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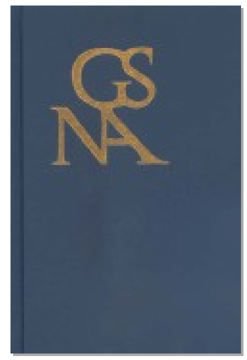

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GOETHE'S FIRST LOOK through a prism showed him the colored fringes that became the foundation for his whole theory of color. In his *Beiträge zur Optik* (1791), he described a series of experiments showing the fringe colors—now usually called boundary colors—produced by looking through a prism at a white strip on a black surface and a black strip on a white surface.[1] The white strip on black gives violet/blue and yellow/orange fringes with white space between. If the viewing distance is increased or the strip is narrowed so that the fringes overlap, blue and yellow eventually give place to green. The remaining sequence is therefore violet / green / orange. The black strip on white gives yellow/orange and violet/blue fringes with black space between. If the strip is narrowed so that the fringes overlap, orange and violet eventually give place to magenta. The remaining sequence is therefore yellow / magenta / blue (see figure 1).[2]

Rupprecht Matthaei, the twentieth century's most knowledgeable writer on Goethe's color theory, argued convincingly that Goethe used the six boundary colors to construct his color circle.[3] The circle's top half consists of the inner boundary colors from the *white* strip, orange and violet, to left and right, with magenta between them in the center. Its bottom half consists of the inner boundary colors from the *black* strip, yellow and blue, to left and right, with green between them in the center (see figure 2). Goethe believed that his circle, which joined the two ends of Newton's open, linear spectrum, thus remedied its lack of structure, bringing symmetry into the realm of color.[4] And of course the circle is indeed a closed, continuous arrangement of the colors, complete by construction.[5]

For Goethe, however, it was not so much a colorimetric convenience as a proof of his deepest philosophical and metaphysical beliefs. A dualist in the tradition of Aristotle, he understood color as a product of the opposition between light and darkness. Therefore he saw yellow, the color he considered closest to light, and blue, which was closest to darkness, as a pair of polar opposites fundamental to the world of color. Green, which had appeared in the boundary experiment in place of blue and yellow, was a mixture of these two in their basic, unaltered form. But yellow and blue were capable, according to Goethe, of a *Steigerung* or heightening, to orange and violet respectively. If these two heightened forms of the basic colors were mixed together, as in the boundary experiment, the result was magenta, which thus ranked

Figure 1(a). Schematic representation of the fringe colors of (i) a wide white strip, and (ii) a narrow white strip.

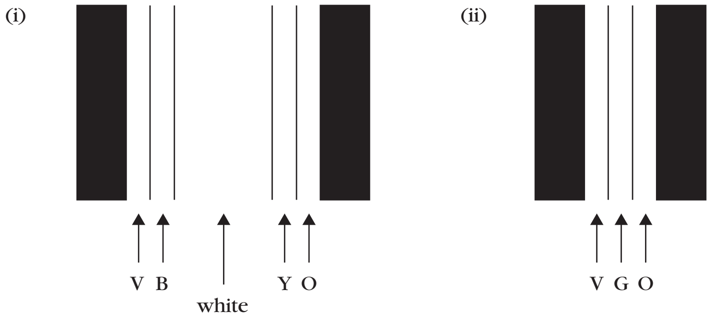
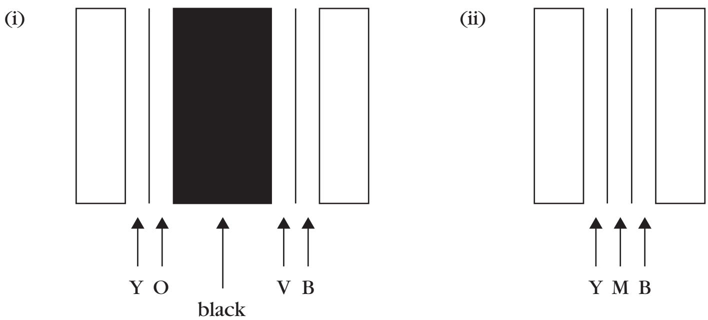


Figure 1(b). Schematic representation of the fringe colors of (i) a wide black strip, and (ii) a narrow black strip.



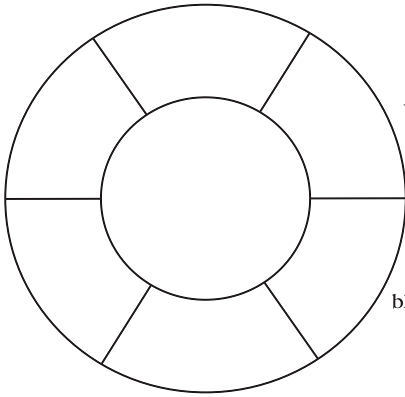
See Goethe, *Beiträge zur Optik*, 1. Stück, § 59 (FA 23.2:34–35) and *Zur Farbenlehre. Didaktischer Teil,* §§ 213–17 and Tafel II (FA 23.1:92–93 and Plate 2).

Note that the positions of black and white in Figure 1(a) are the reverse of those in Figure 1(b), and that the positions of the fringe colors in Figure 1(a) are occupied in Figure 1(b) by their complementaries.

as the culmination of the whole structure: the dominant color that subsumed the rest within itself.[6]

Clearly Goethe's own interpretation of his color circle tended to devalue orange, violet, and green, which were, respectively, nothing but the heightened variants and the "mixture" of yellow and blue, while elevating yellow and blue themselves, and their culmination, magenta, to the status of primary colors. Goethe's explanation of the circle printed to illustrate *Zur Farbenlehre* stated: "Gelb, Blau und Rot sind als Trias gegen einander über gestellt; eben so die intermediären, gemischten oder abgeleiteten" (FA 23.1:1013).[7] The colors of the prismatic experiment with a black strip on a white ground thus came to take precedence in Goethe's mind over those of

Figure 2. Goethe's color circle based on the six fringe colors.



See Goethe, *Zur Farbenlehre*, Plate I.1 (FA 23.1: Plate I.1)

the experiment with a white strip on a black ground. This arrangement had a polemical purpose: Goethe was setting "his" colors above those he thought of as Newton's, which he regarded as a mere derivative of the coalescence of fringes (Sölch 91). Goethe's partisanship is nicely attested by visual materials that he commissioned, such as the picture card showing a rainbow with blue, magenta and yellow bands from the top down, reversing the order of orange, green and violet in nature; and Heinrich Meyer's ceiling fresco of Iris in the entrance-hall of Goethe's house in Weimar, likewise showing the reversed rainbow.[8] The scientist Wilhelm Ostwald, an energetic critic of Goethe despite a similarity between their approaches to color, objected in particular to Goethe's "false doctrine that *Yellow, Red* and *Blue* are the three *Primary Colours.*"[9]

Goethe's intemperance about Newton's theory of color helps to explain the strength of hostility, among contemporaries and successors alike, to his own. But physicists would always have suspected his approach because he preferred to work with boundary colors rather than analyzing the spectrum into its constituent wavelengths.[10] His interpretation of his color circle has proved especially vulnerable at the point where he claimed that green and magenta, which he correctly recognized as complementaries and afterimage contrast colors, were formed in the same way, by a process of mixture involving yellow and blue in the case of green, and orange and violet in the case of magenta. The problem here lies with green. For in an influential paper on color mixture published in 1852, Hermann von Helmholtz showed that when spectral lights are superposed at right angles through a V-shaped slit, blue and yellow merge to form not green but white.[11] Despite some detailed qualifications of this result, Helmholtz used blue and yellow as his prime example of the difference between mixtures of lights and mixtures of pigments, where blue and yellow do make green. From his time onwards, textbooks on color have regularly insisted, without qualification, that blue and yellow lights add to white.

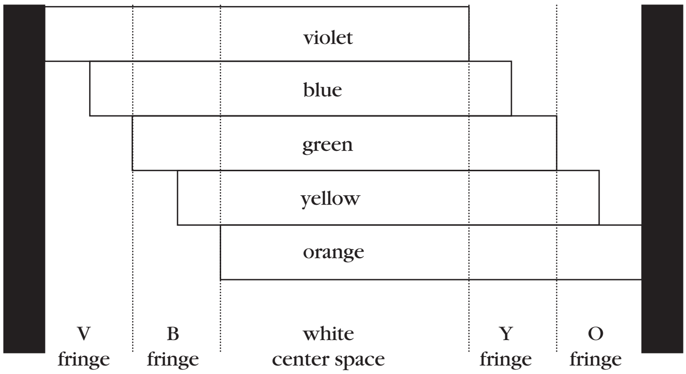
This leaves a puzzle for the uninitiated: if the green in Goethe's experiment cannot be formed by mixing of blue and yellow, how is it formed? Surprisingly perhaps, this question continued to provoke argument almost to the close of the twentieth century. Matthaei never managed a complete explanation. One that he considered, only to reject it forthwith, involved the Bezold-Brücke effect.[12] Much more recently Michael Duck of Harwell likewise suggested that this psychophysiological phenomenon, which causes the fading of spectral blue and yellow with diminishing intensity of the light, could explain the prominence of green between orange and violet in Goethe's experiment.[13] However Duck's explanation is not satisfactory because it relies on diminished light through increased viewing distance in an objective prismatic experiment with a screen, whereas the green effect Goethe talks about can equally well be obtained subjectively by tilting the prism to narrow the strip, without decreasing the intensity of the light.[14]

The standard explanation, already offered by scientific contemporaries of Goethe such as C. H. Pfaff, but periodically lost to view, is that green arises precisely through this narrowing of the strip (see figure 3).[15] A wide white strip produces only boundary colors on either side of a white center, as Goethe saw when he first looked through Büttner's prism and became convinced that Newton's theory of light was wrong. Here the central white is formed by the overlapping of rays of all wavelengths. Eventually, as the strip narrows, only such rays overlap at the center as together produce the appearance of green. Now, the boundary sequence of violet, blue, white, yellow and orange is reduced to the familiar violet, green and orange of Newton's spectrum, separated only by comparatively insignificant bands of blue and yellow. Thus the green of Goethe's boundary experiment is usually explained as being nothing more nor less than the range of monochrome lights that look green in neutral adaptation, that is, the wavelengths between about 495 nm and 566 nm. Though it involves a range of wavelengths, this "spectral green" is in no wise a mixed color. The test is that it can not be broken down by refraction into separate yellow and blue parts. The magenta which appeared in Goethe's second prismatic experiment is a different matter altogether. Here, as he himself correctly assumed, the new color indeed arises as orange light merges with violet, and is a true mixture, which can therefore be broken down by refraction to reveal its orange and violet constituents.[16]

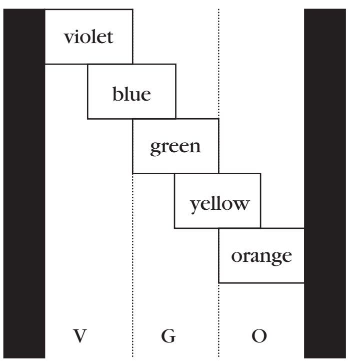
The difference between fringe green and fringe magenta as thus explained has earned Goethe many a rebuke from editors of *Beiträge zur Optik* and *Zur Farbenlehre.* Manfred Wenzel, commenting in the *Frankfurter Ausgabe* on Plate 5 of *Zur Farbenlehre,* points out that it incorrectly shows the green of Newton's spectrum arising from the mixing of blue and yellow, and states that Goethe erroneously believed that green and magenta were formed by an identical mixing process (FA 23.1:1451). Elsewhere Wenzel frequently explains that Goethe, writing as he was well before Helmholz clarified the

Figure 3. The formation of the fringe colors of (i) a wide white strip, and (ii) a narrow white strip.

(i)



(ii)



Based on P[ieter] J[ohannes] Bouma, *Physical Aspects of Colour: An Introduction to the Scientific Study of Colour Stimuli and Colour Sensations*, ed. W. de Groot, A. A. Kruithof and J. L. Ouweltjes (London: Macmillan, 1971) 113–15, and Figs. 53 and 54.

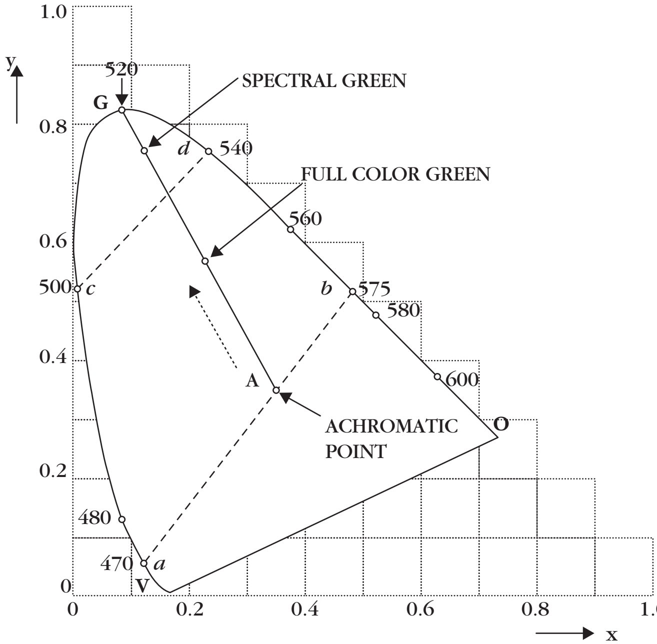
rules of mixture, could not know that the process of adding blue to yellow yields green in paints but only white in lights (FA 23.2:343–44).[17] Rupprecht Matthaei and Horst Zehe, editing Goethe's color treatises for the Leopoldina edition of his scientific works, took the same view.[18] Presumably these editors simply intended to explain how scientific thinking had progressed since Goethe's time. But, decades earlier, Ostwald had seized on the difference between fringe magenta and fringe green as a clinching argument against Goethe's entire metaphysics: "Wir haben hier ein schönes Beispiel für die Trüglichkeit jenes allgemeinen Gedankens der Polarität, den Goethe so ungemein hoch bewertete. Denn das Purpur des zweiten Versuches kann man mit dem Prisma alsbald in seine Bestandteile zerlegen, das Grün des ersten ist dagegen unzerlegbar."[19]

Under such an onslaught, the symmetry of Goethe's circle appears to collapse, calling the value of his system of boundary colors into question. If the relationship of the six colors is not in fact as Goethe understood it, then it must seem that the Newtonian linear spectrum is the only possible basis for colorimetry. But despite Ostwald's certainty, matters are not so clear cut. For Ostwald, in insisting that fringe green could not be broken down, was aligning himself with a largely Anglo-Saxon orthodoxy, whereas a less well-known but still strong continental tradition took the boundary colors more seriously, and developed a more differentiated view of fringe green in particular. One key representative of this tradition was August Kirschmann, author of "Das umgekehrte Spektrum und seine Komplementärverhältnisse" (1917). Kirschmann may have been the first to describe as "inverted" the spectrum formed by overlapping the boundary colors of a black strip on a white background, and dominated by blue, magenta and yellow. Other terms in use are "negative" or "complementary" spectrum. Kirschmann is perhaps most notable for describing the colors of both boundary spectra as strikingly vivid, and suggesting that this vividness arises in different ways for different colors: for violet and orange through a single narrow band of wavelengths; for magenta and green through the combination of two bands of wavelengths; and for blue and yellow through the whole spectrum minus a single narrow band of wavelengths. His claim, quite novel for its time, flew in the face of a common assumption that monochromatic beams produced the most vivid colors. Helmholtz had observed that spectral green was not very vivid; now Kirschmann asserted that the more vivid fringe green was composed of "two" bands of wavelengths, by which he meant blue-green and green-yellow, or blue and green-yellow.[20]

The color relationships described by Kirschmann were eventually analyzed mathematically by P. J. Bouma in his *Physical Aspects of Colour,* first published in Dutch in 1946, and still the fullest account of the boundary colors. Using standard illuminant B, an approximation to sunlight, Bouma calculated the chromaticity coordinates of the colors at ten equidistant numbered points in the boundary spectrum visible at the left margin of a white strip on a black background. He described the colors at the specified points, starting from the black background, as follows: "the violet tints of very low brightness (1 to 3) come first; then the colour gradually changes into a pure blue with increasing brightness (4 to 6); next greenish-blue colours appear (7 to 9) with ever increasing brightness but continually decreasing saturation; and finally the colour passes into white." At the right margin of a white strip on black, he found, beginning from the white center of the strip, "the sequence is as follows: greenish yellow with increasing saturation and slowly decreasing brightness (1 to 4); saturated yellow (5 to 6); then, with gradually further decreasing brightness, orange (7), orange-red (8), and red (9)." These colors of course included no pure green. The reason, Bouma found, was the absence of all wavelengths between 495 nm and 566 nm.[21]

Bouma next explored what happens when the white strip on a black background is narrowed, as in figure 3(ii). His results can be plotted on the CIE

Figure 4. Location on the CIE standard chromaticity diagram of the greens seen as the white strip narrows.



Key:

> **V**, **O**, **G** indicate Violet at the short-wave end, **O**range at the long-wave end, and **G**reen at the center of the tongue-shaped curve.
>
> The line **AG**, linking the **ACHROMATIC POINT** to the curve at 520 nm, is the locus of the ideal greens, with the bright, unsaturated green of the wide white strip close to **A**, and the dull, saturated green of the narrow white strip close to **G**.
>
> The dashed arrow ⇡ indicates the line of travel of fringe green from **A** to **G** as the white strip narrows.
>
> The line *ab* shows the wavelengths (from 470 nm to its complementary, 575 nm) that participate in the **FULL COLOR GREEN**.
>
> The lind *cd* shows the smaller range of wavelenths in **SPECTRAL GREEN**.

Based on Bouma 117, 122–23, and Figs. 58 and 64.

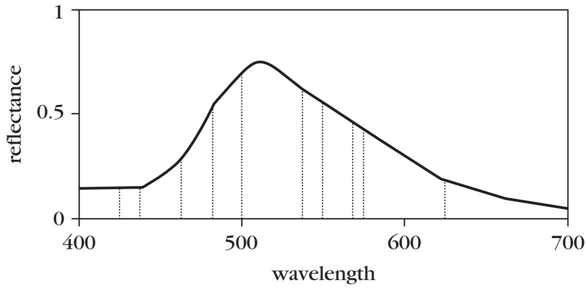
chromaticity diagram (see figure 4), which arranges all possible color stimuli in a space bounded by a curve whose ends are joined by a straight line. The curve represents the spectral colors from violet (beginning at a wavelength of around 400 nm) via green centering on 520 nm to orange (beginning at around 600 nm). The straight line is the locus of the non-spectral purples, including Goethe's magenta. As all spectral colors mix to white, white light appears in the middle of the color space, at the achromatic point.[22] Bouma showed that as the two colored edges of the white strip come together and eventually overlap, the left-hand border of the strip causes "orange" wavelengths greater than 616 nm and the right-hand border of the strip causes "violet" wavelengths smaller than 436 nm to disappear from the boundary spectrum. When these components have disappeared, the color visible at the center of the strip, a color with a wavelength range of 436 nm to 616 nm and a dominant wavelength of 520 nm, is a green of high brightness and low saturation, close to the achromatic point on the CIE diagram. If the strip is narrowed further, fringe green rises from the achromatic point and moves closer and closer to the spectrum locus at 520 nm (see the bold arrow in figure 4). "This result is to be expected," Bouma wrote, "for if we look through a prism at a very narrow strip of light we have Newton's arrangement and we see an ordinary spectrum." With the very narrow strip, then, we do arrive at a point where fringe green has a range of as little as 500 nm to 540 nm. It has increased in saturation as it has moved far away from the achromatic point, but has lost in brightness to the extent of appearing somewhat dull. And it coincides, as Goethe's detractors from Pfaff onwards have observed, with ordinary spectral green (Bouma 110, 115–17, 122–23).

However, further analysis by Bouma showed that Pfaff's assertion, though valid, missed the essential point about fringe green, which in common with the other boundary colors has some special characteristics. Fringe green, at all stages of its progress along the line linking the achromatic point of the CIE diagram to the spectrum locus at 520 nm, is an optimal color: that is, it has the greatest possible brightness for its chromaticity. Optimal colors have a particular form of spectral luminance factor curve (see figure 5). An ordinary green leaf or green-painted surface reflects some light at most wavelengths, so that its spectral reflectance is representable by an irregular, curved line.[23] Optimal colors, by contrast, reflect light of any given wavelength either completely or not at all, and "jump" between the two possibilities at no more than two places in the spectrum. Their spectral luminance factor curves are therefore angular, and show large blocks of wavelengths as present or absent. The curves for various stages of fringe green show that at any given stage it involves only a band of wavelengths from the central part of the spectrum; wavelengths above or below these are entirely absent from its light.[24]

As optimal colors, the various stages of fringe green are all maximally bright for their chromaticity. But this does not mean that an observer will perceive them all as being equally "colorful." Brightness and saturation vary in inverse proportion. As we have seen, a narrow spectral green ranging from 500 nm to 540 nm is saturated but not very bright, whereas fringe green located close to the achromatic point of the CIE chromaticity diagram is bright but lacks saturation. Therefore it is reasonable to suppose that the best compromise will be found near the middle of the line linking the spectral locus at 520 nm and the achromatic point. And it is indeed at the middle of this line that the most colorful fringe green is located (as shown in figure 4). It belongs to the subset of optimal colors to which Goethe's critic Ostwald gave the name "full colors" (*Vollfarben*). He also called them "semichromes"

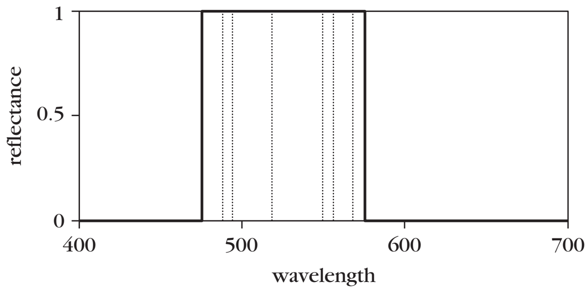
Figure 5. Spectral reflectance curves.

(i). Typical reflectance curve of a non-optimal color.



None of the marked wavelengths within the curve has a value of 0 or 1.
A surface with this sort of reflectance curve would be perceived as a light green.

(ii). Reflectance curve of an optimal color.



All of the marked wavelengths within the curve have a reflectance value of 1.
This is the reflectance curve of an optimal green.

Based on Bouma 117–20.

because, crucially, the range of the spectrum that produces them is bounded by *complementary* wavelengths. In the case of the most colorful fringe green, these wavelengths are 470 nm and 574.86 nm. The green that Goethe and Kirschmann found so striking in their prismatic experiments was this color, shown by Bouma's meticulous measurements to be quite different both from the green of Newton's ordinary spectrum, and from the pale, near-achromatic green that is the first to appear when the boundaries of the white strip begin to coalesce.[25]

Given that the *Vollfarbe* fringe green involves such a wide range of wavelengths, including some that in isolation would look blue, some that would look green, and some that would look yellow, it ought, despite Ostwald's insistence that it was unmixed and irrefrangible, to break down when refracted by a prism, revealing yellow and blue elements. André Bjerke, a Norwegian Goethe scholar who became better known for his creative writing, attempted to refute Ostwald by showing that, given the right experimental conditions, fringe green will break down. Bjerke's essay, originally published in Stockholm in 1961, has scarcely been noticed, much less subjected to serious scientific review, although the experiments he described were conducted with the help of a physicist, Sven Oluf Sørensen. Horst Zehe, commenting on *Zur Farbenlehre. Polemischer Teil* in the Leopoldina edition, dismissed Bjerke in two lines as a misguided Goethe-fanatic.[26] Bjerke's argument nevertheless merits further consideration, given the proven nature of *Vollfarbe* fringe green. He described parallel experiments on fringe green and fringe magenta.

If fringe magenta is projected on to a screen and viewed diagonally through a prism, its component parts are differentially refracted and it splits into partially overlapping patches of violet and orange light, with the overlap still appearing as magenta. This confirms Newton's 7th Experiment in *Opticks* (1704), Book I, which likewise shows that fringe magenta, mixed from the violet and orange ends of two superimposed spectra, splits into its component parts when refracted by a second prism. But Bjerke also showed that if fringe green is similarly projected onto a screen and viewed diagonally through a prism, under conditions which exactly reverse those of the magenta experiment, the green also splits, into partially overlapping patches of blue and yellow light, with the overlap still appearing as green. This can also be shown using Newton's technique in the 7th Experiment. Bjerke was also able to demonstrate that under different experimental conditions, magenta as well as green can remain *intact* when refracted through a second prism.[27] His results seem to tally with work published a few years later in the *American Journal of Physics* by Tørger Holtsmark, professor at the University of Oslo, who claimed that so far as boundary colors are concerned, "rays which are complementarily colored have the same refrangibility," so that, remarkably, "no systematic correlation between colour and refrangibility can be recognized."[28]

The literature thus provides confirmation of two distinctive forms of green (among the infinite number that are possible): spectral green, which is unmixed in the sense that all of its component wavelengths in isolation would appear green; and a fringe green which is a *Vollfarbe* bounded by complementary wavelengths and capable of being broken down into components of which in isolation some would appear yellow, some blue and some green. Ironically, given the confusion that has so long surrounded this issue, both Newton and Goethe seem to have been fully aware of the existence of and the difference between these two particular forms of green. Newton described in the *Opticks* how two "homogeneal" spectral colors could mix to form a color "like in appearance" to the homogeneal color lying between them. Yellow and green would form a yellow-green, and then, he continued,

> if blue be added, there will be made a green the middle Colour of the three which enter the composition. For the yellow and blue on either hand, if they are equal in quantity they draw the intermediate green equally towards themselves in Composition, and so keep it as it were in AEquilibrion, that it verge not

> more to the yellow on the one hand, and to the blue on the other, but by their mix'd Actions remain still a middle Colour. To this mix'd green there may be farther added some red and violet, and yet the green will not presently cease, but only grow less full and vivid, and by increasing the red and violet, it will grow more and more dilute, until by the prevalence of the added Colours it be overcome and turned into whiteness.[29]

Here Newton effectively described the progress of fringe green as a white strip against a black background widened. Goethe, for his part, noted in his *Konfession des Verfassers* at the close of *Zur Farbenlehre* that the white strip on a black background, seen at a particular distance through the prism "das bekannte Spektrum vorstellte, und vollkommen den Newtonischen Hauptversuch in der camera obscura vertrat" (FA 23.1:977). The greater or lesser viewing distance, which Goethe here identified as critical, is of course equivalent to a narrowing or widening of the white strip. Goethe knew that the white strip experiment produced the green of Newton's spectrum before the strip became so narrow that the colors disappeared altogether into darkness.

Even if it is accepted that the *Vollfarbe* fringe green is a mixture to the extent that it involves both blue-green and yellow-green wavelengths, this still leaves unanswered the objection to Goethe's color circle that green and magenta result from different *types* of mixing. Goethe, who did not know the difference between the additive mixture of lights and the subtractive mixture of pigments, assumed that green and magenta were both formed by a process of addition, and therefore paralleled one another. Then Helmholtz showed that blue and yellow lights, when added, approximate to white. But Bouma explained, entirely consistently with Helmholtz, that fringe green results from a form of *subtraction* akin to that effected by colored filters, or indeed by the mixture of pigments. As the white strip narrows, its left-hand border eventually causes wavelengths greater than 575 nm and its right-hand border eventually causes wavelengths smaller than 470 nm to be subtracted from the white light at its center (Bouma 115, 117, 177).

This explanation of the way in which the *Vollfarbe* fringe green is formed still appears to place it in a different category from fringe magenta. Though Bouma, in a rare example of equivocation, sometimes implied that its formation might also be described as subtractive, magenta is generally held to result from additive mixing of violet and orange lights.[30] Commenting on the essay "Von den farbigen Schatten," begun in 1792, Wenzel remarked of green and magenta: "Goethe behandelt diese Farben bereits hier parallel als Mischfarben, da ihm zeitbedingt nicht bewußt sein kann, daß hier zwei völlig unterschiedliche Arten der Mischung (subtraktive und additive Mischung) zugrunde liegen" (FA 23.2: 343–44).[31] So the symmetry of Goethe's color circle still seems to have been a delusion. Even if he did not equate a mixed with a non-mixed color, as Ostwald alleged, he did equate a subtractive mixture with an additive one.

Yet this is not in fact a problem. The colors of the inverted spectrum (blue, magenta and yellow) are the exact complements of those seen in the ordinary spectrum (orange, green and violet). And this is so because the white strip on a black ground and the black strip on a white ground are themselves complementary in a geometrical sense: they exactly reverse the spatial roles of light and darkness.[32] But, being geometrical reversals of one another, green and magenta must necesarily involve opposite forms of mixing. Green emerges by subtraction of wavelengths as the light of the white strip gives way to darkness, while magenta emerges by addition of wavelengths as the darkness of the black strip gives way to light. Their opposition is an essential part of the color circle's geometrical lawfulness. Only if both involved addition or both subtraction of light, as Goethe's critics apparently prefer, would that lawfulness be destroyed. Though he could not explain the relationship of green and magenta, he was right to trust his intuitive perception of the circle's structure: its six colors do indeed relate to one another in a manner that is remarkable for its economy and its beauty.

Rupprecht Matthaei's attempted reconstruction of the circle gave only a partial sense of these qualities. Matthaei used optimal rather than full colors and set the boundaries of green at 491 nm and 570 nm.[33] In other words, he regarded the green of the boundary experiment as equivalent to the green of the ordinary Newtonian spectrum, defined by Bouma as 495 nm to 566 nm. So a truer approximation to the circle Goethe had in mind can now be constructed on the basis of the *Vollfarbe* fringe green, extending from 470 nm to its complementary wavelength, 575 nm. Given their complementary relationships among the colors themselves, all six can of course be expressed in terms of the subdivisions of the spectrum created by these two wavelengths. Green, which occupies the center of the ordinary spectrum, lacks both the short end below 470 nm and the long end above 575 nm. Magenta, its complementary, consists of those wavelengths that are missing from green. Blue lacks only the wavelengths above 575 nm, and orange, its complementary, consists of those wavelengths that are missing from blue. Yellow lacks only the wavelengths below 470 nm, and violet, its complementary, consists of those wavelengths that are missing from yellow.

Despite Goethe's justified enthusiasm for the system of boundary colors, it has had little resonance even in those sections of the scientific world that have been willing to consider ideas other than Newton's. The reason for this seems to have been not so much theoretical as practical. Bouma, who was able to show that the boundary colors and their combinations fill the whole space in the CIE chromaticity diagram between the spectrum locus and the line of the pure purples, argued that Goethe was therefore quite correct in thinking that boundary colors could form the basic building blocks for all color mixing. But, Bouma argued, scientists had adopted spectral colors or monochromatic radiations instead, for the simple reason that they were much easier to use (Bouma 117, 176–77).

Now, however, some within the scientific community are questioning this practical superiority. Jan J. Koenderink and Andrea J. van Doorn of the University of Utrecht have recently suggested, iconoclastically enough, that so far as colorimetry is concerned, "the monochromatic beams are nothing special," for they "rarely occur in real life" and "can only be produced problematically and approximately." By contrast, Goethe's boundary colors "are more robust than monochromatic beams and can actually be produced easily in the laboratory" (Koenderink and van Doorn 29, 53, 31). Accordingly Koenderink and van Doorn have proposed a new way of measuring the color circle, based on the boundary colors and Ostwald's closely related *Vollfarben.* Initial commentary on the proposal was favorable. Donald A. MacLeod welcomed its "liberating effect." "It loosens the grip of the Newtonian paradigm on current thinking about colour and colorimetry," he wrote, "and revives the unduly neglected tradition of Goethe, Schopenhauer, and Ostwald." Paul Whittle noted that "The authors do a fine job of historical rehabilitation on both Goethe and Ostwald."[34] This is not to say that Goethean boundary colors are about to replace Newton's spectrum as a colorimetric resource. But it does mean that so far from being trivial or sheerly erroneous, Goethe's observations were firmly founded in fact, and are sufficiently interesting to provoke thought almost two hundred years after *Zur Farbenlehre* was published.

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NOTES

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1. Where possible, references to Goethe's works are to volume and page number in the Frankfurt edition: Johann Wolfgang Goethe, *Sämtliche Werke,* ed. Karl Eibl et al. (Frankfurt am Main: Deutscher Klassiker Verlag, 1985–). Here FA 23.2:34–35 (*Beiträge zur Optik,* 1. Stück, § 59). See also FA 23.1:92–93 (*Zur Farbenlehre. Didaktischer Teil,* §§ 213–17).

2. To avoid confusion, I call the fringe colors of the white strip (the "additive primaries," which are sometimes known in the scientific literature as red, green and blue), by their names in ordinary parlance: orange, green and violet. For the colors of the black strip (the "subtractive primaries"), I use the names yellow, magenta and blue. The printers' term "magenta" gives a clearer sense of the color than would either "red" or "purple." I retain "blue" because of its familiarity, but its color approximates to the blue that printers call "cyan."

For helpful colored illustrations of Goethe's experiments, and thorough discussion of them, see Rupprecht Matthaei, ed., *Goethes Farbenlehre* (Ravensburg: Otto Maier, 1971). For illustrations of the two basic fringe experiments, see 26, 106–7, 112. However readers should if possible carry out the experiments for themselves, because printed illustrations do not convey the quality of the fringe colors, which can immediately be seen by looking through a prism at figure 1. To see the colors marked in figure 1(a)(i) and (b)(i), place the page on a horizontal surface in bright light. To see green and magenta, either tilt the prism, or hold the page vertically at almost 90° to the eyes.

3. Matthaei 50–53.

4. Reinhold Sölch, *Die Evolution der Farben: Goethes Farbenlehre in neuem Licht* (Ravensburg: Ravensburger Buchverlag, 1998) 91.

5. Compare Jan J. Koenderink and Andrea J. van Doorn, "Perspectives on Colour Space," in *Colour Perception: Mind and the Physical World,* ed. Rainer Mausfeld and Dieter Heyer (Oxford: Oxford UP, 2003) 3, 29.

6. Goethe first set out all of the details of the circle in "Über die Einteilung der Farben und ihr Verhältnis gegen einander" (probably written in 1793), see FA 23.2:116–19. He gives the same interpretation in *Zur Farbenlehre* (FA 23.1:26–27, 226–29).

7. Cf. the "Einleitung" to *Zur Farbenlehre* (FA 23.1:27).

8. For the picture card, see FA 2:689, 1207 and Fig. 23. There is a color reproduction in Matthaei 88. On Meyer's rainbow, see S[iegfried] Rösch, "Der Regenbogen in der Malerei," *Studium Generale* 13 (1960): 426. A color reproduction of the painting is available on the website of Bildarchiv Foto Marburg http://www.bildindex.de (accessed 21 November 2007).

9. Wilhelm Ostwald, *Colour Science: A Handbook for Advanced Students in Schools, Colleges, and the Various Arts, Crafts, and Industries Depending on the Use of Colour,* tr. J. Scott Taylor, vol. 1 (London: Winsor & Newton, 1931) 15. Ostwald (1853–1932) was professor of physical chemistry in Leipzig from 1887 to 1906, and won the Nobel Prize for Chemistry in 1909. After retiring from his chair, he published numerous works on color, including *Die Farbenfibel* (1916) and *Der Farbenatlas* (1917). He constructed a color solid based on twenty-four hues and the modifications obtained from each of them by adding consistent quantities of white, black and grey.

10. Professor Jan J. Koenderink, personal communication.

11. Hermann von Helmholtz, "Über die Theorie der zusammengesetzten Farben," *Annalen der Physik und Chemie* 87 (1852): 45–66. English translation: "On the Theory of Compound Colours," *Philosophical Magazine* Series 4, 4 (1852): 519–34 (for the cited experiment see 526, 528). Helmholtz (1821–1894), who made important contributions to both physiology and physics, held a succession of chairs from 1849 to 1877 and later became director of the Physico-Technical Institute at Berlin-Charlottenburg. He published his *Handbuch der physiologischen Optik* in 1867.

12. Rupprecht Matthaei, "Goethes Spektren und sein Farbenkreis," *Ergebnisse der Physiologie* 34 (1932): 200, 202–3.

13. Michael Duck, "The Bezold-Brücke Phenomenon and Goethe's Rejection of Newton's *Opticks,*" *American Journal of Physics* 55 (1987): 793–96; Duck, "Newton and Goethe on Colour: Physical and Physiological Considerations," *Annals of Science* 45 (1988): 507–19.

14. Michel Treisman, "Why Goethe Rejected Newton's Theory of Light," *Perception* 25 (1996): 1219–20.

15. Christoph Heinrich Pfaff (1773–1852) was appointed professor of chemistry at Kiel in 1802, and wrote chiefly on galvanism and electromagnetism. He was acquainted with many of the outstanding scientists of his time, including Cuvier and Volta. For his criticism of Goethe, see Pfaff, *Über Newtons Farbentheorie, Herrn von Goethes Farbenlehre und den chemischen Gegensatz der Farben* (Leipzig: F. C. W. Vogel, 1813) 154–59. Cf. Johann Wolfgang Goethe, *Die Schriften zur Naturwissenschaft,* Leopoldina Ausgabe, ed. K. Lothar Wolf et al. (Weimar: Hermann Böhlaus Nachfolger, 1947–) 2. 5A: 258. (Subsequent references to this edition are given in the form LA, followed by section, volume and page number.) On the narrowing of the strip, see Treisman 1221–22.

Figure 3(i) corresponds to figure 1(a)(i), and figure 3(ii) to figure 1(a)(ii). Whereas figure 1 illustrated the fringe colors seen by looking at a white strip on a dark ground, figure 3 now shows the pattern of rays that gives rise to those fringe colors. The fringes and the center space are shown as columns, and the various overlapping rays that produce each of the five fringe colors and the central white can be read off from the rows.

16. See George A. Wells, "Goethe's Scientific Method and Aims in the Light of his Studies in Physical Optics," *Publications of the English Goethe Society,* NS 38(1967–68): 87–91 for a detailed discussion of green as a spectral and magenta as a compound color.

17. See also FA 23.2:360, 375, 389; FA 23.1:1230, 1451. Goethe was not in fact wholly ignorant of the differences between pigments and lights: for instance he was well aware that violet and orange mix to magenta in lights but not in pigments, see FA 23.1:228–29, 261.

18. Goethe, LA 2.4:302–3; 2.5A:350.

19. Cited by André Bjerke, *Neue Beiträge zu Goethes Farbenlehre,* tr. Louise Funk (Stuttgart: Verlag Freies Geistesleben, 1963) 57.

20. A[ugust] Kirschmann, "Das umgekehrte Spektrum und seine Komplementärverhältnisse," *Physikalische Zeitschrift* 18 (1917): 195–97, 201–2. Kirschmann (1860–1932) held a chair in psychology at the University of Leipzig from 1922 to 1930. His observations ought not to have been contentious, since the relationship between the spectrum and the inverted spectrum is a trivial application of Babinet's principle: see Koenderink and van Doorn 28.

21. P[ieter] J[ohannes] Bouma, *Physical Aspects of Colour: An Introduction to the Scientific Study of Colour Stimuli and Colour Sensations,* ed. W. de Groot, A. A. Kruithof and J. L. Ouweltjes (London: Macmillan, 1971) 110–13.

Bouma's numbered points can be envisaged as running across the lower edge of figure 3(i), with the first set of 10 points beginning at the left-hand (violet) edge and running towards the white center; and the second set of 10 points beginning at the white center and running to the right-hand (red, i.e. orange) edge.

22. The colored version of the CIE chromaticity diagram may be found in Sölch 50, and in many color handbooks. For a detailed explanation of the diagram, see D. L. MacAdam, "The Physical Basis of Color Specification" in *Readings on Color. Volume 2: The Science of Color*, ed. Alex Byrne and David R. Hilbert (Cambridge, MA: MIT Press, 1997) 33–63.

23. For the reflectance curves of various specific green leaves and pigments, see for example Koenderink and van Doorn 26 and Plate 6; Frederick W. Clulow, *Colour: Its Principles and Their Applications* (London: Fountain, 1972) Plate 23 (after 132); Ralph Mayer, *The Artist's Handbook of Materials and Techniques,* 5th edn (London: Faber & Faber, 1991) 77–82.

24. Bouma 118 gives a diagram of a spectral luminance factor curve for fringe green. Koenderink and van Doorn 33 and Plate 11 illustrate spectra of optimal colors.

25. Bouma 121–22, 124. Bouma's Fig. 64 shows the *Vollfarbe* fringe green at point 3. Koenderink and van Doorn 30 and Plate 9 show some spectra of *Vollfarben.*

26. Goethe, LA 2. 5A: 269–70.

27. Bjerke 50–59 and Figures 19–27; Isaac Newton, *Opticks* (Amherst, NY: Prometheus Books, 2003) 48–52 (Book I, Part I, Prop. II, Theor. II).

28. Torger Holtsmark, "Newton's Experimentum Crucis Reconsidered," *American Journal of Physics* 38 (1970): 1233.

29. Newton, *Opticks* 132–33 (Book I, Part II, Prop. IV, Theor, III).

30. Bouma 115–16 says that magenta appears when the wavelength range from 436 nm to 616 nm is "missing." He also generalises by stating: "when combining boundary colours, there can be no question of additive mixing" (117).

31. The same point is made by Holtsmark in his edition of *Zur Farbenlehre*: *Goethes Farvelære*, ed. Torger Holtsmark (Oslo: Ad Notam Gyldendal, n.d. [c. 1994]) 101.

32. Koenderink and van Doorn 28; Paul Whittle, "Colorimetry Fortified" (Commentary on Koenderink and van Doorn), in *Colour Perception* (n. 5) 66.

33. Matthaei, *Farbenlehre* (n. 2) 48.

34. Donald I. A. MacLeod, "From Physics to Perception through Colorimetry: A Bridge Too Far?," in *Colour Perception* (n. 5) 57; Whittle 66.