

Goethe's Conception of "Experiment as Mediator" and Implications for Practical Work in School Science¹

Wonyong Park and Jinwoong Song
Seoul National University

Abstract

There has been growing criticism over the aims, methods, and contents of practical work in school science, particularly concerning its tendency to oversimplify the scientific practice with focus on the hypothesis-testing function of experiments. In this article, we offer a reading of Johann Wolfgang von Goethe's scientific writings—particularly his works on color as an exquisite articulation of his ideas about experimentation—through the lens of practical school science. While avoiding the hasty conclusions made from isolated experiments and observations, Goethe sought in his experiments the interconnection between natural phenomena and rejected the dualistic epistemology about the relation of humans and nature. Based on a close examination of his color theory and its underlying epistemology, we suggest three potential contributions that Goethe's conception of scientific experimentation can make to practical work in school science.

1 Introduction

The vision of the poet [Goethe] will remain as a truthful and efficient symbol of the wonder and the mystery of nature. – T. H. Huxley, in a lead article for the first issue of *Nature* (Huxley 1869)

Practical work comprises a core part of contemporary science education. Since at least the science education reforms in many countries in the 1960s, the ideal of science education has gradually settled on engaging students with such practices as investigation, discovery, inquiry, and problem solving (Jenkins 1998; Shulman and Tamir 1973), which subsequently motivated an emphasis in curriculum policy documents on practical activities in school science (e.g., AAAS 1991; National Research Council 1996; NGSS Lead States 2013). Indeed, in science education today, few would argue against practical work being understood as a key element of science as well as of its teaching. It was therefore no exaggeration when the Council for Science and Technology (CST) in the UK stated that “studying science without practical experimental work is like studying literature without reading books” (2013, p. 5). As the significance of practical work in school science grows, however, more questions have been posed about the what, how, and why of using practical work in teaching at schools. Among these, one kind of criticism gaining

¹ Correspondence to: Jinwoong Song (jwsong@snu.ac.kr)

This is a post-peer-review, pre-copyedit version of an article published in *Science & Education*. The final authenticated version is available online at: <https://doi.org/10.1007/s11191-018-9965-z>

increasing attention is that too much practical work is designed in a “cookbook” style with some routine exercises, which makes students passive followers or lifeless repeaters by focusing on verification of predetermined conclusions (Dagher and Erduran 2014; Hodson 1993).

Also frequently criticized is the fact that many practical activities in science lessons and textbooks are not teaching the “real” practice of science. At times this criticism points to the methods of science taught through practical work, as Charlesworth and his colleagues (1989) noted: “the neat classical picture of deductions being made from theories and then tested by observation and experiment (the so-called hypothetico-deductive method) scarcely ever corresponds to the reality of the scientific process” (p. 271). Many school science inquiry and practical activities take the form of setting up a hypothesis, experimenting for test, and either justifying or disproving the hypothesis depending on the result (Lefkadtou et al. 2014; Windschitl et al. 2008). However, there are increasing doubts about the validity of the idea that experiments are primarily for testing hypotheses. Not only has it been criticized in the philosophical sense in that it oversimplifies the practice of science (e.g., Hempel 1966), but also this view also seems to result in many additional potential problems when educational considerations are taken into account. One related issue is that hypothesis-testing experiments reflect the characteristics of only *some* sciences (mostly the physical sciences), but not all. Recent nature of science (NOS) frameworks have displayed increased awareness that characteristics such as hypothesis testing may not apply universally to all subareas of natural science (Dagher and Erduran 2014; Irzik and Nola 2014; NGSS Lead States 2013). This is particularly true for the subareas of school science that are historical and interpretive, such as earth science, astronomy, and evolutionary biology. While in experimental sciences “natural phenomena are manipulated within the controlled environments of a laboratory in order to test a hypothesis” (Dolphin and Dodick 2014, p. 557), the subject matters of these historical sciences are not usually conducive to testing in a controlled laboratory.

Still, the hypothesis-testing function of scientific experiments should not be dismissed outright, since so many experiments have been and continue to be, to a certain extent, used for that very purpose. It is hardly deniable that Newtonian universal gravitation gained its explanatory power from what it had predicted, such as the existence of Neptune and Pluto. Einstein’s general theory of relativity has also certainly been supported by Eddington’s observation of the solar eclipse, along with the recent detection of gravitational waves by the Laser Interferometer Gravitational-Wave Observatory (LIGO). The problem with the school version of experimentation is therefore not that it is a complete misrepresentation of science; rather, it is that the currently taught experiments are inevitably a *partial* rendition of the real practice of scientific experimentation. Philosophers, historians, and educators of science have pointed out that such a hypothetico-deductive view of science is not an appropriate model of science, nor is it suitable for school practical work (e.g., Bencze 1996; Lakatos 1970; Millar 1994).

What can be done to make the situation better? We believe that two possible approaches can be imagined. The first approach is to venture to better determine the characterization of scientific practice (including experimentation) by means of philosophical investigation and consider the ways of implementing it into school curricula. A series of educational studies that aim to offer reconceptualizations of NOS for science education in diverse ways are good examples of this case (e.g., Allchin 2013; Dagher and Erduran 2014; Hodson 2014; Irzik and

Nola 2014; Lederman 2007; Schwartz and Lederman 2008). Though a comprehensive review of these studies exceeds our scope, they have mainly dealt with issues involving the desirable NOS elements that accurately capture the “real” science done in the laboratory—better than the conventional hypothetico-deductive model—and how these can be effectively taught in science lessons that include practical activities. There is no doubt that this approach has led to a number of fruitful outcomes that have contributed to responding to the challenges practical work has faced.

The second approach to the problems of practical work in school science is to take what might be called an “education first” stance and start by asking what the *educationally* valuable things to be taught with the use of scientific experiments are: What are the things that are worth teaching to students using practical work? What changes can we expect for students after the use of practical work? How would the assumed learning outcomes of practical work serve the aims of schooling? As opposed to the first approach, this asks questions about education before those about science; the result is not necessarily incompatible with or contradictory to the first approach, but rather has the potential to collaboratively deepen our understanding of the aims and means of school practical work. One benefit that this approach allows is that while seeking solutions, we no longer have to be confined within the currently accepted aims, values, methods, etc. of contemporary science, but we can explore more diverse areas of study, as long as the result is not contradictory to the aims of science education. The idea we develop in this article is based on this second approach, which opens up a greater possibility for probing into a scientific thought from the 18th and 19th century—Goethe’s natural philosophy—which has only rarely been considered as a serious scientific idea among mainstream scientists. It has also not attracted the attention of NOS researchers, since the ontological and epistemological tenets on which Goethe’s theory is based are not easily and neatly interpreted in terms of contemporary NOS frameworks. Nonetheless, we believe that Goethe’s ideas about nature, and especially his theory of color, have rich educational values, particularly on the challenges of school practical work with which we are confronted.

Contrary to the significance of his name in the history of literature, Johann Wolfgang von Goethe (1749–1832) has drawn far less interest in the scientific or educational scholarship. Not only did his scientific study attract little attention from his contemporaries, it is still rarely recognized (at least outside of Europe) that Goethe devoted a substantial portion of his intellect to the study of nature and left a vast amount of published and unpublished works. Reactions to Goethe’s scientific works were mostly negative and even scornful, as one can find in a comment by a historian of science, who, while admitting the salience of his studies in morphology, said that Goethe’s “intrusion” into natural science was not only “hostile to physical science and misleading, even if stimulating, to biology,” but also a “dismaying anachronism,” for his nature was not “objectively analyzed” but rather “subjectively penetrated” (Gillispie 2016, pp. 179–198). It is thus no surprise that “Goethean” science has, for more than a century, often been considered no more than an object of historical interest. It has mostly been historians and philosophers of science who have displayed some interest towards Goethe’s scientific works on chromatics, geology, botany, and comparative anatomy. For centuries, little if any literature had addressed how his experimental methodology may possibly relate to some real-world issues in the contemporary society, such as science education. It seemed that Goethe’s ambitious project

would never have a chance to impact the world.

During the past few decades, however, there have been efforts to reappraise the educational values of Goethean science. Espinet (1990), for example, viewed Newton's and Goethe's methodology of color science as two different but equivalent processes of inquiry, and drew from comparing the two theories some implications for alternative framework research in science education. It is also well known that Steiner, the founder of Waldorf education, was deeply engaged and influenced by Goethe's ideas on nature (e.g., Steiner 2001; Steiner 1988). Goethe's theory has often been interpreted in relation to Husserl's phenomenology (Dahlin 2001; Østergaard et al. 2008; Seamon and Zajonc 1998), in that Goethe's writings often show some aspects that resonate with the phenomenological attitude of the primacy of qualitative aspects and lived experience. A more recent work by Hadzigeorgiou and Schulz (2014) considered the romanticists of the late 18th and early 19th century—including Goethe—in relation to natural sciences and discussed their potential contributions to science education, such as its emphasis of the centrality of sense experience, importance of the notions of mystery and wonder, the power of science to transform people's outlook on the natural world, etc. While these studies concentrate more on the general aspects of the Goethean science, fewer efforts have been made to analyze the content of Goethe's individual scientific theories and their relation to science teaching today. Among the few exceptions is Rang and Grebe-Ellis's (2009) study, which suggested a more effective way to reproduce Newton and Goethe's respective color spectra with a mirror-slit diaphragm and presented a way to use it to demonstrate the two forms of spectra in classrooms, as well as the interdependence of these spectra.

In this article, among a vast amount of scientific works by Goethe, our particular attention is given to his writings on the theory of color, the work with which Goethe regarded himself proudly as "the only person in this [his] century who has the right insight into the difficult science of colors" (Crone 1999, p. 115). We focus on this particular area of study because it is perhaps the best reflection of his unique scientific methods; at the same time, since it stands in sharp contrast with the scientific method we teach in school science, it allows us to develop critical reflections on how ideas that do not belong to the current mainstream science can still provide effective insights to actual teaching practice. After a schematic introduction to his scientific biography and works, we sketch out the fundamental methodological beliefs and assumptions underlying Goethean science. In so doing, we particularly concentrate on two aspects of his conception of scientific experimentation: the pursuit of the interrelation of natural phenomena and the emphasis on human-nature interaction in studying nature. We then explicate how Goethe's conception of experimentation became manifested while articulating his color theory and show how his experimental philosophy gives clues to some of the key concerns about practical work in schools that have been outlined above. Our main argument is that Goethe's conception of "experiment as mediator" and the related methodology can be considered as providing an educationally beneficial alternative view of scientific experimentation. This benefit will be examined from three different angles: the exploratory character of the method, the search for interconnectedness of natural phenomena, and the intimacy of humans and nature throughout the experimentation.

2 Goethe as a Scientist

Johann Wolfgang von Goethe, known as a poet, dramatist, novelist, diplomat, and state minister, was born on August 28, 1749 in Frankfurt, Germany. Though his reputation comes primarily from his literary accomplishment, represented by *Die Leiden des jungen Werther* (*The Sorrows of Young Werther*, 1774) and *Faust* (1808–1832), his works ranged from fiction to non-fiction, drama to tragedy, and politics to science. Not only did the massive volume of his literary composition have a strong impact on the art and culture in German-speaking countries, but also many of his non-fiction writings have directly and indirectly influenced many of his contemporary thinkers and those that came later, such as Hegel, Schopenhauer, and Nietzsche. The influence of Goethe on 19th century European culture is so gigantic that he is considered a German cultural icon, and many of his original ideas later became widespread. His scientific works, on the contrary, were considered by many to be no more than amateurish or shameful waste of time on matters extraneous to his intellect (Wells 1979). This attitude is also found in Young's review of *Farbenlehre*, where he called the book “a striking example of the perversion of human faculties” (Young 1814, p. 427).

The late 18th and early 19th centuries during which Goethe lived were the age of Romanticism (with its peak during ca. 1800–1850), which flourished in Britain and especially in Germany and influenced many fields of study such as literature, culture, and politics. As with the Enlightenment tradition, Romanticism also firmly and widely influenced not only culture and humanities but natural science as well; however, there were some significant differences between the two traditions. The dominant view of nature in the 18th century was a so-called clockwork perception of the world in which nature was regarded as working by mechanical cause and effect. Nature as a clock, driven by physical and chemical forces, was understood to be regularly and rhythmically running (Dijksterhuis 1986; Kuhn 2012), and the world was believed to be created as stable, coherent, and perfect from beginning to end (Richards 2002, p. 11). This idea became predominant throughout the Age of Enlightenment—with contributions from Galileo, Descartes, Newton, etc.—and towards the end of 18th century, when Goethe started working on natural science. The romantic conception of nature, on the contrary, emphasized such things as human sensual experience and the unity of natural objects and phenomena, being skeptical of the mechanical and mathematized practice of the Enlightenment science. Nature was no more regarded as the mere product of an intelligent Creator but was understood as something that self-produces and develops from a simpler form or state to a more sophisticated one (Richards 2002, p. 11). This was the intellectual background upon which Goethe grew up, was educated, and developed his ideas on natural sciences.

Born and raised in Frankfurt, Goethe's early encounter with science began while he attended lectures in Leipzig as a law student, where he spent more time and effort in studying nature than law (Seamon and Zajonc 1998). There he had a chance to interact with medical students who were disappointed with the mechanistic view and with whom he studied natural theories such as the French materialist Baron d'Holbach's *Système de la Nature* (*The System of Nature*; 1775). Engaging in this enabled Goethe to conceive some fundamental questions about nature, but the content of this book that reflected the French mechanistic view popular in his time also became a source of his disappointment. Recalling this period, Goethe later wrote in his autobiography on his dissatisfaction with d'Holbach's view:

I mention as an instance, to serve for all, the “Systeme de la Nature,” which we took in hand out of curiosity. We did not understand how such a book could be so dangerous. It appeared to us so dark, so Cimmerian, so deathlike, that we found it a trouble to endure its presence, and shuddered at it as at a spectre . . . A system of nature was announced; and therefore we hoped to learn really something of nature, our Idol . . . But how hollow and empty did we feel in this melancholy, atheistic half-night, in which earth vanished with all its images, heaven with all its stars (Goethe 1811/1974, pp. 108–111).²

Young Goethe was strongly inspired by the 18th century natural philosophers. Von Linné’s classification system for living things and Buffon’s studies of animal structure set up a basis for Goethe’s later studies in morphology. Von Haller’s conception of nature as a well-ordered creation by the God, “with man at the top leading down past the animals, the plants to the minerals and to the realm of elements” (Kuhn 2012, p. 6) also strongly influenced him, though he later perceived it was wrong. Goethe learned from all these works that the actions of nature, which were at one time regarded as independent, indeed depended upon each other and opposed each other. His early engagement in scientific experiments began in around 1771, when he returned home to Frankfurt from the university in Leipzig after a serious illness. Staying home for recovery, Goethe met Dr. Johann Friedrich Metz, a physician-teacher, and Susanna Katharina von Klettenberg, a relative of Goethe’s mother, who were interested in alchemy and recommended to him reading the works of alchemists such as Paracelsus, Helmont, and Starkey (Goethe 1974/1811, p. 284). Goethe’s early encounter with alchemy stimulated his interest in scientific experiments and led him even set up his own chemical laboratory at home. Goethe’s years in Frankfurt (1771–1775) became not only a fruitful source for his later scientific works but were also highly productive in his literary accomplishments and included his famous *The Sorrows of Young Werther*, first published in 1774.

Goethe moved to Weimar in 1775, where he became a companion of Duke Karl August upon invitation, and within a few years he took on an extravagant amount of duties. After moving to Weimar, Goethe’s science gained even greater maturity and sophistication. During his practical administrative duties, he immersed himself in science. Goethe’s scientific achievement in Weimar stretched from anatomy, botany, optics, meteorology to mineralogy, and his eagerness to study nature did not cease until his last years. It should be noted that part of his scientific work is still famously credited. For example, the discovery of the human intermaxillary bone in human skulls that supported the evolutionary relationship between man and other mammals is usually credited to Goethe (Goethe 1920/1988a). He is also said to have discovered the homologous nature of leaf organs in plants, from cotyledons to photosynthetic leaves and then to the petals of a flower (Brady 2012; Goethe 1790/1988d). In addition to his achievements in individual sciences, another significant influence of his years in Weimar can be seen in the shift of his attitude towards nature. While in Weimar and thereafter, Goethe became critical of those who employed speculative approaches to the nature and “appealed to hidden forces on the basis

² Note that all quoted material is reproduced verbatim from the source material.

of subjective judgment rather than empirical study” (Steigerwald 2002). Understanding such an attitude plays a crucial role in understanding the philosophy of experimentation later articulated in the scientific works (see Section 4).

Amongst the wide range of science topics that Goethe studied during his lifetime, his study in color theory spanned more than 40 years and was built on an enormous amount of observations made by himself. Though he expressed occasional interest in color phenomena since he was a student in Leipzig, a main motivation for studying color began during his first Italian journey (1776–1788), when he realized that systematic principles of color were required for artistic use. In an early work in 1791, Goethe reported a series of experiments to investigate the conditions for the emergence of color in a paper titled *Beiträge zur Optik* (*Contribution to Optics*). The idea in *Beiträge* reached its culmination later in his contentious 1810 treatise *Farbenlehre* (*Theory of Colors*), which was published almost 20 years after *Beiträge*. These two works are the main interest of this article and are considered practical exemplars that elucidate Goethe’s epistemology, which is of importance particularly in the pedagogical context.

3 Goethe’s Conception of “Experiment as Mediator”

The first step in articulating how Goethe’s view of scientific experiments can benefit practical science education is to reformulate his scientific ideas in a way that can explicate how his view diverges from the traditional account of experimentation. Goethe recognized the value of experimentation as a necessary and primary source of natural science throughout his entire scientific study, yet what he conceived as its ends and methods were quite contrary to the common view. His experimental philosophy starts from defining experimentation as the activity with which “we intentionally reproduce empirical evidence found by earlier researchers, contemporaries, or ourselves, when we recreate natural or artificial phenomena” (Goethe 1823/1988h, p. 13). In his essay *Der Versuch als Vermittler von Objekt und Subjekt* (*The Experiment as Mediator between Object and Subject*), he describes the role of experiments as a “mediator” through which the acquisition of scientific knowledge occurs. To understand what Goethe intended by this, it is useful to start from his two-fold attitude towards the role of experimentation in science (Hegge 1972). While he appreciated that experimentation is “the method which enables us to work most effectively and surely” (Goethe 1823/1988h, p. 13), elsewhere he contended that “the experiment in itself proves nothing” (Goethe 1810/2016, p. 26). The latter remark arose from his general conviction that a scientist must investigate the relationship between natural phenomena “without the intervention of a theory or hypothesis” (Sepper 2003, p. 67, emphasis added), which led him to conclude that the aim of experimentation is something very far from “proving” a hypothesis or theory.

Goethe called the use of experimentation to prove hypotheses its “direct” use, which is “detrimental”; it is when it is used indirectly, i.e., to find the connections between seemingly isolated phenomena, that it has its full potential to be “beneficial” (Goethe 1823/1988h, p. 15). While rejecting “test[ing] one’s abstract hypotheses by constructing an artificial experience in which individual phenomena are torn out of context,” Goethe instead “stay[ed] with the phenomena” (Seamon and Zajonc 1998, p. 37) and sought their patterns and structure. As a whole, we may summarize that for Goethe, though experiments constitute the core of natural

sciences, it is at least not for their hypothesis-testing power as is often believed in conventional science. Standing against Newton's mechanical philosophy in which experimentation only leads to hypothetical connections, Goethe claimed that experimentation has the function of mediating the subject and the object (Hegge 1972).

What it means for experiments to be “mediators” becomes even more apparent in Goethe's explanation of objectivity. For Goethe, as Wahl (2005) explained, objective thinking (*gegenständliches Denken*) rests in “the fundamental unity of the observer and the observed—the fact that ultimately subject and object are not two, but participate in a wider process that unites them into mutual dependency.” This was in sharp contrast to Cartesian objective thinking, where mind and matter, self and world, and subject and object were regarded as belonging to dichotomous categories that are mutually exclusive. In a book review of Heinroth's *Lehrbuch der Anthropologie* (*Textbook of Anthropology*; 1822), Goethe wrote about Heinroth's comment on his own scientific method, in which an observer always keeps contact with the observed (i.e., natural phenomena):

Here he [Dr. Heinroth] means that my thinking is not separate from the objects; that the elements of the object, the perceptions of the object, flow into my thinking and are fully permeated by it; that my perception itself is a way of thinking, and my thinking a perception (Goethe 1823/1988f, p. 39)

The primary aim of experiments in the study of nature, Goethe wrote, is making evident the “archetypal phenomenon” (*Urphänomen*), and he thought that this in turn allows an experimenter seeing the implicit laws and structure behind what can be perceived (Steigerwald 2002). In other words, Goethe used the archetypal phenomenon in lieu of Newton's hypotheses (Hegge 1972). For Goethe, the purpose of experimentation was placing the phenomena within a body of interconnections in which a complex phenomenon can be understood in terms of a simpler and ultimately irreducible archetypal phenomenon (Hegge 1972). To achieve this aim, Goethe believed that experiments should not be intended to prove some a priori hypothesis, but instead one ought to let phenomena “speak for themselves” (Sepper 2003, p. 45). In this vein, what scientists do is akin to what artists do: Just as artists pursue a “symbol” or an essence of an artistic object, scientists aim to arrive at the archetypal phenomenon (Rueger 1992). Goethe believed that the powers of scientific perception and human understanding cannot exceed the archetypal phenomenon. Citing a passage from the didactic section of *Farbenlehre* will help clarifying how Goethe took archetypal phenomena to be of critical importance in scientific inquiry:³

³ Heinemann (1934) pointed out the complexity that lies in the meaning of *Urphänomen* and argued that this term carries at least seven different meanings: (1) an appearance, (2) the thing that appears insofar as it appears, (3) the thing that appears insofar as it cannot appear, (4) that which becomes apparent, (5) a specific attitude to reality, (6) the law of the appearance of that which was before invisible, and (7) the laws of the appearances themselves. While this plurality of meanings shows the phenomenological character of Goethe's methodology, to avoid confusion, the usage of the term in this article is limited to a particular class of observed phenomena, as Goethe explicitly explained in the quoted material.

In general, events we become aware of through experience are simply those we can categorize empirically after some observation. These empirical categories may be further subsumed under scientific categories leading to even higher levels. In the process we become familiar with certain requisite conditions for what is manifesting itself. From this point everything gradually falls into place under higher principles and laws revealed not to our reason through words and hypotheses, but to our intuitive perception through phenomena. We call these phenomena *archetypal phenomena* because nothing higher manifests itself in the world; such phenomena, on the other hand, make it possible for us to descend, just as we ascended, by going step by step from the archetypal phenomena to the most mundane occurrence in our daily experience (Goethe 1810/1988g, pp. 194–195, italics in original).

To Goethe, who recognized the primacy of archetypal phenomena in scientific research, the mechanical—more precisely, Newtonian—study of color was erroneous and even grievous. While developing his account of color in *Farbenlehre*, Goethe remarked that in the way science was studied his time “a secondary phenomenon has been placed in a superior position and an archetypal phenomenon in an inferior one; moreover, the secondary phenomenon itself has been turned upside down by treating what is compound as simple and what is simple as compound”, which resulted in “the most bizarre complications and confusions have come topsyturvy into natural science, and science continues to suffer from them” (Goethe 1810/1988g, p. 195).

Goethe was especially skeptical of the validity of Newton’s so-called crucial experiment (*experimentum crucis*) concept that was then accepted as a successful proof of Newton’s refraction theory. For Goethe, a single experiment—whether it is crucial or not—cannot prove anything (Sepper 2003, p. 67), and this is particularly so when the experiment is designed as an *artificial* one. Newton’s series of experiments to prove his theory was accused by Goethe as being produced “[not] in a natural order, but in an artificial order” (Goethe 1810/2016, p. 135).⁴

On the value of mathematics in the natural sciences, Goethe showed a somewhat ambivalent position in his writings. Though he was not critical of mathematics itself, he regarded mathematics as being seriously misused, particularly with its “perverted use” in physics (Hegge 1972). He found the most evident example of this use of the mathematical method in Newton’s theory of color, where “a ‘mathematical-philosophical theory,’ namely the theory of primary and secondary sense-qualities, has led precisely to an attempt to trace the phenomena of light and color back to movements in a physical medium” (Hegge 1972, p. 200). The impact of Newton’s new theory of color was so strong that it dominated scientific theories and practices with “almost tyrannical authority” in 18th-century optics (Crone 1999, p.78). It is thus especially important in understanding Goethe’s science since, as Gjertsen (1986) noted, that Newton’s mathematical method and particularly the use of crucial experiments “became part of the

⁴ A detailed account of Goethe’s criticism of the Newtonian optical theory exceeds the purpose of this article. Ribe (1985), Duck (1988, 1993), Zemplén (2001), Cartwright (1999, Chapter 4), Sepper (2003), Marcum (2009), and Müller (2016, 2017) are useful sources that addressed this matter.

language of science with, over the centuries, the call for other crucial experiments to enable scientists to choose between alternative, competing theories” (p. 193).⁵ Goethe, standing against such a trend during his time, complained in a conversation with a young Eckermann:

I receive mathematics as the most sublime and useful science, so long as they are applied in their proper place; but I cannot commend the misuse of them in matters which do not belong to their sphere, and in which, noble science as they are, they seem to be mere nonsense . . . The mathematicians did not find out the metamorphosis of plants. I have achieved this discovery without mathematics, and the mathematicians were forced to put up with it. To understand the phenomena of colour nothing is required but unbiased observation and a sound head, but these are scarcer than folks imagine (Goethe 1836/1850, p. 304).

In a similar vein, Goethe thought that the use of scientific instruments contaminates the human mind and therefore interferes in the quest for the archetypal phenomenon:

It is a calamity that the use of experiment has severed nature from man, so that he is content to understand nature merely through what artificial instruments reveal and by so doing even restricts her achievements . . . Microscopes and telescopes, in actual fact, confuse man’s innate clarity of mind (quoted in Lehrs 1985, p. 107).

The task of an experimenter, argued Goethe, was therefore neither acquiring mathematical skills nor mastering the instruments. Nor was it acquiring a pre-existing scientific knowledge system, since in doing so one “[loses] its innocence, and the objects no longer appear in its purity,” resulting in a state that “we obtain . . . no actual truth with reference to the objects themselves; but we always receive these objects with a taste of a strong, subjective mixture” (Goethe 1836/1850, p. 170). Rather, what experimenters really need to do is to train and cultivate their senses in order to see and hear what they speak for themselves. On this point Goethe wrote:

The calm exercise of our powers of attention will quickly lead us to a rather clear concept of the object, its parts, and its relationships; the more we pursue this study, discovering further relations among things, the more we will exercise our innate gift of observation (Goethe 1823/1988h, pp. 13–14).

The act of observing as understood by Goethe was not limited to mere visual perception. Instead, he noted that in the advancement to the observation of the archetypal phenomenon “much depends on his [the observer’s] mood, the state of his senses, the light, air, weather, the physical object, how it is handled, and a thousand other circumstances.” Hence “it is like trying to drink the sea dry if we try to stay with the individual aspect of the phenomenon, observe it, measure it, weigh it, and describe it” (Goethe 1893/1988c, p. 24). To Goethe, the concept of observation in analytic, mechanistic, and especially Newtonian science seemed to “refine as many

⁵ From a historical viewpoint, Gingras (2001) discussed how mathematization led science to the exclusion of some actors, changed the meaning of the term “explanation,” and caused material substances to vanish. This analysis has some resonance with Goethe’s critical appraisal of mathematization in his time.

details as possible out of a given object” (Goethe 1833/1988b, p. 48) , which prevents an observer from pursuing the diverse manifestations and inner relationships between individual natural objects and phenomena.

The foregoing remarks by Goethe provide an important clue to appreciate his “experiment as mediator” as a fruitful source of educational values that is developed further in the rest of this article. In the following section, we address one remaining question about Goethe’s own theory of experimentation: the question of *how* he developed his claims and used experimentation in pursuing his aims, that is, finding archetypal phenomena. In so doing, we examine Goethe’s experimental philosophy in more detail and demonstrate that there still exist important aspects of Goethe’s methodology that resonate with some of the main concerns of today’s practical activities in science.

4 Goethe’s Delicate Empiricism in His Color Theory

If the primary aim of science is to find archetypal phenomena, with what method can those phenomena be found? Goethe believed that this cannot be done by mere luck or momentary inspiration, but only through repeated and refined experience. In this respect, Goethe was an empiricist, and he referred to his own position more precisely as “delicate empiricism” (*zarte Empirie*; Goethe 1906/1988e, p. 307): the effort to understand the nature through direct experience and careful appreciation of it. He felt that the observers in the history of scientific investigation were “leaping too quickly from phenomenon to theory; hence they fall short of the mark and become theoretical” (Goethe 1906/1988e, p. 308). Goethe’s empiricism is most clearly distinguished from “reductive” empiricism, in which one looks for quantifiable characteristics in a phenomenon and relates those quantities to each other (Amrine and Zucker 1987). What he wrote in one essay makes it clear that his empiricism was far from reductive:

There are many empirical fractions which must be discarded if we are to arrive at a pure, constant phenomenon . . . However, the instant I allow myself this, I already establish a type of ideal. But there is a great difference between someone like the theorist who turns whole numbers into fractions for the sake of a theory, and someone who sacrifices an empirical fraction for the idea of the pure phenomenon (Goethe 1893/1988c, p. 24).

In 1791, Goethe reported a series of experiments to investigate the condition for emergence of color in a paper entitled *Beiträge zur Optik* (*Contribution to Optics*). These experiments became a primary motivation for his much more comprehensive treatise *Farbenlehre* (*Theory of Colors*), which was published almost 20 years later in 1810. Goethe’s *Farbenlehre* has a three-section structure: the didactic, the polemic, and the historical. Goethe’s original accounts of diverse color phenomena is presented in the didactic section, where he began “with the momentary experience of color in the human eye, then moving to the transitory creation of color through colorless media (such as prisms), and finally to the permanent colors found in inorganic and organic objects” (Miller 1988, p. xv). This first section concludes with what Goethe called the “sensory-moral” effect of colors. In the polemic section, each of Newton’s 32 experiments and related propositions in *Opticks* (1730) are presented and then criticized based on the theory Goethe himself developed. The last section describes the development of color theory from antiquity to the 18th century and

Goethe's advanced criticism of Newton's theory. In what follows, we concentrate on the two aspects of his delicate empiricism found in his study of color: the pursuit of the interrelation of natural phenomena and the emphasis of human-nature interaction in studying the nature, both of which were crucial in Goethe's experimental method in pursuit of the archetypal phenomena of color. Each aspect is illustrated using examples from Goethe's own writing on colors.

4.1 The Interrelation of Natural Phenomena

For Goethe, to reach an archetypal phenomenon, it is far from enough to design a single experiment, conduct it, and interpret it on its own, since diverse natural phenomena—for instance, the prismatic colors—are interconnected to each other. The method he employed to pursue this interrelation was to vary different conditions under which a certain phenomenon appears. An empirical phenomenon, Goethe explained, is something everyone finds in nature, which is raised through experiments to the level of scientific phenomenon. It is precisely this process that requires “producing it [the empirical phenomenon] under circumstance and conditions different from those in which it was first observed, and in a sequence which is more or less successful” (Goethe 1893/1988c, p. 25). From this, Goethe intended “to collect all the empirical evidence in this area, and to set up [his] own experiments, and carry them out with the greatest diversity, via methods which are easily duplicated and which are more accessible” (Goethe 1823/1988h, p. 17). The real task of a scientific researcher is thus “to follow every single experiment through its variations” (Goethe 1823/1988h, p. 16). In an essay titled *Empirical Observation and Science*, Goethe explicated his methodology:

After observing a certain degree of constancy and consistency in phenomena, I derive an empirical law from my observation and expect to find it in later phenomena. If the law and the phenomena are in complete agreement, I have succeeded; if they are not in complete agreement, my attention is drawn to the circumstances surrounding each case, and I am forced to find new conditions for conducting the contradictory experiments in a purer way. But if a case which contradicts my law arises often and under similar circumstance, I realize that I must go further in my research and seek out a higher standpoint (Goethe 1893/1988c, p. 24).

This “higher standpoint” (also often referred as “higher experience”) is the sort of experience we should reach through scientific study. A series of immediate experiments were “thought of as representing a single experiment, a single piece of empirical evidence explored in its most manifold variations” (Goethe 1823/1988h, p. 16); the composition of many other experiments was “clearly of a higher sort.” While “every piece of empirical evidence, every experiment, must be viewed as isolated,” he made it clear that “this is not to say that they are, in fact, isolated” (p. 15) in order to find the implicit connection between individual, seemingly isolated phenomena. Goethe regarded this work as indeed bringing the “greatest accomplishments” in the science of color:

Earlier we found those thinkers most prone to error who seek to incorporate an isolated fact directly into their thinking and judgment. By contrast, we will find that the greatest accomplishments come from those who never tire in exploring and working out every possible aspect and modification of every bit of empirical evidence, every experiment

(Goethe 1823/1988h, p. 15).

What Goethe reported in *Beiträge* shows a good example of this process of modifying and diversifying experiments. In an early experiment pursued for the purpose of investigating prismatic colors, Goethe began by picking up a prism and looking through it at what surrounded him. In the scene seen through the prism, he found that objects were displaced from their original positions and that some new colors originated and blurred the borders of objects. Goethe, in spite of the new colors and some blurring, noted that most objects were still identifiable to the observer by their shape and color and the whole scene did not look completely decomposed. When he rotated the prism upside down, the case was basically identical, with only the direction and orientation of the blurry fringes being changed (Sepper 2003).

A series of experiments followed this initial set of observations. Goethe's starting point was abstracting the phenomenon into a more simplified form. Since he observed from the previous experiment that a new spectrum of colors arises at the edge, to concentrate on this issue, he tried another experiment in even more simplified conditions. The simplification he chose was to look at black and white objects, e.g., black spots on a white wall, white sky seen through black window frames, etc. through a prism. Such a process of simplification made it possible for Goethe to confirm "the initial impressions that the colored fringes conform to the borders of objects and that the width of the fringes depends on the mutual orientation of the prism and the borders" (Sepper 2003, p. 47).

The next step in simplification was made by the observation of a single white rectangle on a black background. In this experiment, Goethe held a prism with its refracting angle facing downward (i.e., in the shape of a triangle upside down) and looked through it at the rectangle. What he observed was a spectrum of five distinct colors, ranging through red, yellow, green, blue, and violet (Fig. 1, left). The boundaries between each color were parallel to the prism axis. When he changed the condition from a white rectangle on black to a black rectangle on white, he observed a different spectrum of colors (Fig. 1, right). This led Goethe to suspect that these seemingly irrelevant phenomena were related in some intricate manner.



Fig. 1 As a simplification of what he observed through the prism, Goethe looked through a prism at a white rectangle on black background, which produced a vertical series of the colors red, yellow, green, blue, and violet (left). When he inverted the black and white and then observed, the colors appeared in the order of blue, violet, magenta, red, and yellow (right).

red, and yellow (right) (Redrawn from Sepper 2003, p. 49).⁶

To get a better understanding of these results, Goethe proceeded to his next and final simplification towards the archetypal phenomena, in which he tried a simple vertical juxtaposition of black and white. When he observed through a prism a rectangle that was half black (top) and half white (bottom) (Fig. 2, left), red and yellow consecutively emerged, from the upper black half towards the lower white half. When the object was flipped vertically (Fig. 2, right), blue and violet were seen instead of red and yellow. Goethe considered this observation the archetypal phenomenon of color: colors arise (a) at the boundary of black and white and (b) in a way that warm colors (red, yellow) advance from black to white and cool colors (blue, violet) from white to black.

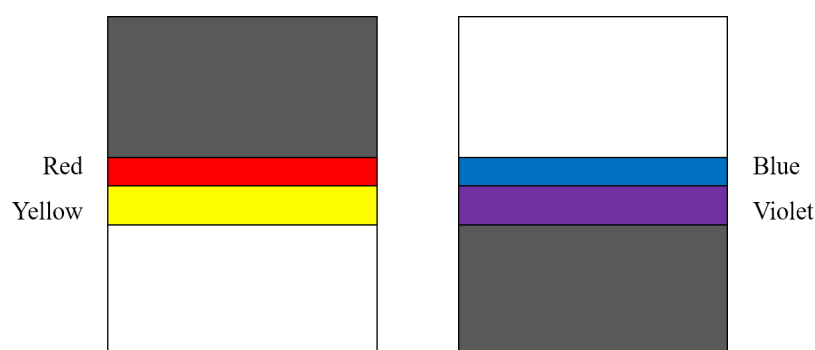


Fig. 2 Goethe further simplified the experiment in Fig. 1, observing a rectangle that is half black on top and half white on the bottom (left) and vice versa (right). Seen through the prism, each produced red-yellow (left) and blue-violet (right) originating from the boundary (Redrawn from Sepper 2003, pp. 50–51).

This last simplification and abstraction enabled Goethe to fully understand the observation of the previous experiment. What was seen in Fig. 1 on the left and right now could be understood as two different combinations of the left and right of Fig. 2: The middle green in Fig. 1, left, was now understood as the composition of yellow and blue; the middle magenta in Fig. 2, left, as violet and red. In this process of sequential simplification, Goethe showed an example of how complex phenomena can be explained in terms of simpler phenomena. In addition, he diversified the experiment in Fig. 2 to make it even clearer, by viewing the same thing from a gradually increasing distance (Fig. 3). The middle white seemed to diminish as the observer gets farther away, and green was produced as the composite of blue and yellow. From this “multiplication” of experiments, Goethe was able to determine that the colors seen to an observer changed depending also on the distance from the prism, and, in addition, that green

⁶ Ribe and Steinle (2002, p. 45) replicated several experiments by Goethe and presented some actual photographs of the images they produced, which include the results shown schematically in Figs. 1 and 2.

originates as a combination of blue and yellow. A set of the individual, seemingly isolated experiences described so far led Goethe to reach what he referred as a “higher sort of experience.” He wrote:

Such a piece of empirical evidence, composed of many others, is clearly of a higher sort. It shows the general formula, so to speak, that overarches an array of individual arithmetic sums. In my view, it is the task of the scientific researcher to work toward empirical evidence of this higher sort—and the example of the best men in the field supports this view (Goethe 1823/1988h, p. 16).

Throughout a series of experiments, each of Goethe’s experiences had become not only interconnected to its different variations, but they also contributed to mutually explaining what was observed in another level of abstraction. In other words, Goethe’s experimental sequence took relations and connections from the very observation of complex, everyday phenomena up to the higher, simpler, and more abstract archetypal phenomena. His series of experiments, as Sepper (2003) wrote, was “not to reach a level of generalization that leaves the empirical basis behind, but rather to work through the empirical givens toward the discovery of a unifying appearance or event that can be recognized in all the individual instances” (p. 73).

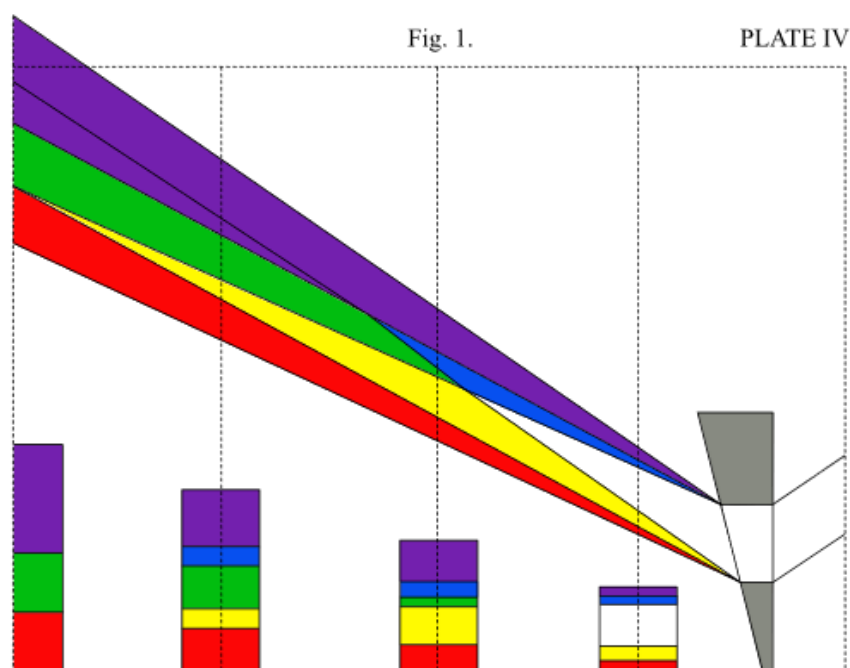


Fig. 3 After reaching the archetypal phenomenon, Goethe diversified the experiment in Fig. 2 to make it even clearer, by viewing the same thing from gradually increasing distances. The middle white seemed to diminish as the observer gets farther away, and green was produced as the composite of blue and yellow (Cut out and redrawn from Fig. 1, Plate IV, Goethe 1810/2006).

4.2 The Primacy of the Human-Nature Interaction

Goethe thought scientific inquiry was a process of transforming subjective experiences into

objective knowledge (Jackson 2008), from which the second important methodological maxim of his “experience as mediator,” albeit not independent of the first one, follows: the importance of the human-nature interaction in the study of nature. In pursuit of archetypal phenomena through the “higher experience,” said Goethe, what changes and moves is not only the object of observation, as the subject (natural scientist) also changes during this process (Wellmon 2010). What is crucial in this process is the direct contact between the human subject and the natural object. In fact, Goethe always directed his study of nature to things that can be “immediately perceived by the senses,” which left him disinterested in such areas as astronomy, which requires “recourse to instruments, calculations, and mechanics” in addition to direct senses (Goethe 1836/1850, p. 361). One of the finest elaborations with respect to Goethe’s emphasis on the human-nature interaction and sense experiences is found in his account of what he observed in the Harz Mountains, described in the first (didactic) part of *Farbenlehre*:

Once, on a winter’s journey in the Harz Mountains, I made my descent from the Brocken as evening fell. The broad slope above and below me was snow-covered, the meadow lay beneath a blanket of snow, every isolated tree and jutting crag, every wooded grove and rocky prominence was rimed with frost, and the sun was just setting beyond the Oder ponds. Because of the snow’s yellowish cast, pale violet shadows had accompanied us all day, but now, as an intensified yellow reflected from the areas in the light, we were obliged to describe the shadows as deep blue.

At last the sun began to disappear and its rays, subdued by the strong haze, spread the most beautiful purple hue over my surroundings. At that point the color of the shadows was transformed into a green comparable in clarity to a sea green and in beauty to an emerald green. The effect grew ever more vivid; it was as if we found ourselves in a fairy world for everything had clothed itself in these two lively colors so beautifully harmonious with one another. When the sun had set, the magnificent display finally faded into gray twilight and then into a clear moonlit night filled with stars (Goethe 1810/1988g, p. 181).

Goethe called what was observed in this example as an instance of “colored shadows,” in which shadows that looked colored had in fact originated from the interaction between the environment and the eye. As the snow on the mountain was yellowish, shadows looked bluish instead of grey as an outcome of the interaction. In like manner, Goethe extended our encounter with nature, by providing striking examples of colors as they appear in the world that we daily take for granted. Clearly, this involves individuals directly with color and light as they reflect themselves upon their own experience. In so doing, Goethe was convinced that “the manifestation of a phenomenon is not detached from the observer—it is caught up and entangled in his individuality” (Goethe 1906/1988e, p. 307). He also believed that to “attain in some measure a living comprehension of nature, we must ourselves remain as mobile and plastic as the example nature presents to us” (quoted in Colquhoun 1997, p. 149).

5 Implications for Practical Work in School Science

In the preceding two sections, we have examined the key attributes of Goethe’s scientific epistemology and methodology in general, as well as how they were manifested in his extensive

work on color theory. From the repeated process of abstraction and diversification, he concluded that the essence of scientific experimentation consists in finding the interrelated nature of natural phenomena and human beings. With such an account of experimentation in mind, the task now is to articulate its educational value in relation to today's school practical work. Given the similarity between what Goethe criticized about the science of his time and the problems of school science in our time, it seems reasonable to expect that his scientific epistemology may bear some value for science educators. As shall be seen in what follows, we expect from Goethe's conception of experiment at least three distinctive contributions to school science and practical work.

The first contribution of Goethe's science involves the type of experimental method that he conceived, which can be regarded as a complement to the ordinary hypothesis-testing view of experiments in school science. The idea here is that there are several senses in which we can say that Goethe's conception and practice of experimentation (although not appreciated much) have practical utility as scientific method. In other words, they show an example of scientific experimentation that is distinct from that which is found in the hypothetico-deductive model of scientific practice. One way to characterize Goethe's experimental method is to use what Steinle (1997, 2002, 2016) called "exploratory experimentation"—an experimentation not driven by specific theories. Unlike the typical "theory-driven" type of experiments, exploratory experiments are driven by the desire to seek empirical regularities and the proper concepts and classifications that may be the underlying causes of those regularities, so often play a "constructive" role in science. They feature "the systematic and extensive variation of experimental conditions to discover which of them influence or are necessary to the phenomena under study" (Ribe and Steinle 2002, p. 46), unlike their classical counterpart (represented by Newton's crucial experiment) that aimed to verify hypotheses in a meticulously controlled environment. Ribe and Steinle (2002) nicely illustrated how Newton's and Goethe's color study represent the theory-testing and exploratory style of experimentation, respectively.

Given that school practical work is often accused of delivering a too naïve and limited picture of scientific methods to students, the exploratory character of Goethe's methodology offers an opportunity to expand the narrow conception of scientific experiments in school science. To examine what Goethe's contribution might be, let us begin by comparing the expected student performances assumed in theory-testing and exploratory practical activities. In the traditional theory-testing model of experimentation, the virtue of a good experimenter is to make the best setting subtly designed to test a given hypothesis, and students thus learn to control and manipulate the variables and equipment to get the anticipated result. The primary outcome expected here is that it makes sense to students that the process and result prove theoretically well-founded claims. On the contrary, exploratory activities (such as those Goethe carried out) focus not on verifying a proposed hypothesis; rather, they aim to "explore" the various possibilities of a particular natural phenomenon, without a specific theoretical framework. In fact, being suspicious of previous knowledge is encouraged. Thus, there are no specific listings of knowledge to be learned from an activity. The procedural features of exploratory experimentation that Steinle (1997) listed, that is including varying a large number of different experimental parameters, determining which of the experiment conditions are indispensable and which are only modifying, looking for stable empirical rules, and finding

appropriate representations by means of which those rules can be formulated, are much more open-ended in their methods and conclusions. Such learning objectives are not frequently seen in current science curricula, which normally attend only to theory-testing experiments; nevertheless, they deserve to be part of school science. It is important to note that while these learning outcomes are distinct from what students learn from replicating Newton's crucial experiment, the two are not incompatible. Goethe's experimental method, understood as exploratory experimentation, thus provides a useful supplement to the traditional conception in school science. In short, the process described in Goethe's color theory offers a chance to broaden the conception of practical work by providing a wider understanding of the aims, methods, and learning outcomes of experiments.

The second major contribution of Goethe's experimental philosophy comes from his relentless search for the connections among a diversity of phenomena and experiments. As illustrated in Section 4.1, Goethe sought the interrelation between simple and complex phenomena by diversifying and multiplying experiments. When several isolated observations can be put together by an experimenter, explained Goethe, this leads to a "higher sort" of experience that produces a new understanding of the phenomenon. The significance of such an approach becomes clear when contrasted to "piecemeal empiricism," in which, according to Kosso (2009), one theory is taught almost in isolation from other theories. This form of empiricism has delivered to students an impression that science involves just "one theory or hypothesis at a time that moves through absolute progress, confronting nature just one observation at a time," which has misleadingly "[hidden] the essential feature of the nature of science" (Kosso 2009, p. 35).

What Goethe was concerned with while elaborating his series of experiments was precisely the avoidance of a hasty conclusion made from insufficient and piecemeal empirical observations. He believed that every single phenomenon is interrelated to others, which as a whole constitute the unity of nature; therefore, the observer should aim to discover such relationships underlying the phenomena. On the series of experiments we examined from *Beiträge*, Goethe wrote, "these experiments could even be thought of as representing a single experiment, a single piece of empirical evidence explored in its most manifold variations" (Goethe 1823/1988h, p. 16). Taking this as a remedy for school science, it implies that, rather than presenting individual experiments and observations as conclusive proofs of a particular theory, students should be given opportunities to extend and diversify their experiences on a particular natural phenomenon or event with plenty of variations in the experiments. This would help students formulate a consistent system of knowledge in which each experiment and observation is interconnected with others and introduce them to a more interrelated and dynamic understanding of natural objects and phenomena.

A careful reading of Goethe's scientific writings reveals that the separation he sought to counter was not only between diverse natural phenomena. As hinted in his explanation of colored shadows, Goethe also had serious concerns about the way humans and their objects of study were being alienated from each other (see Section 4.2). This leads us to the third implication of Goethe's epistemology for school science: restoring the subject-object relationship in scientific inquiry. The significance of this third message by Goethe becomes even clearer when we recall the longstanding criticism that science is taught in a way that alienates the human observer from nature. Eger (1992) noted that today, "the *study* of things [science] is still

remote from the things studied [nature],” and this remoteness causes students to look at science “from the outside” and not enter into nature (p. 342; emphasis in original, brackets added). This is to say, we are teaching the “created objective world” rather than the lifeworld where we are bodily situated (Postma 2006, p.165). Similarly, Dahlin (2001) has argued that school science is contributing to “the establishment of a dualistic, external, and unmediated relation between our subjective experience on the one hand and objective nature on the other” (p. 468). Modern science, as Heisenberg (1966) discussed, “no longer deals with the world of direct experience but with a dark background of this world brought to light by our experiments.” In this regard, Goethe’s color theory—and his natural philosophy in general—can be taken as “an attempt to save the immediate truth of the ‘sense-impression’ from the attacks of science” (Heisenberg 1966, p. 79), which can have an important role in improving science education and practical work.

At this point the reader may ask: So, how could we incorporate Goethe’s epistemology into school practical lessons? In other words, what are some “down-to-earth” implications of Goethe’s experimental method? One example that hints at several possible benefits of the approach is found in Seamon (2005), who described a surprisingly simple exercise using a single prism. In the remainder of this section, we outline Seamon’s practical activity about how the Goethean idea of color theory could be applied in classroom settings. In this activity, students are given a prism and paper with black-and-white drawings on it and are encouraged to observe various phenomena with the materials. They carefully observe what is being seen and share it with a group of four or five classmates to reach a consensus on how and where colors appear. Below is what Seamon (2005) listed as exemplary descriptions that students are likely to produce after the exercise:

- Black, white, and uniformly pure surfaces show no color through the prism; rather, colors only appear at edges, which can be defined as places of contrast made by darkness and lightness.
- Colors, however, do not appear along all edges; rather they appear only along edges that are more or less parallel to the axis of the prism.
- The more marked and strong the edge of darkness and light, the brighter and more lively the colors.
- Usually, the colors at the edges arrange themselves in two different groups: a yellow-orange-red edge and a blue-indigo-violet edge.
- Less frequently, the colors green and magenta appear (p. 89).

While Seamon’s focus in interpreting this exercise lies in the qualitative character of these descriptions (as opposed to the typical quantitative observations about colors), a mindful reader might have noticed some further pedagogical implications. For example, as Seamon himself clearly pointed out, the knowledge resulting from the experiment does not assume any theoretical concepts such as the index of refraction or light frequency. They instead remain in the phenomenal level and show the condition and characteristics of colors. Not only does such knowledge itself deserve to be learned through practical work, but also the type of experiment employed to produce the knowledge (that is, a type of exploratory experimentation) is

something we can teach as a form of scientific practice. For example, the observation that colors appear in the edges parallel to the prism axis in two different groups is made without any hypothesis; yet the value of this sort of knowledge seems no lower than knowledge about Snell's law of refraction. In addition, in such exploratory experiments, we might expect that students would be more creative and autonomous, as the activity is much more open-ended than when they are told to replicate Newton's crucial experiment with detailed step-by-step instructions. We can expect that this creativity and autonomy can be facilitated to an even greater extent by sharing individual observations to group members.

When it comes to examining the interrelatedness between different scientific explanations and between natural phenomena and human perception, these can be tried out by extending this simple activity. The exercise can be both abstracted and diversified in various ways (in ways similar to the variation shown throughout Section 4) by, for example, rotating or inverting the prism; varying the prism size, object-prism, or prism-eye distance; using simpler or more complicated (colored) diagrams; or changing the lighting to another color. During these variations, an experimenter can "go back and forth" between abstract and complex phenomena, obtain a sense of the relation among them, and deepen the previous understanding gained from the simplest activity.⁷ Underlying this process is the primacy of direct human experience in experimentation. Rather than letting students simply replicate some "crucial" and stepwise experiments, they can be given opportunities to systemically expand their bodily experience with nature. Students' experience in this procedure would be intrinsically an *educational* one: interacting with the surrounding nature, discovering the patterns of it, and linking their previous and future experiences. That Goethe's theory was rejected by his contemporaries should not hinder the use of these educational experiences in school science.

To be sure, we should not limit the possibility of drawing on Goethe's experimental philosophy only to what is discussed in the example, at least in two distinctive senses. First, while Goethe described an extensive body of experiments to study colors, it does not mean that all we can do is to replicate in practical lessons what Goethe did. The process described in his writings (and in this essay) should rather be taken as instances of a larger idea he developed about scientific experimentation, as seen in Section 3. Textbooks and teachers should invite students to more diverse versions of experiments (even ones not discussed by Goethe) and sometimes let them discover their own way to vary the conditions. Second, it should be noted that the implications of Goethe's conception of experimentation are not restricted to teaching and learning about *color* science. In other words, we expect the three contributions of Goethe's science to apply not just to the physics of color, but to be extended to a wider range of school practical work that concerns other subject matter in science.

6 Conclusion

⁷ Here one may also recall John Dewey's idea that present experience is given as a function of the mutual interaction between the past experience and the present situation (Dewey 1934/2005), which in this case means the relational understanding between diversified experiments examining the same phenomena.

This article attempted to make a case for the significance of Goethe's scientific epistemology and related methodological characteristics through the lens of practical work in science education. We examined some important characteristics of Goethe's conception of experimentation, and how it was explicitly articulated in his study of color. Based on the historical examination, we advanced some educationally important aspects drawn from Goethe's scientific studies and explored how his ideas could possibly shed light on aspects of practical work that have been largely overlooked and neglected. In short, our claim is that what Goethe learned from his method of experimentation, represented by his color theory, bears fruitful educational value that deserves to be included as part of school science. The purpose of bringing Goethean ideas to school should be in maximizing its positive potential, not in replacing the Newtonian color theory taught in schools with the Goethean. Considering that our article has a conceptual character, more elaborated design and implementation of concrete practical activities based on these ideas will be left for another work.

While linking Goethe's conception of scientific experiment to contemporary issues of science education, we chose not to take an approach that aims to determine what his method shows about the nature of science, as discussed in the beginning of this article. That approach would not be the best choice to take with Goethe's works, as it is difficult to say that Goethean science comprises a part of today's scientific enterprise or the currently accepted paradigm; his science was clearly "extra-paradigmatic" (Seamon and Zajonc 1998, p. 35) and "unorthodox" in the view of the mainstream history of science. Instead of examining Goethe's color theory with one or another NOS framework, we turned our attention to what educational values can be drawn from examining Goethe's conception of scientific experimentation and what clues they can offer to an individual's educational experience. Underlying our work is the assumption that though Goethe's color science is not part of today's school science, we can still learn from it. What is advanced in this article thus points much more to discussing educationally valuable experiences from Goethe's scientific works than to simply identifying those aspects of Goethean science that correspond to the existing lists of NOS.⁸ If we were to do the latter, there would be many other better examples in mainstream history of science. In our analysis, Goethe's conception of experimentation was found to be "interconnecting" individual observations by means of repeating an experiment with varied conditions and levels of simplification and emphasizing the close contact and interaction of the observer to the object of inquiry by grounding his science in direct experience. These aspects of Goethe's science imply much about the aims and methods of practical work in schools, which has often been criticized for its cookbook-style implementation, piecemeal empiricism, and students' alienation from nature (Erduran and Dagher 2014; Kischner 1992; Kosso 2009; Wallace 1996).

⁸ Though not much covered in this article, there are some interesting interpretations of Goethe's methodology in terms of the currently shared ideas of NOS. As a notable example, Müller (2016) considered Goethe a forerunner of Duhem and Quine's underdetermination problem (Quine 1969), convincingly showing that the two competing (Newtonian and Goethean) accounts of the complementary spectrum (Fig. 1, right) are not only equally explanatory, but also are equally elegant, simple, and economical as scientific theories.

It comes as no surprise that interest in Goethe's empiricism has been slowly but gradually increasing among researchers from diverse academic backgrounds, with modern science beginning to move beyond the limitations related to Cartesian methodology: the idea of nature as a great machine, the cause-and-effect model of natural phenomena, and the dualism between subject and object. This calls for "educational" attention above all, since how to live with nature and other subjects is fundamentally an educational question. The methodology we identified in Goethe's "*zarte Empirie*"—his delicate empiricism—may be considered as an important epistemological tool that can guide us towards a fuller appreciation of nature and therefore towards a more meaningful practical work in school science. It informs us how we, the students of nature, can construct an educational experience through recognizing interrelations between diverse phenomena around us based on an active transaction between the human subject and natural objects. Again, we believe that the form of scientific experimentation that Goethe envisioned surely has its place in complementing the current aims, methods, and contents of school practical work. In addition, we hope that what is done in this article would be taken as an attempt to "learn from an alternative viewpoint" in educational research. Examining a scientific theory of the past—that is not part of today's science—with a contemporary mind gives us a chance to critically reflect on where we are situated now and to broaden the possibility of our learning about school science.

References

- American Association for the Advancement of Science (AAAS) (1991). *Science for all Americans*. Oxford: Oxford University Press.
- Allchin, D. (2013). *Teaching the nature of science: Perspectives & resources*. Saint Paul: SHiPS Education Press.
- Amrine, F. (1998). The metamorphosis of the scientist. In D. Seamon, & A. Zajonc (Eds.), *Goethe's way of science: A phenomenology of nature* (pp. 33–54). Albany: State University of New York Press.
- Amrine, F., & Zucker, F. J. (1987). Introduction. In F. Amrine, F. J. Zucker, & H. Wheeler (Eds.), *Goethe and the sciences: A reappraisal* (pp. xi–xvi). Dordrecht: Reidel.
- Bencze, J. L. (1996). Correlational studies in school science: Breaking the science-experiment-certainty connection. *School Science Review*, 78(282), 95–101.
- Brady, R. H. (2012). Form and cause in Goethe's morphology. In F. R. Amrine, F. J. Zucker, & H. Wheeler (Eds.), *Goethe and the sciences: A reappraisal* (pp. 257–300). Dordrecht: Springer.
- Cartwright, N. (1999). *The dappled world: A study of the boundaries of science*. Cambridge: Cambridge University Press.
- Charlesworth, M., Farrall, L., Stokes, T., & Turnbull, D. (1989). *Life among the scientists: An anthropological study of an Australian scientific community*. Melbourne: Oxford University Press.
- Colquhoun, M. (1997). An exploration into the use of Goethean science as a methodology for landscape assessment: The Pishwantan Project. *Agriculture, Ecosystems & Environment*, 63(2), 145–157.
- Council for Science and Technology. (2013). Science, technology, engineering and mathematics education: Update. Retrieved January 03, 2018, from <https://www.gov.uk/government/publications/science-technology-engineering-and->

- mathematics-education-update
- Crone, R. A. (1999). *A history of color: The evolution of theories of lights and color*. Dordrecht: Kluwer Academic Publishers.
- Dagher, Z. R., & Erduran, S. (2014). Reconceptualizing the nature of science for science education. *Science & Education*, 25(1–2), 147–164.
- Dahlin, B. (2001). The primacy of cognition—or of perception? A phenomenological critique of the theoretical bases of science education. *Science & Education*, 10(5), 453–475.
- Dewey, J. (2005). *Art as experience*. New York: Penguin. (Original work published 1934)
- Dijksterhuis, E. J. (1986). *The mechanization of the world picture*. (C. Dikshoorn, Trans.). Princeton: Princeton University Press.
- Dolphin, G., & Dodick, J. (2014). Teaching controversies in earth science: The role of history and philosophy of science. In M. R. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (pp. 553–599). Dordrecht: Springer.
- Domin, D. S. (1999). A review of laboratory instruction styles. *Journal of Chemical Education*, 76(4), 543–547.
- Duck, M. J. (1988). Newton and Goethe on colour: Physical and physiological considerations. *Annals of Science*, 45(5), 507–519.
- Duck, M. J. (1993). *Goethe's rejection of Newton's Opticks: An analysis of Enthuellung der Theorie Newtons*. (Unpublished doctoral dissertation). Imperial College London (University of London), London, United Kingdom.
- Eger, M. (1992). Hermeneutics and science education: An introduction. *Science & Education*, 1(4), 337–348.
- Erduran, S. & Dagher, Z. R. (2014). *Reconceptualizing nature of science for science education*. Dordrecht: Springer.
- Espinet, M. (1990). Newton's and Goethe's process of inquiry. In D. E. Herget (Ed.), *More history and philosophy of science in science teaching: Proceedings of the first international conference of philosophy of science in science teaching* (pp. 3–12). Florida State University.
- Gillispie, C. C. (2016). *The edge of objectivity: An essay in the history of scientific ideas*. Princeton: Princeton University Press.
- Gingras, Y. (2001). What did mathematics do to physics?. *History of Science*, 39(4), 383–416.
- Gjertsen, D. (1986). *The Newton handbook*. London: Routledge and Kegan Paul.
- Goethe, J. W. von (1850). *Conversations of Goethe with Eckermann and Soret*. (J. Oxenford, Trans.). London: Smith. (Original work published 1836)
- Goethe, J. W. von (1974). *The autobiography of Johann Wolfgang von Goethe*. (J. Oxenford, Trans.). Chicago: University of Chicago Press. (Original work published 1811)
- Goethe, J. W. von (1988a). *An intermaxillary bone is present in the upper jaw of man as well as in animals*. In D. Miller (Ed., & Trans.), *Goethe: Scientific studies* (pp. 111–116). New York: Suhrkamp Publishers. (Original work published 1820)
- Goethe, J. W. von (1988b). *Analysis and synthesis*. In D. Miller (Ed., & Trans.), *Goethe: Scientific studies* (pp. 48–50). New York: Suhrkamp Publishers. (Original work published 1833)
- Goethe, J. W. von (1988c). *Empirical observation and science*. In D. Miller (Ed., & Trans.), *Goethe: Scientific studies* (pp. 24–25). New York: Suhrkamp Publishers. (Original work published 1893)

- Goethe, J. W. von (1988d). *The metamorphosis of plants*. In D. Miller (Ed., & Trans.), *Goethe: Scientific studies* (pp. 76–97). New York: Suhrkamp Publishers. (Original work published 1790)
- Goethe, J. W. von (1988e). *Selections from Maxims and Reflections*. In D. Miller (Ed., & Trans.), *Goethe: Scientific studies* (pp. 303–312). New York: Suhrkamp Publishers. (Original work published 1906)
- Goethe, J. W. von (1988f). *Significant help given by an ingenious turn of phrase*. In D. Miller (Ed., & Trans.), *Goethe: Scientific studies* (pp. 39–41). New York: Suhrkamp Publishers. (Original work published 1823)
- Goethe, J. W. von (1988g). *Theory of color: Didactic section*. In D. Miller (Ed., & Trans.), *Goethe: Scientific studies* (pp. 157–298). New York: Suhrkamp Publishers. (Original work published 1810)
- Goethe, J. W. von (1988h). *The experiment as mediator between object and subject*. In D. Miller (Ed., & Trans.), *Goethe: Scientific studies* (pp. 11–17). New York: Suhrkamp Publishers. (Original work published 1823)
- Goethe, J. W. von (2006). *Theory of colours*. (C. L. Eastlake, Trans.). Mineola: Dover (Original work published 1810).
- Goethe, J. W. von (2016). *Goethe's "Exposure of Newton's Theory": A polemic on Newton's theory of light and colour*. (M. Duck & M. Petry, Ed., & Trans.). Singapore: Imperial College Press. (Original work published 1810)
- Hadzigeorgiou, Y., & Schulz, R. (2014). Romanticism and Romantic science: Their contribution to science education. *Science & Education*, 23(10), 1963–2006.
- Hegge, H. (1972). Theory of science in the light of Goethe's science of nature. *Inquiry*, 15, 1–4.
- Heinemann, F. (1934). Goethe's phenomenological method. *Philosophy*, 9(33), 67–81.
- Heisenberg, W. (1966). *Philosophic problems of nuclear science*. (F. C. Hayes, Trans.). Greenwich: Fawcett.
- Hempel, C. G. (1966). *Philosophy of natural science*. Upper Saddle River: Prentice Hall.
- Hodson, D. (1993). Re-thinking old ways: Towards a more critical approach to practical work in school science. *Studies in Science Education*, 22(1), 85–142.
- Hodson, D. (2014). Nature of science in the science curriculum: Origin, development, implications and shifting emphases. In M. R. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching*. Dordrecht: Springer.
- Huxley, T. H. (1869). Goethe: Aphorisms on nature. *Nature*, 1, 9–11.
- Irzik, G., & Nola, R. (2014). New directions for nature of science research. In M. R. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (pp. 999–1021). Dordrecht: Springer.
- Jackson, M. W. (2008). Putting the subject back into color: Accessibility in Goethe's *Zur Farbenlehre*. *Perspectives on Science*, 16(4), 378–391.
- Jenkins, E. (1998). The schooling of laboratory science. In J. Wellington (Ed.), *Practical work in school science* (pp. 35–51). London: Routledge.
- Kirschner, P. (1992). Epistemology, practical work and academic skills in science education. *Science Education*, 1, 273–99.
- Kosso, P. (2009). The large-scale structure of scientific method. *Science & Education*, 18(1), 33–42.

- Kuhn, D. (2012). Goethe's relationship to the theories of development of his time. In F. R. Amrine, F. J. Zucker, & H. Wheeler (Eds.), *Goethe and the sciences: A reappraisal* (pp. 3–16). Dordrecht: Springer.
- Lakatos, I. (1970). Falsification and the methodology of scientific research programmes. In I. Lakatos & A. Musgrave (Eds.), *Criticism and the growth of knowledge: Proceedings of the International Colloquium in the Philosophy of Science, London, 1965* (pp. 91–196). Cambridge: Cambridge University Press.
- Lederman, N. G. (2007). Nature of science: Past, present, and future. In S. Abell & N. Lederman (Eds.), *Handbook of research on science education* (pp. 831–880). Mahwah: Lawrence Erlbaum Associates.
- Lefkadtou, A., Korfiatis, K., & Hovardas, T. (2014). Contextualising the teaching and learning of ecology: Historical and philosophical considerations. In M. R. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (pp. 523–550). Dordrecht: Springer.
- Lehrs, E. (1985). *Man or matter*. Forest Row: Rudolf Steiner Press.
- Marcum, J. A. (2009). The nature of light and color: Goethe's "der versuch als vermittler" versus Newton's experimentum crucis. *Perspectives on Science*, 17(4), 457–481.
- Millar, R. (1994). What is "scientific method" and can it be taught. In R. Levinson (Ed.), *Teaching science* (pp. 164–177). London: Routledge.
- Miller, D. (1988). Introduction. In D. Miller (Ed.), *Goethe: Scientific studies* (pp. ix–xix). New York: Suhrkamp Publishers.
- Müller, O. L. (2016). Prismatic equivalence – A new case of underdetermination: Goethe vs. Newton on the prism experiments. *British Journal for the History of Philosophy*, 24(2), 323–347.
- Müller, O. L. (2017). Goethe contra Newton on colours, light, and the philosophy of science. In M. Silva (Ed.), *How colours matter to philosophy* (pp. 73–95). Dordrecht: Springer.
- National Research Council. (1996). *National science education standards*. Washington, DC: National Academy Press.
- Newton, I. (1730). *Opticks, or a treatise of the reflections, refractions, inflections and colours of light*. London: William Innys.
- NGSS Lead States. (2013). *Next generation science standards*. Washington, DC: National Academy Press.
- Østergaard, E., Dahlin, B., & Hugo, A. (2008). Doing phenomenology in science education: A research review. *Studies in Science Education*, 44(2), 93–121.
- Polanyi, M. (2009). *The tacit dimension*. Chicago: University of Chicago Press.
- Postma, D. W. (2006). *Why care for nature?: In search of an ethical framework for environmental responsibility and education*. Dordrecht: Springer.
- Quine, W. V. O. (1969). *Ontological reality and other essays*. New York: Columbia University Press.
- Rang, M., & Grebe-Ellis, J. (2009). Komplementäre Spektren: Experimente mit einer spiegel-spalt-blende. *Mathematisch-Naturwissenschaftlicher Unterricht*, 62(4), 227–230.
- Ribe, N. M. (1985). Goethe's critique of Newton: A reconsideration. *Studies in History and Philosophy of Science*, 16(4), 315–335.
- Ribe, N., & Steinle, F. (2002). Exploratory experimentation: Goethe, Land, and color theory. *Physics Today*, 55(7), 43–49.

- Richards, R. J. (2002). *The Romantic conception of life: Science and philosophy in the age of Goethe*. Chicago: University of Chicago Press.
- Rueger, A. (1992). The cultural use of natural knowledge: Goethe's theory of color in Weimar Classicism. *Eighteenth-Century Studies*, 26(2), 211–232.
- Schwartz, R., & Lederman, N. (2008). What scientists say: Scientists' views of nature of science and relation to science context. *International Journal of Science Education*, 30(6), 727–771.
- Seamon, D. (2005). Goethe's way of science as a phenomenology of nature. *Janus Head*, 8(1), 86–101.
- Seamon, D., & Zajonc, A. (1998). *Goethe's way of science: A phenomenology of nature*. Albany: SUNY Press.
- Sepper, D. L. (2003). *Goethe contra Newton: Polemics and the project for a new science of color*. Cambridge: Cambridge University Press.
- Shulman, L. S., & Tamir, P. (1973). Research on teaching in the natural sciences. In R. M. W. Travers (Ed.), *Second handbook of research on teaching* (pp. 1098–1148). Skokie: Rand McNally & Co.
- Steigerwald, J. (2002). Goethe's morphology: Urphänomene and aesthetic appraisal. *Journal of the History of Biology*, 35(2), 291–328.
- Steiner, R. (1988). *Goethean science*. New York: Mercury Press.
- Steiner, R. (2001). *The light course: First course in natural science*. Herndon: Anthroposophic Press.
- Steinle, F. (1997). Entering new fields: Exploratory uses of experimentation. *Philosophy of Science*, 64(Proceedings), S65–S74.
- Steinle, F. (2002). Experiments in history and philosophy of science. *Perspectives on Science*, 10(4), 408–432.
- Steinle, F. (2016). *Exploratory experiments: Ampère, Faraday, and the origins of electrodynamics*. (A. Levine, Trans.). Pittsburgh: University of Pittsburgh Press.
- Wahl, D. C. (2005). "Zarte Empirie": Goethean science as a way of knowing. *Janus Head*, 8(1), 58–76.
- Wallace, G. (1996). Engaging with learning. In J. Rudduck (Ed.), *School improvement: What can pupils tell us?* (pp. 56–69). London: David Fulton.
- Wellmon, C. (2010). Goethe's morphology of knowledge, or the overgrowth of nomenclature. *Goethe Yearbook*, 17(1), 153–177.
- Wells, G. A. (1979). *Goethe and the development of science 1750–1900*. Dordrecht: Springer.
- Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education*, 92(5), 941–967.
- Young, T. (1814). Review of *Zur Farbenlehre*, by Johann Wolfgang von Goethe. *Quarterly Review*, 10(20), 427.
- Zemplén, G. Á. (2001). *An eye for optical theory—Newton's rejection of the modificationist tradition and Goethe's modificationist critique of Newton*. (Unpublished doctoral dissertation). Budapest Technological University, Budapest, Hungary.