of a water prism. Goethe wanted to adjust the orientation of the prism such that rays of light could enter at an angle independent of the sun's position.

(Photo: Universitätsbibliothek der Humboldt-Universität zu Berlin, Historische Sammlungen: 2942:tafe:'a':F8)

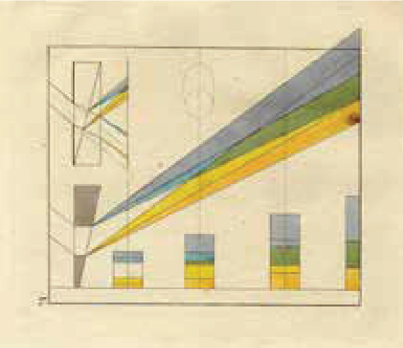

fig. 12

Newton's spectrum at various distances. In Plate V of his Farbenlehre, Goethe shows how the spectral colours of sunlight change with distance. The green centre of Newton's spectrum only emerges at a distance of more than one metre. *(Photo: Universitätsbibliothek der Humboldt-Universität zu Berlin, Historische Sammlungen: 2942:tafe:'a':F8, image rotated; the plate is available, for example, in Goethe 'Theory of Color', plate VII before p. 207).*

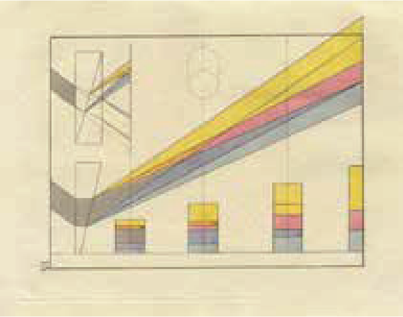

fig. 13

Goethe's spectrum at various distances. In Plate VI of his Farbenlehre, Goethe shows how the spectral colours of darkness (that is, of a shadow) change with distance. This image is the polar opposite of the previous one. *(Photo: Universitätsbibliothek der Humboldt-Universität zu Berlin, Historische Sammlungen: 2942:tafe:'a':F8, image rotated; the plate is available, for example, in Goethe 1988, plate VIII before p. 207).*

144 PPI

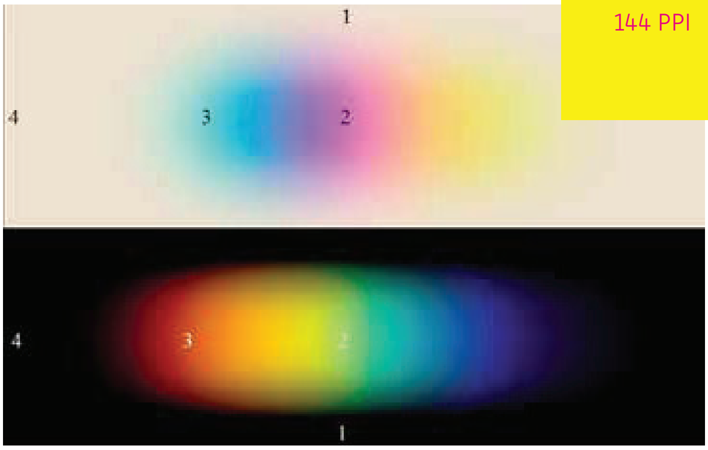

fig. 14

Polar inversion of infrared heat radiation. Lower part: Herschel began by measuring the temperature in the dark area below Newton's spectrum (position 1). Moving the thermometer to the green centre of Newton's spectrum (position 2), he detected an increase in temperature, which increased further as he moved the thermometer into the red area of the spectrum (position 3). To his surprise he found that the maximum temperature was beyond the red end of the spectrum (position 4), where we nowadays speak of infrared heat radiation. Upper part: When Matthias Rang and Johannes Grebe-Ellis repeated Herschel's experiment with modern means in Goethe's spectrum, they detected inverted relative temperatures. They began by measuring the temperature in the bright area above Goethe's spectrum (position 1). Moving the thermometer to the magenta centre of Goethe's spectrum (position 2), they detected a decrease in temperature, which decreased further as they moved the thermometer into the turquoise area of the spectrum (position 3). Beyond that end of the spectrum (position 4), they found a temperature minimum; here we could speak of 'infraturquoise coldness radiation'.

(Illustration by Olaf Müller; source: Müller 2017, p. 317, ill. 10).

matches the data – and so his claim to have proven it experimentally is mistaken.[48] Any proof Newton could 'derive' from his experiments can be countered by means of inverted experiments with a structurally analogous counterproof of the theory that darkness, rather than light, is composed of colours of diverse refrangibility.[49] From this Goethe drew the philosophical conclusion that is still valid today: several distinct theories can be compatible with one and the same set of data; physics is less determinate than it appears.[50] Is the objectivity of physics perhaps in danger?[51]

Polarity beyond the visible parts of the spectra

I'll now turn to two further cases that demonstrate the success of a Goethean search for spectral polarity. One of these is from Goethe's time, the other from ours.[52]

Around 1800 William Herschel discovered infrared radiation beyond the red end of Newton's spectrum fig. 14 bottom but no radiation beyond the opposite end.[53] When Goethe's allies heard of this discovery, they sensed danger for his research programme.[54] How could Goethe's claim of spectral polarity be correct if the spectrum has an invisible extension at one end but not at the other? Can the spectral symmetry be salvaged in view of Herschel's results?

Such worries were soon assuaged. Johann Ritter, a talented young physicist, searched for effects observable beyond the other end of the spectrum. He was successful. On 22 February 1801 he discovered the effects of what is now known as ultraviolet light.[55] This discovery secured him a place in the annals of science. Ritter

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[48] Here is but one of Newton's statements in this regard: 'the Theory wich I propounded was evinced to me, *not by inferring tis thus because not otherwise*, that is not by deducing it onely from a confutation of contrary suppositions, but *by deriving it from Experiments concluding positively & directly*' (Newton, letter to Oldenburg dated 6 July 1672 (see Turnbull 1959, p. 209); italics unchanged; see also Newton 1984, pp. 86–7, Newton 1964, p. 5).

[49] Goethe 1957b, p. 86; Goethe merely defended this theory for the sake of the argument (as a *reductio ad absurdum* of Newton's proofs). Joseph Reade, however, did champion the darkness theory (Reade 1814).

[50] See the *locus classicus* (with deplorable lack of examples) in Quine 1975.

[51] For details see Müller 2016, Sections 7 and 8.

[52] For a more detailed account of both cases, see Müller 2018b, Section 4 and Müller 2018a, Section 3.

[53] The *locus classicus* is Herschel 1800a and b.

[54] TFriedrich Schelling, letter to Goethe, dated 17 April 1801 (see Goethe 1947–2011: II.3, p. 135). For an English translation of this passage, see Müller 2018b, Section 4.

[55] Ritter 1806. For a discussion in English, see Frercks et al. 2009.

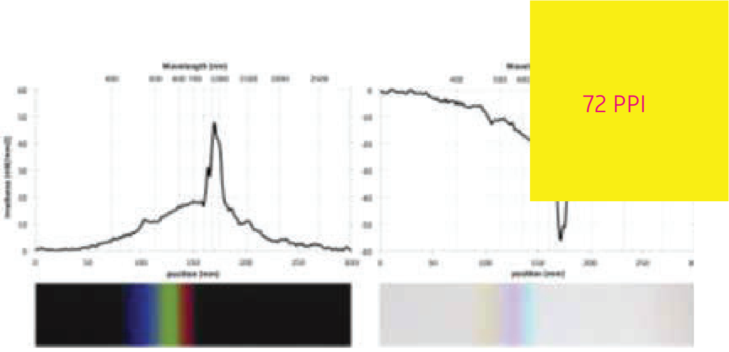

fig. 15

Experimental results from Newton's and in Goethe's spectrum. The left-hand graph shows the radiation detected in Newton's spectrum as a function of the position within the spectrum (given at the top in terms of wavelength). The polar results from Goethe's spectrum are shown in the right-hand graph.

(Image by Matthias Rang; source: Rang and Grebe-Ellis 2018, ill. 2 and ill. 3).

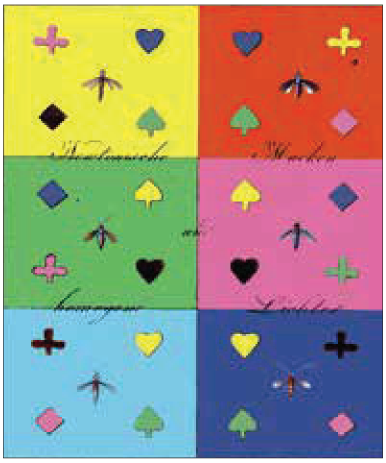

fig. 16

Goethe's prism template modernised.

When Newton peered through a prism at small black insects in monochromatic light, he noticed no changes in colour or shape (Newton, 'Optics', p. 49 [Book I, Part I, Experiment 14]). Goethe mistakenly claimed that this experiment could be tested using plate XII of his Farbenlehre, where he presented pictures of insects on differently coloured backgrounds. Prismatic observations of these pictures obviously cannot reproduce Newton's results because the reflected light isn't monochromatic. Nonetheless the pictures are valuable as they can be used as templates for experiments in which coloured shapes are observed against a differently coloured background. Goethe can thus be seen as anticipating Nussbaumer's discovery of the disorderly spectra.

Image by Matthias Herder; source: Müller 2015, colour plate 29 knew of the significance of his findings and how delighted Goethe would be on hearing about them. Instead of informing his colleagues in Jena, he packed his bags, headed straight for Weimar and met Goethe.[56] Goethe was captivated. After their meeting he composed a long letter to Ritter in which he suggested further experiments in line with his polar research programme.[57] Only recently have these experiments been carried out with results that fit Goethe's claims.[58] Parallel to Newton's spectrum, in Goethe's spectrum colour correlates with temperature – and changes of temperature continue beyond the visible part of the spectrum. Herschel measured a temperature maximum beyond the red end of Newton's spectrum (infrared heat radiation); a corresponding minimum has recently been measured beyond the turquoise end of Goethe's spectrum, as if there were infra-turquoise coldness radiation fig. 14 top and 15.

A multitude of colourful polarities

As I have outlined, Goethe pursued a polarity between light and darkness: exchanging these two poles in any of Newton's experiments leads to an inversion of the results, in terms of both colour (Sections VII and VIII) and temperature (Section IX). In the former case there is the opposition of colour and its complement, while in the latter there is the opposition of heat and coldness (as Kant had speculated; see section "The eart, a giant tourmaline?").

In this final section I'll extend the concept of the polarity of light and darkness to chromatic colours. So far we have only considered what happens if the achromatic complementary colours (that is, black and white) are decomposed with a prism; Newton's experiment featured a white ray of light in black surroundings fig. 12, while Goethe's inverted experiment involved a black shadow in white surroundings fig. 13. What happens if these experiments are conducted using chromatic complementary colours instead?

Goethe seems to have considered this question fig. 16, though he was unable to investigate it empirically for lack of suitable sources of coloured light.[59] Today these technological limitations have been overcome, and the matter has been taken up by painter and

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[56] For more details see Müller 2018b, Section 4 with references to the original literature.

[57] Ritter published Goethe's letter shortly before his death (Goethe, letter to Ritter dated 7 March 1801 [see Ritter 1808, pp. 724–7]).

[58] On this and the following, see Rang and Grebe-Ellis 2018.

[59] Goethe 1957b, p. 98.

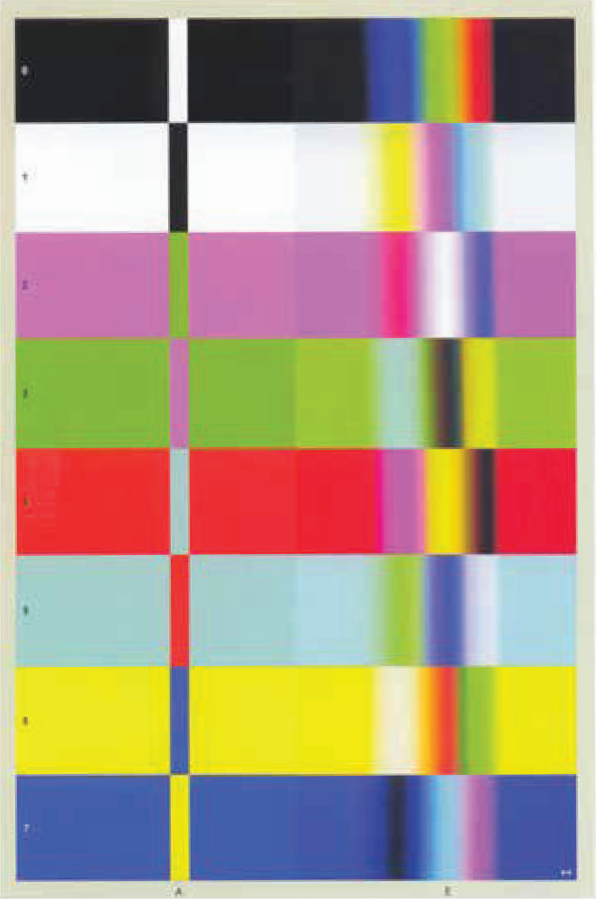

fig. 17

Photographs of the eight spectra.
The original contrast (left) seen through a water prism (right).
All spectra are of the same size and differentiation.

(Images and photos by Ingo Nussbaumer; source: Nussbaumer 2008, p. 132, plate XX).

colour researcher Ingo Nussbaumer.[60] He investigated the following question: What happens if white light is replaced, for example, by yellow light and darkness by blue light (the complement of yellow)? Nussbaumer's experiments yield astonishing results. In every experiment new and different spectra emerge, but each of these spectra contains at least one of the two achromatic colours, white and black. A yellow ray of light against a blue background, for example, creates a spectrum of black, green, turquoise, white and magenta, and a complementary blue ray of light against a yellow background produces a spectrum of white, magenta, red, black and green:

Septral results of a blue/yellow/blue contrast fig. 17, row no. 7	Septral results of a yellow/blue/yellow contrast fig. 17, row no. 6
black	white
green	magenta
turquoise	red
white	black
magenta	green

The other pairs of complementary colours lead to four further spectra, which are similar to those we have just considered in terms of diversity, size and structure but again differ in colour:

Spectral results of a magenta/green/magenta contrast fig. 17, row no. 2	Spectral results of a green/magenta/green contrast fig. 17, row no. 3
red	turquoise
yellow	blue
white	black
turquoise	red
blue	yellow

Spectral results of a red/turquoise/red contrast fig. 17, row no. 4	Spectral results of a turquoise/red/turquoise contrast fig. 17, row no. 5
magenta	green
white	black
yellow	blue
green	magenta
black	white

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[60] On these experiments, which are described here for the first time in English, see Nussbaumer 2008, pp. 200–6 *et passim*. I provide a brief overview of the matter in Müller 2008, Section V; for more details, see Müller 2013b and Müller 2015, §§III.5.11–III.5.16.

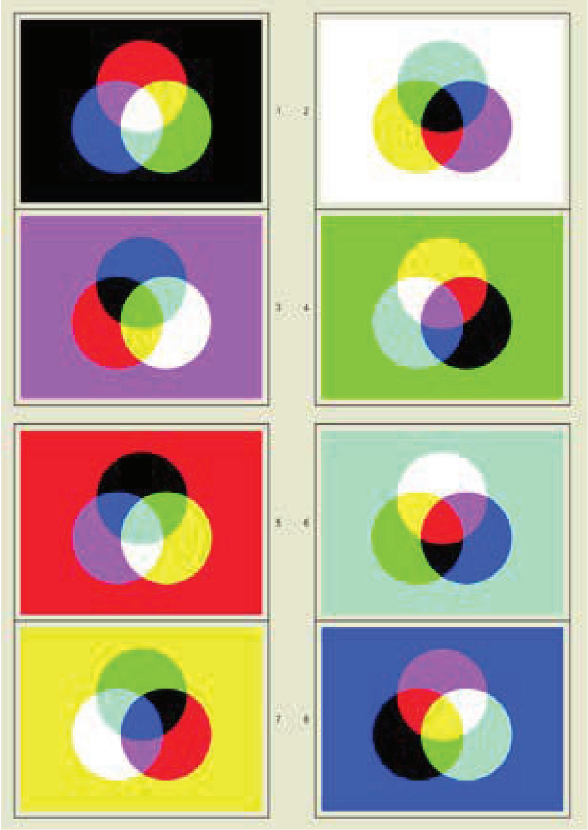

fig. 18

The eight colour-mixing diagrams. Newton's additive rules of colour mixing show how the colours of his spectrum can be mixed to create white (in dark surroundings, image 1). In its inversion the colours of Goethe's spectrum are mixed to create black (in bright surroundings, image 2). Colour mixing functions for the disorderly spectra as well (images 3–8)

(Diagram by Ingo Nussbaumer; source: Nussbaumer 2008, p. 133, plate XXI)

Nussbaumer calls these newly discovered spectra the 'disorderly' spectra, although they do exhibit a fascinating order fig. 18.

Outlook

To avoid a potential misunderstanding, none of the experiments I have presented refutes modern physics or Newtonian optics. The disorderly spectra of the previous section can be explained by optics and colorimetry. The decrease in temperature beyond the turquoise end of Goethe's spectrum follows from the law of conservation of energy.[61] Friends of science thus need not be concerned; there is no need to change physics.

Nonetheless the foregoing considerations should give us pause for thought. If Goethe's idea of spectral polarity can be extended this far, what would have happened if this thought had found more adherents and been systematically pursued during his lifetime? Would our physical theories look completely different? I don't know, but I find the question itself disconcerting enough.[62]

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[61] Rang and Grebe-Ellis 2018, Section 4.

[62] I have defended an agnostic view on these counterfactuals in Müller 2016, pp. 342–3.

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