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EXPLORATORY EXPERIMENTATION: GOETHE, LAND, AND COLOR THEORY

The style of investigation exemplified by Goethe's experiments with color is often undervalued, but has repeatedly proved its worth.

Neil Ribe and Friedrich Steinle

Johann Wolfgang von Goethe's *Theory of Colors*[1] has continued to fascinate physicists for almost two centuries since its publication in 1810. Hermann von Helmholtz, Werner Heisenberg, Walter Heitler, and Carl Friedrich von Weizsäcker are among those who have written substantial essays on Goethe.[2] More recently, chaos theorist Mitchell Feigenbaum consulted Goethe's work and was surprised to find that "Goethe had actually performed an extraordinary set of experiments in his investigation of colors." Not only that, Feigenbaum persuaded himself that "Goethe had been right about color!"[3]

We agree with Feigenbaum that the experiments contained in *Theory of Colors* are what gives Goethe's work its abiding interest. In this article, we suggest that Goethe was a remarkable representative of a research style that we call exploratory experimentation. Long ignored by historians and philosophers of science, exploratory experimentation has nevertheless played a crucial role in the history of physics. Among others, Michael Faraday's investigations into electromagnetism followed the exploratory approach; they are discussed in boxes 1 and 2 on pages 48 and 49. In the main, though, we tell the story of exploratory experimentation by looking at two investigations of color from different historical periods—Goethe's experiments with prismatic colors and Edwin Land's experiments on color vision. To understand properly their work, one must first consider a classic example of a very different approach to understanding color, that of Isaac Newton.

Newton's experimental approach

Newton first announced his "New Theory about Light and Colours" in a famous letter to the Royal Society of London.[4] In it, he described several experiments, including the classic one—illustrated in figure 1a—in which a beam of sunlight refracted by a prism casts an oblong colored spectrum on a wall. Starting from the observation that the image was not circular like the original sunbeam, Newton inferred the principles of his new theory: that sunlight was a mixture of rays of different "refrangibility," that colors were not "Qualifications of Light, . . . but Original and connate properties," and that colors could be either simple or compound. The crucial element of Newton's theory was his extension of the traditional concept of the ray, which he associated with a definite degree of refrangibility. Newton's reliance on this new concept served both to guide the interpretation of his experiments and to rule out competing explanations. Chief among those explanations were theories that attributed color to some modification of the light during refraction, such as mingling with shadow or (as was proposed by René Descartes) a frictional slowing of the rotation rates of light corpuscles. Newton ascribed to his experiments extraordinary demonstrative power: His theory, he said in his letter, "is not an Hypothesis but most rigid consequence, not conjectured by barely inferring 'tis thus because not otherwise or because it satisfies all phaenomena . . . but evinced by ye mediation of experiments concluding directly & wthout any suspicion of doubt." Indeed, Newton chose to model his later *Opticks* after Euclid's Elements, with each of the central propositions followed by a "Proof by Experiments."[5]

The role of preexisting hypothesis in Newton's optical work is revealed by an early notebook (1664–65), which gives a more reliable picture of his research practice than the carefully constructed letter of 1672.[6] Newton reported that when he looked through a prism at a cardboard with its two halves painted in different colors, he observed colored fringes at the border between the two, as illustrated in figure 1b. Newton varied the colors of the cardboard halves and noted in a table the colors of the resulting fringes. He connected those observations immediately with considerations of how different velocities of light "globuli" cause different color sensations. Evidently a corpuscular theory of light formed the background of Newton's experiments, serving both to guide their design and to conceptualize their results. For example, the corpuscular hypothesis implied that swifter rays would be less refracted by a prism than slower ones because they were exposed for a shorter time to the prism's influence.

In contrast to Goethe and Land, Newton was not primarily concerned with color as such, which he regarded as an indicator of more abstract and mathematizable properties of light rays. Among the few propositions in *Opticks* that deal with color per se is one (book one, part 2, proposition 6) proposing a geometrical procedure for determining the compound color that results from mixing simple spectral colors. The color wheel Newton used for this purpose is illustrated in figure 1c. He left unclear, though, how the relative "number of rays" of each of the component colors was to be defined, and Newton admitted that he was

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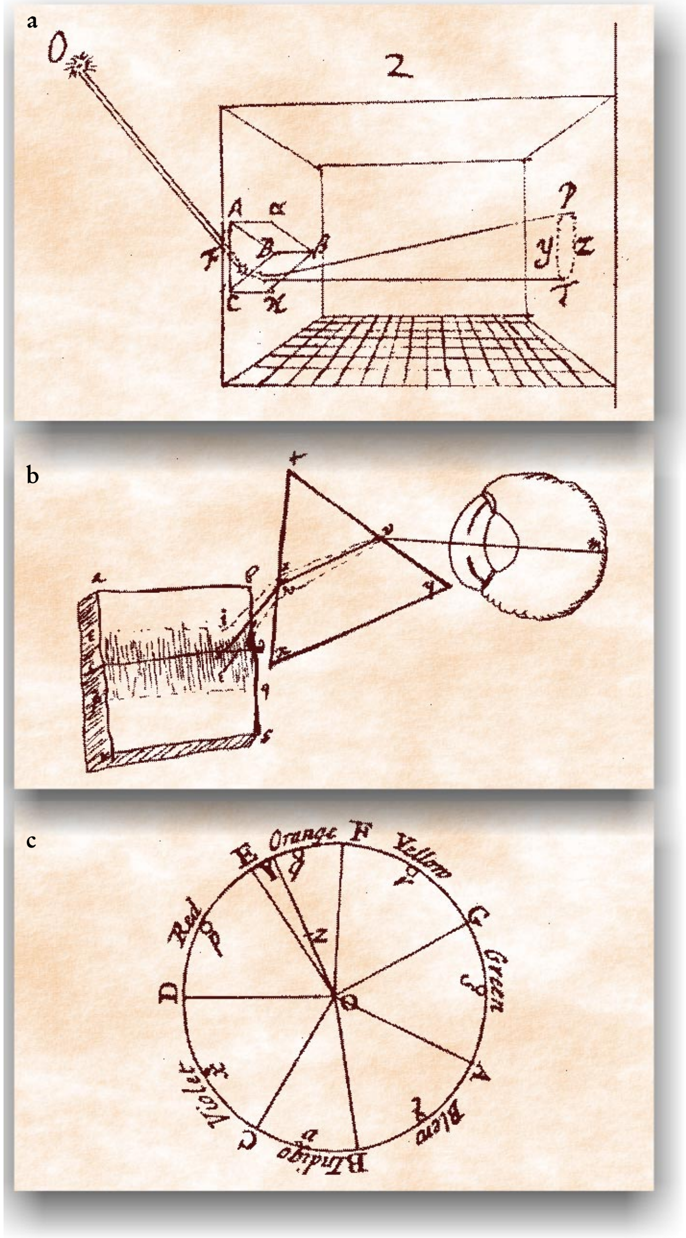


FIGURE 1. ISAAC NEWTON'S SKETCHES illustrating some of his investigations of color. **(a)** A circular sunbeam refracted through a prism casts an oblong image. From this and other experiments, Newton concluded that color was an inherent quality of light, that each spectral color had its own degree of refrangibility, and that colors could be simple or compound. (Adapted from manuscript Add. 4002, Cambridge U. Library.) **(b)** Fringes of color are observed at the boundary of two different color fields painted on cardboard. (Adapted from manuscript Add. 3996, Cambridge U. Library.) **(c)** Newton's color circle. The sizes of the seven sections are proportional to the intervals of the diatonic musical scale. The circle illustrates a "center of gravity" calculation of the compound color that results from mixing spectral colors. The areas of the circles *p*, *q*, *r*, *s*, *t*, *v*, and *x* are proportional to the "number of rays" of each color in the mixture. The center of gravity is the point *z*: Its azimuth predicts the color of the mixture; its radius, the saturation. (Adapted from ref. 5.)

unable to generate white from two colors, although his scheme predicted that possibility. But those failures did not worry him: Such color-mixing problems, he remarked,[7] were "Curiosities of little or no moment to understanding the Phaenomena of Nature."

Goethe's color experiments

Goethe's scientific interest in color was inspired by the natural optical phenomena and the coloristic traditions of Renaissance painting that he encountered during his first journey to Italy (1786–88). Goethe's first publication on color theory, *Contributions to Optics* followed a few years later.[1] The *Contributions* centered around a series of experiments in which Goethe viewed various painted images on paper through a prism. Like Newton before him, he observed colored fringes along boundaries. Unlike Newton, however, Goethe systematically varied the experimental conditions—the shape, size, color, and orientation of the images viewed; the refracting angle of the prism; and the distance of the prism from the figure—to determine how they influenced what he saw.

Goethe's experimental procedure comprised two stages: an analytic one that moved from complex appearances through simpler ones to a first principle, and a synthetic stage that moved in reverse order, showing how more complex appearances are related to the first principle. The analytic stage is illustrated by a set of experiments with black-and-white images. Figure 2 shows how a few of the images Goethe used look when viewed through a prism with its refracting angle held downward. The general law determined by Goethe was that colored fringes arose at black–white borders parallel to the prism's axis: yellow and red when the white was below the black, blue and violet when it was above, as shown in the prism view of figure 2e. For Goethe, these fringes constituted an elementary appearance of prismatic color from which all others could be derived. For example, Goethe's experiments with black and white rectangles showed that the Newtonian and complementary spectra (see the prism views of figures 2c and d) were generated when the colored fringes from two closely spaced black–white boundaries encountered each other: The yellow and blue fringes mixed to produce green; the red and violet produced magenta. For Goethe, therefore, the Newtonian and complementary spectra were compound phenomena that could be derived from the law of colored fringes.

The synthetic stage of Goethe's investigation is illustrated by his experiments on the colored fringes that appear when gray and colored images on various backgrounds are viewed through a prism. Figure 3 shows how part of one of Goethe's diagrams (see the cover of this issue), from *Theory of Colors*, looks through a prism with its refracting angle held downward. Experiments with squares in different shades of gray against white and black backgrounds showed that the intensity of the colored fringes increased with the lightness contrast at the boundary. More complex phenomena were seen using colored squares, which exhibited fringes with new colors not seen in the previous experiments. Goethe argued, quite plausibly, that those new colors were due to the mixing of the elementary fringe colors with the colors of the squares themselves. Goethe regarded that mixing as the true explanation of Newton's observation that a red square, viewed through a prism against a black background, appears displaced slightly higher than a blue one, as seen in the upper right of figure 3. Whereas Newton had adduced this obser-

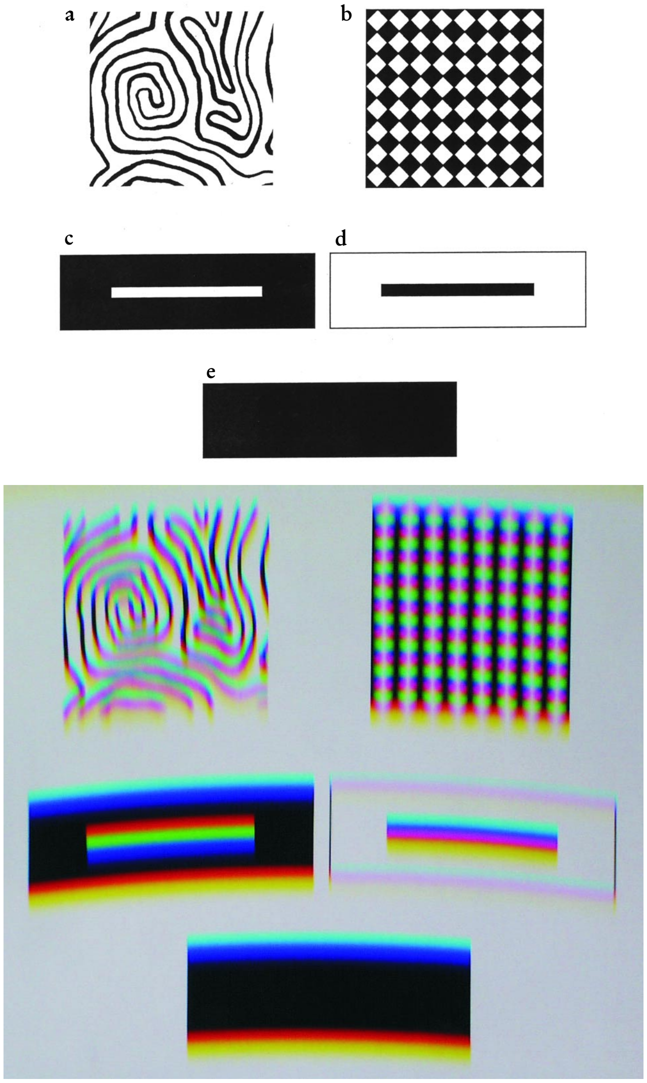


Figure 2. Goethe's analytic investigations proceeded from the complex to the simple. Shown are five black-and-white images selected from a series studied by Goethe, viewed with the naked eye (top, adapted from *Contributions to Optics*, ref. 1) and through a prism with its refracting angle held downward (bottom). The up–down sequence of all the colors is reversed if the refracting angle is held upward. **(a)** An irregular arrangement of black and white exhibited colored fringes with no apparent order. **(b)** The colors generated by a simpler checkerboard pattern were periodic and exhibited regular changes as the checkerboard was rotated, but were still too complicated to be expressed in a law. **(c)** The colored fringes generated by a white rectangle depended on the width of the rectangle and its distance from the prism. A very narrow rectangle, or one at a great distance, exhibited a spectrum with just three colors. Wider rectangles, such as the one shown, displayed fringes whose colors—red, yellow, green, blue, and violet—were consistent with those of the Newtonian spectrum. **(d)** A black rectangle on a white background exhibited a spectrum—blue, violet, magenta, red, and yellow—complementary to that of **(c)**. The complementary spectrum's central magenta, called "pure red" by Goethe, is not in the Newtonian spectrum. **(e)** The boundaries of wider rectangles acted as isolated black–white contrasts, displaying red and yellow fringes when the black was above, blue and violet when it was below. No colors appeared at vertical black–white borders.

vation to prove that different colors of light have different refrangibilities—the first proposition of his *Opticks*—Goethe saw it as merely a special case of the more general law of colored fringes.

The experiments just described are only a small fraction of those that Goethe performed during his career. Others included novel experiments with refracted sunlight that displayed at a glance the evolution of both the Newtonian and complementary spectra as a function of distance from the prism, and careful replications and variations of many of the experiments in book 1 of Newton's *Opticks*. Particularly important are Goethe's experiments on colored shadows, such as one in which the shadow of a pencil cast by a lighted candle and illuminated by the setting sun is observed to be bright blue. Goethe was among the first to recognize the importance of this phenomenon, for which no account is given in Newton's theory.

As an epitome of his research, Goethe proposed a symmetric color circle, illustrated in figure 4, that applied in all areas he had studied. By contrast, Newton's color circle, with seven colors subtending unequal angles, did not exhibit the symmetry and complementarity that Goethe regarded as essential characteristics of color. For Newton, only spectral colors could count as fundamental. By contrast, Goethe's more empirical approach led him to recognize the essential role of (nonspectral) magenta in a complete color circle, a role that it still has in all modern color systems. Artisans such as painters, dyers, and tanners, who had to deal practically with color, generally felt much more attracted to Goethe's color circle than to Newton's. One painter strongly influenced by Goethe's work was J. M. W. Turner (1775–1851), whose annotated copy of *Theory of Colors* is extant and whose painting "Light and Colour (Goethe's Theory)" is on display at Tate Britain in London.

Contrasting research strategies

Newton's and Goethe's respective approaches to color illustrate two very different approaches to experimental research. We call them theory-oriented and exploratory experimentation. Theory-oriented experimentation is often regarded as the only relevant kind: It corresponds roughly to the "standard" view in the philosophy of science

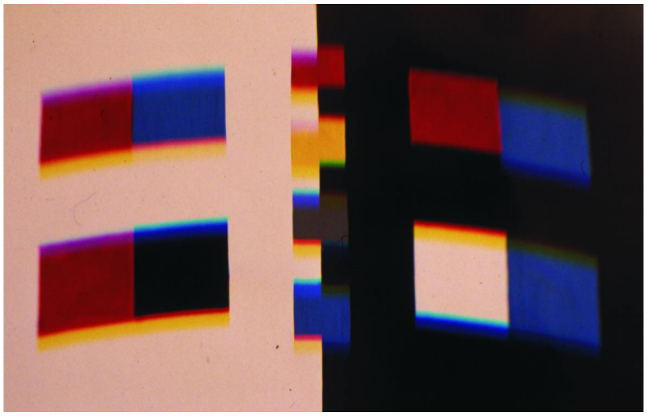


Figure 3. Goethe's synthetic investigations involved the study of the colored fringes that appear when images of various colors are viewed through a prism. Goethe argued that the apparent relative displacements of the various squares followed from his law of colored fringes.

that experiments are designed with previously formulated theories in mind and serve primarily to test or demonstrate them. Such a view was stated forcefully by Karl Popper, who wrote, “The theoretician puts certain definite questions to the experimenter, and the latter, by his experiments, tries to elicit a decisive answer to these questions, and to no others. . . . Theory dominates the experimental work from its initial planning up to the finishing touches in the laboratory.”[8] According to this view, it makes sense to perform an isolated experiment, and in particular an *experimentum crucis*, designed to judge between competing hypotheses. Newton largely followed such an approach in his experiments on color.

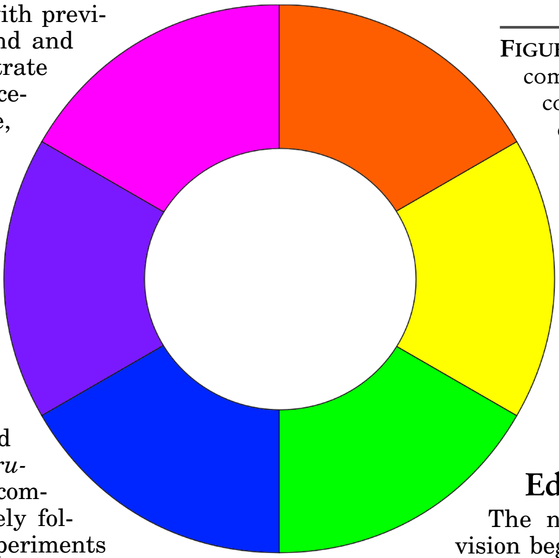


Figure 4. Goethe’s color circle comprises both the Newtonian and the complementary spectra observed in experiments with prisms. In addition, its three pairs of opposite colors are complementary in a variety of contexts, including prismatic color generation, colored shadows, afterimages, and color mixing. (From *Theory of Colors*, ref. 1.)

By contrast, exploratory experimentation has been relatively neglected by historians and philosophers of science. Its defining characteristic is the systematic and extensive variation of experimental conditions to discover which of them influence or are necessary to the phenomena under study. The focus is less on the connection between isolated experiments and an overarching theory, and more on the links among related experiments. Exploratory experimentation aims to open up the full variety and complexity of a field, and simultaneously to develop new concepts and categories that allow a basic ordering of that multiplicity. Exploratory experimentation typically comes to the fore in situations in which no well-formed conceptual framework for the phenomena being investigated is yet available; instead, experiments and concepts codevelop, reinforcing or weakening each other in concert.

Exploratory experimentation often results in the establishment of a hierarchy within a realm of phenomena. At the pinnacle are those phenomena—Goethe calls them primordial—that involve only the essential conditions and that are therefore attributed a special status. All other effects can be deduced or explained from those elementary ones by progressively complicating the experimental arrangement and adding new conditions. The connection between a particular effect and an elementary phenomenon is revealed by establishing a chain of intermediate effects. In his methodological essay *The Experiment as Mediator Between Object and Subject*,[9] Goethe described the result of such an approach as a “series of experiments that border on one another closely and touch each other directly; and which indeed, if one knows them all exactly and surveys them, constitute as it were a single experiment. . . .” He regarded this care to connect the “closest to the closest” as an experimental analog of mathematical deduction, which “on account of its deliberateness and purity reveals every leap into assertion.” In that context, isolated experiments are not very informative, let alone demonstrative, as they well might be in theory-oriented work. The difference is nicely illustrated by the exchange between Newton and an early critic, the Liège Jesuit Anthony Lucas, who brought forward many new experiments (including variations of Newton’s own), which he claimed could not be accounted for by Newton’s theory. Newton’s response was to insist that one “try only the *experimentum crucis* [*Opticks*, book 1, part 1, experiment 6],” for “where one will do, what need of many?”[10]

Edwin Land and color vision

The now-classic experiments on color vision begun in the 1950s by Land are not only a fine example of exploratory experimentation at the frontier between physics and biology, they also have a direct bearing on the theoretical content of Goethe’s *Theory of Colors*. Land’s research began with a simple experiment using two black-and-white transparencies of the same colored scene. The first transparency, the “long record,” was taken through a filter that passed only long-wavelength light. The second, the “short record,” was taken through a filter that passed only short wavelengths. The two records differed only in the lightness or darkness of corresponding points; neither had any color. The transparencies were then projected onto a screen, directly on top of one another, using a beam of light from the red part of the spectrum for the long record and a beam of incandescent light for the short record. According to the classical color theory based on the work of Newton, Thomas Young, James Clerk Maxwell, and Hermann von Helmholtz, the image on the screen could only be some shade of pink. What the observer saw, however, was an image brilliantly and diversely colored, almost like the original scene.

Although Land was not the first to observe such two-color projection effects, his observation initiated a program of exploratory experimentation lasting more than two decades. He began with a series of 22 variations on the two-projector experiment. Those experiments demonstrated that the unexpected or “nonclassical” colors appeared essentially instantaneously, and could not be explained by time-dependent adaptations in the eye. The experiments also showed that the colors were not substantially affected by such factors as the intensities of the ambient illumination or of the projecting beams, the angle subtended by the image, or the filters used to produce the short and long records. Land then performed a more precise series of experiments using a dual monochromator that allowed the experimenter to vary at will the wavelengths of the projecting beams, and to study the range of colors observed as a function of those wavelengths.[11]

From the experiments, Land concluded that classical color theory was valid only for spots of light observed in totally dark surroundings and that it had only limited relevance to color perception in natural situations involving multiple objects and variable illumination. In particular, he concluded that the stimulus for the color seen at a point in an image was not, as usually supposed, the wavelength composition of the radiant energy reaching the eye from that point. His subsequent experiments were aimed at uncovering the nature of the stimulus. Most of these exper-

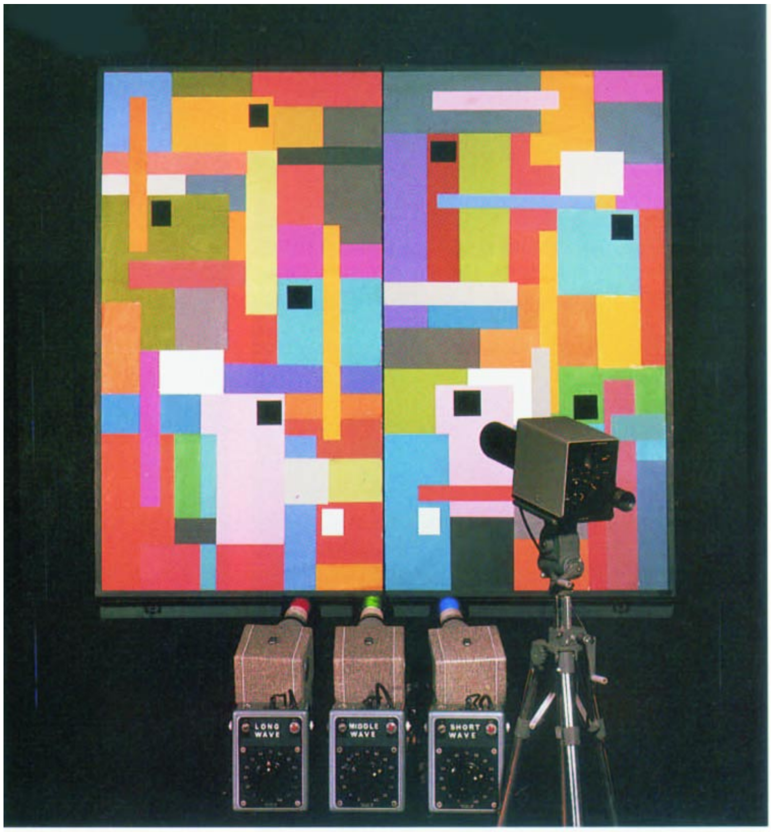


FIGURE 5. MONDRIAN-LIKE COLLAGES were key elements of Edwin Land's experiments on color vision. The Mondrians were illuminated by the three projectors at the bottom with light comprising various proportions of short, medium, and long wavelengths. A telephotometer, seen on a tripod to the right, measured the wavelength composition of the light reflected from a given colored patch to the eye. Land thereby showed that the perceived color of the patch is not determined by the wavelength composition of the light reflected from it. (Photograph by J. Scarpetti, courtesy of the Rowland Institute, Cambridge, Mass.)

iments used "Mondrians," collages of paper rectangles with different shapes and colors.

Land began with experiments in which colorless Mondrians in white, gray, and black were viewed through dark goggles that allowed only the eye's rod (night-vision) system to operate. By adjusting the illumination of the Mondrians, Land showed that the patches maintained a constant rank order of perceived lightness, even though a patch that appeared dark might be sending much more light to the eye than one that appeared light. This suggested to Land that the eye was able to discover lightness values independent of the flux of energy it received; the reflectance, the physical correlate of lightness, might be the color stimulus he was seeking. This idea led Land to a series of experiments in which he illuminated colored Mondrians with long-, middle-, and short-wavelength light that could be mixed in any proportion (see figure 5). In one set of experiments, the illumination was adjusted so that, for example, a white area of one Mondrian sent to the eye exactly the same triplet of radiant energies as a green area of another Mondrian. The two areas continued to appear white and green, a dramatic demonstration that their perceived colors were independent of the flux of energy they emitted as a function of wavelength. In another set of experiments, observers were asked to choose from a standard set of 1150 color chips the one that best matched the color of a given area on an illuminated Mondrian. Land found that when a match was made, it was the reflectances of the two areas that corresponded, and not the triplets of radiant energy being sent to the eye in the three illuminating wave bands.[12]

The "retinex" theory of color vision that Land developed on the basis of his experiments has two essential elements: It recognizes lightness (that is, reflectance) as the fundamental stimulus of color, and it emphasizes the importance of boundaries, which allow the eye to estimate lightness by seeking out singularities in the ratio of energy flux from closely spaced points. The parallel with Goethe's theory, which itself emphasizes the crucial roles of lightness and of boundaries, is striking.

Complex systems

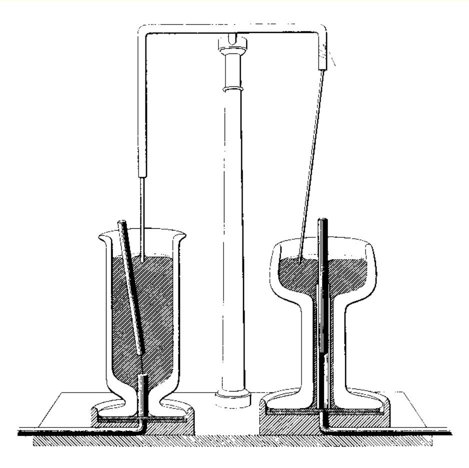
Textbook accounts of the history of physics usually highlight discoveries involving simple systems, that is, those consisting of relatively few interacting elements. Such systems lend themselves to study by means of isolated experiments designed to demonstrate directly an underlying physical principle. Most of the celebrated experiments of physics, from Galileo's with balls on inclined planes to Robert Millikan's with oil drops, are of this type. The physicist studying a simple system deliberately removes complicating influences, like an intensely focused road builder cutting a straight road with little interest in the surrounding landscape.

Newton's investigations into optics were guided by the metaphysical belief that color was merely a subjective correlate of mechanical properties of light rays. He therefore abstracted from the complex world of normal visual perception, working in a dark chamber illuminated only by a single sunbeam. The system he studied was thus a simple one, comprising entities of a single kind—rays with diverse refrangibility—whose mutual interactions, such as color mixing, were purely superpositional. Newton's approach was entirely reasonable given his aim: His mathematization of light and color could best take flight from a few particular effects. But the price paid was that his experiments had only limited relevance to color as usually perceived.

Physicists studying complex systems that consist of numerous interacting elements face a task different in kind from that confronting Newton. They often start with a multitude of empirical findings whose interconnections and underlying principles are unclear. They must use experiments not so much to demonstrate propositions as to develop the concepts needed to make sense of multiplicity. The traditional isolated experiment is of little help here. Instead, the student of complexity must be an explorer, performing numerous laboratory or numerical experiments under different conditions, sufficiently "close" to one another that no important feature of the behavior is missed. Such a physicist is not so much a road builder as a mapmaker, whose principal interest is the physiognomy of a complex landscape.

The role of relative complexity in motivating the choice of experimental strategy is clearly illustrated by the

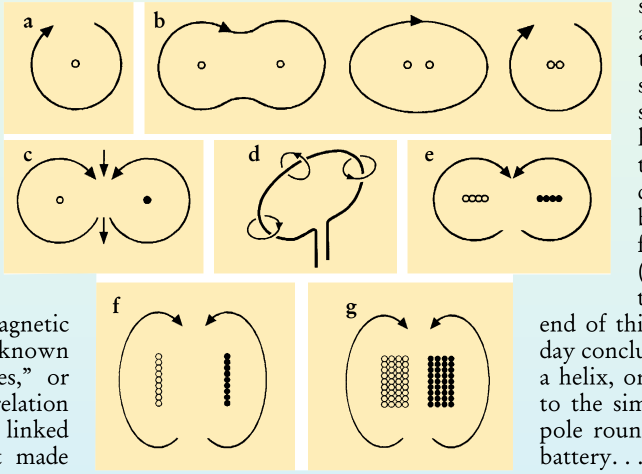
Box 1. Faraday's Synthetic Investigation of Solenoids



Exploratory experimentation has proved successful not only in optics, but also in other fields of physics. In the field of electricity and magnetism, for example, we note the work of Alexander von Humboldt, Johann W. Ritter, and Christoph H. Pfaff in reaction to Luigi Galvani's discovery of animal electricity in the 1790s; André-Marie Ampère's early electromagnetic research in 1820; Julius Plücker's research on discharge in rarefied gases in the mid-1800s; and Wilhelm Röntgen's first investigations of x rays in 1895. A particularly striking case is the work of Goethe's contemporary, Michael Faraday.

Faraday began his electromagnetic investigations in 1821, just a year after Hans Christian Oersted's remarkable discovery of the interaction between the current of a voltaic battery and magnetic needles. Initially, Faraday focused on the behavior of a horizontal magnetic needle suspended near a vertical wire, a problem that Ampère had studied briefly but left unsolved. Faraday found that the traditional language of attraction and repulsion was not adequate to capture the observed behavior of the needle, but that the concept of circular motion—of the wire around a magnetic pole or vice versa—did better. After many attempts, he realized each of the two kinds of rotation experimentally, and later displayed both simultaneously with the device shown above.[13] It remained unclear, however, just how the circular motion was related to other electromagnetic phenomena, such as the well-known magnetic effects of "wire helices," or solenoids. Faraday analyzed the relation by establishing a chain of closely linked effects (see figure at right) that made clear how the solenoidal effect could be obtained by successive variation of the simple case of a pole rotating around a wire. His analysis nicely illustrates his general approach to a whole range of phenomena, including the motions of wires or wire loops toward a nearby magnet, the rotation of a free vertical loop toward an east–west orientation, and the rotation of a cylindrical magnet around its axis when traversed by a current.

Faraday began by varying the conditions of the simple experiment—(a) in the figure—in which a magnetic pole rotates around a wire. Using two parallel wires with variable separation and currents in the same direction (b), he found that the speed of rotation was increased, but that the effect was not fundamentally altered. If, however, the currents were in opposite directions (c), something resembling attraction and repulsion occurred in the symmetry plane between the wires. Faraday recognized that this new effect could be understood simply as a combination of circular motions. The attractive and repulsive effects were intensified when the straight wires were replaced by a loop (d). Further intensification was achieved by forming a spiral, whose cross section is shown in (e), or a cylindrical helix (f), effectively combining the intensifying effects of a doubled wire and a ring. Combining a spiral and a helix finally led to a configuration (g) whose behavior resembled that of a bar magnet. At the end of this series of experiments, Faraday concluded, "Thus the phenomena of a helix, or a solid cylinder, are reduced to the simple rotation of the magnetic pole round the connecting wire of the battery. . . ."[13]



contrast between Newton and the exploratory cases we have discussed. Goethe and Land were interested in color as an irreducible quality, not as an epiphenomenon. Recognizing that the human eye and the external world constitute a complex interactive system, both chose to explore it under diverse aspects, performing literally hundreds of experiments during their careers. The result was a deeper understanding of the complexity of the conditions under which colors appear in the world of everyday experience. Faraday also studied phenomena that exhibited a bewildering diversity and complexity in which many interacting factors played important roles: the shapes of wires; the strength of magnets; the speed and direction of the relative motion between them; and the strength, direction, and time-dependence of currents. Although the laws describing these phenomena may seem simple to us today, this simplicity was not evident to Faraday, who chose to follow an exploratory path.

Theory-oriented and exploratory experimentation are not exclusive categories, but rather members of a spectrum of experimental research strategies. Which is more productive in a given context depends on many factors, including a field's state of development, the sort of knowledge (for example, underlying mechanisms versus phenomenal regularities) sought by the physicist, and the complexity of the system being studied. Our aim in emphasizing the exploratory path has been to bring to light an experimental style that has played an important, but hitherto underrecognized, role in the history of physics.

The authors thank Gérard Bienfait and Catherine Carbonne for assistance with the preparation of figure 2.

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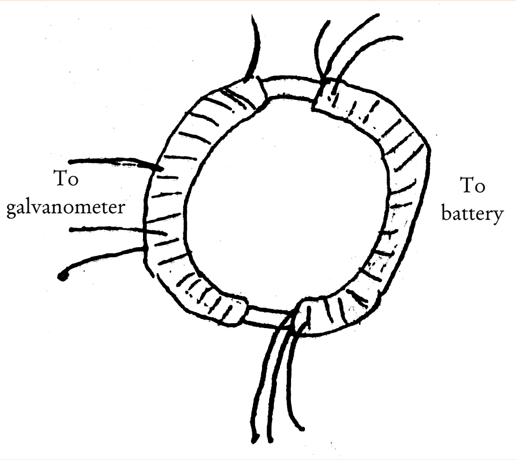
1. The standard edition of Goethe's scientific writings, which contains both *Theory of Colors* and *Contributions to Optics*, is G. Schmidt, W. Troll, L. Wolf, D. Kuhn, W. von Engelhardt, eds., *Die Schriften zur Naturwissenschaft*, Böhlaus, Weimar, Germany (1947–), in particular, vols. 3–6. Modern English translations of portions of *Theory of Colors* and related works can be found in J. W. von Goethe, *Scientific Studies*, D. E.

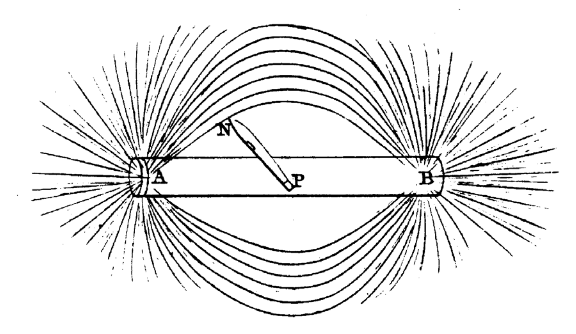
Box 2. Faraday's Analytic Investigation of Induction

On returning to electromagnetic research in 1831 after a nine-year hiatus, Michael Faraday focused on electromagnetic induction, an effect that had been sought in vain since Hans Christian Oersted's discovery that magnetic needles interact with currents. Faraday quickly succeeded in realizing induction in his laboratory, using a soft iron ring with one set of coils connected to a battery and another to a galvanometer, as illustrated in his sketch at left below.[14] But the effect raised many questions. Was the induced current in one coil caused by a magnetism of the ring, a magnetism caused by the current of the second coil, or was there some direct influence between the two coils? And why was induction observed only when the current was switched on or off, and not when the current was steady? Instead of publishing his discovery immediately, Faraday kept it secret and undertook several months of exploratory experimental work. In analyzing the induction of currents by magnets (as opposed to by currents), he varied the magnets' shape and strength, the shape and thickness of the wires, and the overall configuration. Quickly realizing that the relative motion of wire and magnet was an essential factor, he varied both its direction and speed, but the underlying principle still proved elusive. In particular, it was not clear just what features of the apparatus should be used to describe the motion. Faraday tried the magnetic poles, the directions of the wire and the magnet, the compass directions, and even André-Marie Ampère's hypothetical circular currents within the magnet—but in no case could he formulate a regularity consistent with the experimental results. Finally, he tried the set of "magnetic curves" described by iron filings around a magnet (see Faraday's sketch shown to the right), which had long been known but never considered more than a curiosity. Success was immediate: All the experimental results could now be comprehended under a single principle, the "law of electromagnetic induction," which stated that currents were induced when the magnetic curves were "cut by the wire."[15]



Faraday later undertook synthetic investigations in an attempt to deduce other induction effects from the law of electromagnetic induction. In general, synthetic and analytic methods were interwoven in Faraday's work, corroborating, and occasionally conflicting with, each other.

Faraday shared with Goethe more than merely an experimental approach. Just as Goethe made no attempt to theorize about the "hidden" nature of light, so Faraday declined to speculate about the "real" nature of electric currents and magnets. Instead, they both aimed to develop appropriate concepts for formulating phenomenological regularities and, in the process, emphasized the establishment of experimental links between simple and complex phenomena. These methodological similarities were noted by Hermann von Helmholtz in an 1881 lecture on Faraday, in which he stressed Faraday's aim to express only "observable and observed facts, most carefully avoiding any interference of hypothetical elements," and explicitly noted the similarity between Faraday's and Goethe's approaches.[16]



Miller, ed. and trans., Suhrkamp, New York (1988). All Goethe quotes in this article are given in our own translation.
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