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The Development of Newton's Theory of Color

By Richard S. Westfall *

"TO perform my late promise to you, I shall without further ceremony acquaint you, that in the beginning of the Year 1666 (at which time I applyed my self to the grinding of Optick glasses of other figures than Spherical,) I procured me a Triangular glass-Prisme, to try therewith the celebrated Phaenomena of Colours." [1] Thus Isaac Newton, introducing his first paper on light, introduced himself to the scientific world of his day. If the words, as introduction, lead us to look forward, not only to his work in optics, but to the entire career which would see him in the end enthroned as reigning monarch over British science, so also they look backward toward a long tradition of optical research and speculation. The phenomena of colors were, as Newton said, celebrated. When he darkened his chamber to play a spectrum against the wall opposite the window, however, he was not, as the words might be taken to imply, repeating an experiment established in optical tradition. Newton's experiment differed, deliberately, in crucial factors from any that the tradition presented to him. Indeed it was designed to overthrow the received doctrine of colors which the tradition, tracing its descent back some two thousand years, had delivered to him. The planning of the experiment, not its observed results, constituted the revolution in the theory of colors.

The mechanistic philosophy established as the foundation of seventeenth century science by Descartes set the context of Newton's investigation and provided the immediate complex of ideas that his work in optics overturned. The phenomena of light and colors had acquired new significance in the eyes of Descartes and of those following him who saw in the mechanical philosophy the key to the riddles of nature. When Descartes argued that light distinguishes the three basic elements or orders of corpuscles from which *res extensae* are composed, so that bodies are either luminous, transparent, or opaque, he could not fail to be interested in optics.[2] The phenomena of colors, moreover, took on major importance in his attack on Aristotelian real qualities. If we say that we see color in a body, Descartes asserted, it is the same as saying that we see something but are absolutely ignorant as to its nature. We are utterly unable to conceive what it could

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[1] Newton to Oldenburg, 6 February 1671/2; *Isaac Newton's Papers & Letters on Natural Philosophy*, ed. I. Bernard Cohen (Cambridge, Mass., 1958), p. 47.

[2] *Principles of Philosophy*, Part III, 53.

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be as a reality existing outside our minds. We can have clear and distinct knowledge of colors only when we consider them as sensations. If we think that we perceive color in an object, we err in equating the sensation we experience with something we suppose to be in the object.[3] Sensations of color, like other sensations, are merely local motions in our nerves produced by local motions in the world outside. Descartes objected to a distinction made by some Scholastic philosophers between the " real " colors of bodies and the " apparent " colors of the rainbow. Since it is the nature of colors to appear, no valid distinctions can be drawn between the sources of color sensations. Of the local motions that excite sensations and of the sizes and shapes of the bodies moved we can form clear and distinct ideas. We can in no wise comprehend how real qualities such as color, supposed to exist in bodies, can cause local motions in our nerves. Color became virtually the test case of Cartesian metaphysics as it applied to qualities. When Robert Boyle — not a Cartesian really but very much one in this respect — began to publish the histories of qualities by which he intended to support the mechanical philosophy, his *History of Colours* was one of the first in the series. So also to Robert Hooke colors appeared to be of primary importance for the mechanical philosophy.

An inveterate artisan of verbal mechanical models, Descartes employed three mechanical analogies in his treatment of light. The three agree little enough except in their mechanical nature. He explained light first as a pressure transmitted instantaneously through matter. Like the stick by which a blind man " sees " obstacles in his path, the matter of transparent bodies transmits an impulse which produces a sensation in the eye. Second, the impulse we call light is like the tendency of the juice in a barrel of grapes (our mechanic philosopher savours a drop of the organic here) to flow out of a hole in the bottom while the grapes remain stationary. In the third example pressure gives way entirely to motion, and light is compared to a moving ball.[4] To explain the laws of reflection and refraction, Descartes relied on his third analogy; from it he was able to derive for the first time (in print) the law of sines for refraction. Color likewise was explained by the third figure. Some surfaces deaden the motion of the particles of light, as sand destroys the motion of a ball falling into it. Such surfaces appear black. Others, which reflect them without altering anything but direction, appear white. Still others give the particles a spinning motion like that of a tennis ball hit with a chopping stroke; such spinning motions produce the sensations of color.

In the *Dioptrique* Descartes did not attempt to explain color more fully; the theory of the rainbow in the *Meteores* required that he do so. If his explanation of the rainbow were valid, colors must be produced by refraction — by a single refraction which is not reversed by a second one. When a beam that has undergone a single refraction is limited by darkness or shadow, colors are produced. The corpuscles at the edge of the beam find

[3] *Ibid.*, Part I, 68-70.

[4] *Dioptrique*, Discours 1; *Oeuvres de Descartes*, ed. Charles Adam and Paul Tannery, 12 vols. (Paris, 1897-1910), *6*, 83-93.

themselves confined between quiescent particles to one side, and moving ones to the other. The combined pressures operate to change their speed of rotation. If the quiescent particles are on the side toward which the beam is refracted, the particles of light " do not rotate as fast as they move rectilinearly," and blue results. On the opposite side of the beam contrary stresses cause the particles " to turn with more force than to move rectilinearly," and red appears.[5] When the corpuscles turn with a speed equal to their forward velocity (by which Descartes seems to have meant the motion of a rolling ball) light produces the sensation of white. As the speed of rotation increases, colors toward the red end of the spectrum appear; as it decreases, colors toward the blue end. All color sensations can be referred to a common source; a simple rotating motion. Since Descartes held that surfaces reflecting light can impart similar rotations, he considered refraction, not as the sole cause of colors, but as the simplified case allowing analysis.[6]

Light passing through a refracting medium normally undergoes two refractions, one at each of its surfaces; if the surfaces are parallel, as in a pane of glass, the second refraction, in Descartes' opinion, reverses the first and destroys its effect. His problem was to isolate a single refraction, and the prism with one face set perpendicular to the incident ray allowed this to be done.[7] Although the appearance of the prismatic spectrum had been known at least since the age of Seneca and had been a common citation in medieval treatises, Descartes established its role in seventeenth century optics when he saw in the prism the ideal instrument to establish his theory. In designing his experiment, he had one point to demonstrate — that a single refraction generates colors. The details of the experiment naturally derived from its purpose. The prism would have to be moveable so that its face could be set perpendicular to the sun's rays. It would be convenient to have the screen that would receive the image moveable with the prism. Descartes set the prism on a board that was held more or less horizontal. A hole in the board allowed a small beam to pass. A second board, attached perpendicularly to the first and thus roughly vertical, served as the screen to receive the image. Descartes' spectrum thus had a trajectory of only a few inches in which to spread. Since it was intercepted by a screen that cut it at roughly a 45° angle, the possibility of observing dispersion was obscured. The relatively small refracting angle of the prism (30° to 40°) — undoubtedly chosen for its convenience in this arrangement — further obscured the possibility.[8] For all that, Descartes' diagram clearly shows the rays of the spectrum diverging. They diverge, however, at much the angle of convergence of the incident beam from the sun. The diagram shows the rays at one side of the beam incident from one edge of the sun, and those at the other side from the other edge. If he intended the dispersion of the refracted pencil of rays to differ from the 31′ of the incident pencil, the man who had just announced the law of sines had an obvious explanation at hand.

[5] *Les meteores*, Discours 8; *Ibid.*, *6*, 331-4.

[6] *Ibid.*, *6*, 335.

[7] Surely Descartes' insistence on a single refraction that is not destroyed by a contrary one determined one aspect of Newton's *experimentum crucis*; Newton invariably set the second prism in a position opposite to the first.

[8] *Ibid.*, *6*, 329-30. Descartes does not explicitly say that he used boards; they are just opaque slabs which I have assumed to be boards.

In formulating his theory of colors Descartes self-consciously played the rebel, casting out the peripatetic doctrine of qualities and colors in order to substitute a mechanical explanation. Little did the rebel comprehend how closely the bonds of tradition still confined him. Even in rejecting the peripatetic doctrine, he accepted, unquestioned and apparently unperceived, basic assumptions concerning colors. Employed throughout the Scholastic investigations of the rainbow, these assumptions traced their ancestry beyond Aristotle to earlier stages of Greek philosophy.

Aristotle had adopted the theory of Anaximenes to explain the colors of the rainbow. He maintained that the colors appear when sunlight is mixed with the blackness of a cloud. Aristotle's treatment of the rainbow appears to stand in some conflict with his other discussions of light and color. Whereas, in *De Anima,* he considered light to be the instantaneous activity of transparent media and colors the terminating surfaces of visible bodies, he treated light in the *Meteorologica* as a substance modified into colors by the medium through which it passes.[9] The seeming incompatibility of the two positions gave rise to the discussions among the Scholastics as to the reality of the rainbow's colors. One of the problems set for seventeenth century optics by Descartes — and triumphantly solved by Newton — was to find a single explanation for all the phenomena of color. Nevertheless this problem does not materially affect Aristotle's conception of colors, which in either case considers them to be mixtures or compounds.[10] The fundamental assumption of this conception of colors, stated from the point of view of the *Meteorologica,* holds colors to be modifications of pure light. A second assumption equates strength with brilliance. Thus red is considered the nearest approach to white — produced when strong light is modified by a dark medium or reflected from a dark surface. As the strength of light declines and the admixture of darkness increases, there appear first green and finally violet, dark, weak, and the last step before blackness. These three colors Aristotle held to be primary; the other colors are produced by further compounding the three compounds of darkness and light. In accordance with his general treatment of qualities Aristotle's conception of colors bases itself on a third fundamental notion — namely, that all of the colors fall on a scale between the contrary extremes of black and white.[11]

Medieval optics quickly moved beyond Aristotle's understanding of the rainbow. But if it comprehended the production of the bow in a different manner, it did not challenge his doctrine of colors. The seeming embodiment of common sense, it appeared neither to invite questioning nor to require alteration. Grosseteste, for example, defined color as light mixed with a transparent medium (*lumen admixtum cum diaphano*).[12] Media can vary in purity, and light in brilliance and density; from the various combinations of the three variables the different colors arise. Although Albertus Magnus did not accept all of Grosseteste's theory of the formation of the

[9] *De anima,* Bk. ii, 7; *Meteorologica,* Bk. iii, 4.

[10] Cf., *De sensu,* Chap. iii.

[11] *Ibid.,* Chap. vi.

[12] *De iride seu de iride et speculo; Die Philosophischen Werke,* ed. Ludwig Baur, (*Beiträge zur Geschichte der Philosophie des Mittelalters,* 9, Münster i. W., 1912), p. 77.

rainbow, his conception of colors repeated the fundamental Aristotelian ideas.[13] Once again Witelo altered the components of the rainbow's theory without changing the fundamental ideas about color.[14] The theory of color held by Theodoric of Freiberg rested on the same conception, that is, weakening through refraction which allows the admixture of an amount of darkness from the medium.[15] One of the latest repetitions of the modification theory appeared in the optical lectures of Newton's own teacher, Isaac Barrow. White bodies are those that reflect light copiously to all sides, black those that reflect virtually no light. Red bodies reflect a little less than white ones, blue a little more than black. All other colors are mixtures of red and blue.[16] Although Aristotle had maintained the existence of three primary colors, and Theodoric four, Barrow's statement reveals most clearly the ineradicable dualism in a conception which considered that all colors are modifications of pure light by the admixture of darkness. Because the doctrine thought of colors in terms of a scale arranged between the opposing extremes of light (or white) and darkness (or black), neither of which could be measured objectively, it was inherently incapable of mathematical treatment.

Descartes accepted the Aristotelian conception of color also. The notion of strong and weak colors translated itself into a "clear and distinct" mechanical model with such fatal ease that Descartes failed even to perceive what he was doing. The strength of red now had a mechanical equivalent, it is true, the high angular velocity of the particles of light, and the weakness of blue was referred to a low angular velocity. But the colors continued to be ranged on a scale between extremes as indeterminate as Aristotelian black and white — if anything, more indeterminate since they were imaginary velocities of unobservable particles. Perhaps nothing reveals Descartes' submission to the peripatetic tradition more clearly than his treatment of purple. To his eye purple revealed a spark of vivacity and radiance, a touch of *incarnat*, which was wholly incompatible with the languid rotation of the blue corpuscles. Purple appears, he decided, when the combination of forces working to slow down the blue-producing particles causes some of them to flip over. As the hands of a watch turned on its face would appear to one looking through its back to be moving counter-clockwise, so now the initial spinning motion of the particle would be effectively reversed in relation to it neighbors, and the forces earlier working to slow it down would become accelerators. Hence the vivacity of purple on the side of the dullish blues.[17] Descartes' conception of color revealed its agreement with the Aristotelian especially in its continued reliance on the idea of modification. Perhaps it is not wholly fanciful to see in Descartes' condition, that the refracted beam must be terminated by a dark quiescent medium, another facet of his Aristotelian heritage.

[13] A. C. Crombie, *Robert Grosseteste and the Origins of Experimental Science, 1100-1700* (Oxford, 1953), p. 199.

[14] *Ibid.*, pp. 229-31.

[15] *Ibid.*, p. 246; cf. Carl B. Boyer, *The Rainbow: From Myth to Mathematics* (New York and London, 1959), p. 113.

[16] *Lectiones Opticae; Mathematical Works*, ed. W. Whewell (Cambridge, 1860), pp. 107-8.

[17] *Les meteores*, Discours 8; *Oeuvres, 6*, 334.

Descartes' work in optics exercised a peculiar dominion over the minds of investigators in the following generation. On the one hand, the shortcomings of his mechanical model were obvious. Hooke needed only two pages to dismantle it completely, and in fact no significant investigator of optics accepted it. On the other hand, the vision of a mechanical explanation of colors had only to be voiced to become the theme of every important discussion. Those who smashed the Cartesian model proceeded without delay to the construction of their own. And the basic concept of modification remained as unquestioned in the mechanical age as it had in the peripatetic.

Marcus Marci, a writer on optics and the rainbow in the middle of the seventeenth century who was cited at one time as a foreshadower of Newton, held that colors originate in the refraction of light through a prism. " Light is not changed (*mutatur*) into colors except by a certain refraction in a dense medium; and the divers species of colors are the products (*partus*) of refractions." [18]

A more important investigator, Grimaldi, launched a more fully articulated attack on Aristotelian conceptions of light and color than Descartes had done. Light, he maintained, is a substantial fluid propagated at immense, though not infinite, velocity; sensations of colors are excited by vibrations in the fluid. As Descartes had also done, Grimaldi rejected the Aristotelian doctrine of real colors, and one of the primary goals of his investigation was to destroy any distinction between real and apparent colors. Colors are only modifications of light. By various experiments he sought to demonstrate how reflection, refraction, and diffraction (which he discovered) can modify light so as to produce sensations of color. When Grimaldi projected a prismatic spectrum, he too had definite objectives in mind. He had demonstrated already how a simple reflection can generate colors. Now he would prove that a simple refraction can do as much. Instead of a board with a hole in it, Grimaldi blackened one face of his prism leaving only a small spot uncovered. On a screen he received the colored spectrum; clearly simple refraction produces colors. Grimaldi further saw how the prismatic experiment could be analyzed to reveal what the nature of the modification is. He noted explicitly the divergence of the refracted beam. As Descartes' sketch had suggested the phenomena, so it had suggested the explanation, and Grimaldi was too versed in optics to miss it. The apparent diameter of

[18] Cited in L. Rosenfeld, " Marcus Marcis Untersuchungen über das Prisma und ihr Verhältnis zu Newtons Farbentheorie," *Isis, 17* (1932), 327. I have not been able to see a copy of Marci's rare *Thaumantias, Liber de Arcu Coelesti* (Prague, 1648). Inevitably accounts of his work are guided, at least to a considerable extent, by questions different from mine. I have not been able to find a detailed account of his prismatic projection. Apparently, as the quoted sentence would indicate, he equated the production of each color with a definite angle of refraction, in which the light is " condensed " a certain degree. The angle of incidence is the determining factor in this theory, and the spectrum is possible because of the inclination of rays in an incident pencil of light. " Condensed " light is apparently different from intense light. Indeed condensation seems to mean rarefaction, and his conception appears to repeat Witelo's idea of the weakening of light through refraction. The best discussion of Marci's theory of colors that I have seen is found in Boyer, *Rainbow*, pp. 220-1. Cf. Rosenfeld's article cited above and Edmund Hoppe, " Marcus Marci de Kronland," *Archiv für Geschichte der Mathematik, 10* (1927), 282-90.

the sun means that the rays of the incident beam are not parallel, and the law of sines explains the divergence of the refracted beam. The phenomena is, indeed, necessary. Certainly Grimaldi did not consider that it required careful measurement by him for confirmation. But the law of sines suggested a further consequence. Considering three rays in the incident beam, the ray at either edge and the bisector of the included angle, Grimaldi calculated their refractions and concluded that the middle ray no longer bisects in the refracted beam. It emerges closer to one edge. Since the rays incident to one side of the middle ray are still included between that ray and the edge, the refracted beam is more concentrated at one side than at the other. The uneven densities, he argued, introduce tensions as it were within the beam of light, modifying the vibrations that produce sensations of color. As to which side of the beam appears red, tradition offered an obvious explanation: "Therefore, the color red appears in that place where the light is more intense or dense, blue in that where the light is more diffuse and extended; nor can it be doubted that red is more lucid and cheerful than blue . . ." [19]

More clearly than Grimaldi's work, Robert Boyle's investigation of color reveals the importance of optical theory for the mechanical philosophy. His *Experimental History of Colours* fairly radiates Cartesian influence.[20] Employing Descartes' third figure and reflecting his discussion of color, Boyle speaks of "the unimaginably subtile corpuscles that make up the beams of light . . ." [21] The work abounds in reference to "intelligible and mechanical principles," by which he intends to explain colors, "not as the schools by airy qualities, but by real, though extremely minute bodies . . ." [22] Necessarily his argument explicitly denies a distinction between real and apparent colors. Colors are merely sensations stimulated in the optical nerves by certain local motions. By refraction as well as by reflection from opaque surfaces light may be "troubled," that is, modified, in such a way that it arouses a given sensation. To say that a body is colored is only to say that the mechanical arrangement of particles on its surface is such that it modifies light, in reflecting it, in a certain way. As the rest of his generation, Boyle refused to accept the Cartesian mechanical model. In contrast to some, he refrained from constructing another, reserving final judgment until all the evidence was in.[23] On one point, however, there was not apparently any reason to hesitate; when he referred to "modified light, called colour . . . ," a phrase which repeats the outlook of the entire work, he was accepting without question the tradition of common sense handed down through the Aristotelian school.[24]

The philosophical legacy of Descartes had become the common property of all those concerned with optics and colors. Boyle's peculiar interests and

19 Francisco Maria Grimaldi, *Physico-mathesis de lumine, coloribus, et iride* (Bononiae, 1665), pp. 254-62.

20 Its full title is *Experiments and Considerations Touching Colours*; *The Works of the Honourable Robert Boyle*, ed. Thomas Birch, new ed. 6 vols. (London, 1772), *I*, 662-788.

21 *Ibid.*, *I*, 689.

22 *Ibid.*, *I*, 696, 746.

23 *Ibid.*, *I*, 695-6.

24 *Ibid.*, *I*, 670.

his normal Baconian delight in phenomena as such helped to determine the lines along which he exploited his inheritance. As a chemist he was interested primarily in changes in the composition of substances. Most of the *Experimental History of Colours* is devoted to observations relating changes of color to changes in the mechanical arrangement of parts. When he dealt with " emphatical " colors produced by a prism, he was not consciously simplifying the phenomena of color to their clearest example; he was merely adding, ant-like, another grain to the growing heap of experimental evidence. Boyle was interested in colors, any colors. He placed the prism so that the incident beam fell directly on one angle and was thus as it were split in two, with each half refracted by a different face of the prism. By a combination of refractions and internal reflections four irises and four uncolored images emerged. Boyle's eyes seem to shine with delight — here were colors indeed! Far from wishing to simplify the experiment to deal with a single spectrum, he was more apt to desire a version producing eight irises. It is true that Boyle modified the experiment in one instance by covering the face of the prism except for a tiny hole, thus reducing the " prismatical iris into a very narrow compass . . ." The tiny iris thus formed he examined with a microscope — to announce that the colors were apparent even on the microscopic scale. Boyle's purpose in the prismatic experiment was to demonstrate that " emphatical " colors are no less real than, and indeed no different from, other colors. Further reflecting and refracting the image, he recorded, did not cause the iris to lose its colors. One time he reflected the iris to a focus with a concave mirror. Another time he refracted it with a large double-convex burning glass so that " one part of the iris might be made to appear either beyond, or on this side of the other parts of the same iris; but yet the same vivid colours would appear in the displaced part (if I may so term it) as in the other." [25] How nearly these experiments approach to some of Newton's. How nearly — and yet how deep the chasm still to be crossed. Perhaps it was mere chance that he failed in either experiment to bring the iris to a true focus, but it was hardly an accident that he failed to appreciate the fact of differential refraction spread directly before him. Boyle's experiments were performed within a framework of ideas which governed the evidence he sought. His use of the word " iris " to indicate the colored image is indicative of his conceptions. He did not mention divergence of the refracted beam, and the apparent short trajectory (he mentions using the floor to receive the image) did not allow it space to become manifest. Boyle was interested only in demonstrating the reality of prismatic colors — " reality " meaning virtually " durability " in this case — and his experimentation was planned with that in mind. On the following page he proceeded to examine how colored papers appear in candlelight. The entire *Experimental History of Colours* is a fascinating study in Baconian futility. Only when its loving accumulation of facts was replaced by a systematic plan of experimentation inspired by a new idea was the riddle of color solved.

[25] *Ibid., I,* 726-7.

In the same period of a few years during which Boyle was completing his *History of Colours* and Newton initiating his career in experimental optics, Robert Hooke was also investigating colors. Although Hooke presented a brief and devastating critique of the Cartesian theory of colors in his *Micrographia,* he was fully under the domination of the Cartesian vision of nature.[26] In the preface he had proclaimed what the microscope might accomplish — that it might increase mechanical knowledge by enabling men "to discern all the secret workings of Nature, almost in the same manner as we do those that are the productions of Art, and are manag'd by Wheels, and Engines, and Springs, that were devised by humane Wit." [27] The very mechanical genius that picked out the deficiencies of the Cartesian model so keenly would not allow him to stop with destruction. In his optical work at least Hooke seems to be driven by a compulsion to translate ideas into picturable palpable images. He seems unable to do otherwise. The flimsiest evidence sets him at work constructing a model. As in the case of Descartes, his experimentation with colors was guided by that end. "There must be therefore some other propriety of refraction that causes colour," he concluded the critique of Descartes. "And upon the examination of the thing, I cannot conceive any one more general, inseparable, and sufficient, than that which I have before assign'd." [28]

Descartes had lit upon the prism as a means of isolating a single refraction. Although Hooke's observations on thin plates explicitly refuted Descartes' contention that the refractions at two parallel surfaces of a plate cancel each other, he saw the advantage of the prismatic spectrum for analysis. In actual fact Hooke did not employ the prism at this point, but he obtained an identical result by a means Grimaldi had also employed at times. He refracted a beam at the surface of a deep vessel of water and received the image on the bottom. Hooke had already stated his conception of light: it is a swift vibrating motion transmitted through media susceptible of such vibrations. Because the velocity of light varies in different media, refraction renders the front of the pulse oblique to the direction of the beam; and the obliquity causes sensations of color. Hooke's experiment with the spectrum was performed to demonstrate this theory. His sketch of the experiment shows the refracted beam diverging, with the rays at each edge coming, of course, from the two sides of the sun. He was confirmed in his view when he looked up at the sun through the bottom of the beaker and saw one of its edges tinged red and the other blue.[29] According to Hooke's explanation the forward angle of the oblique pulse is "deadened" by the resistance of the dark medium bordering the beam. (Again the role of darkness in modifying light!) The further the pulse moves from the refracting surface, the further the deadness penetrates the ray, and the profile of the refracted beam reveals a triangular dead — inevitably blue — region with its apex at the refracting surface. On the opposite side of the beam, mean-

[26] *Micrographia: or Some Physiological Descriptions of Minute Bodies Made by Magnifying Glasses. With Observations and Inquiries Thereupon* (London, 1665), pp. 60-1.

[27] *Ibid.,* Preface.

[28] *Ibid.,* p. 61.

while, the following edge, its way prepared by the buffeted leading angle, waxes strong and propagates a motion into the adjacent quiescent medium. Hence a triangular strong, red, area is found on the other side of the beam. Hooke was convinced that there are only two primary colors. " Blue is an impression on the Retina of an oblique and confus'd pulse of light, whose weakest part precedes, and whose strongest follows." " Red is an impression on the Retina of an oblique and confus'd pulse of light, whose strongest part precedes, and whose weakest follows." [30] Other colors are compounds of these two. Thus where the two triangular areas in the refracted beam begin to overlap, green appears. Hooke's explanation of the spectrum suggested a means of confirmation by varying the distance of the screen. Unfortunately his use of a water surface instead of a prism imposed a considerable inflexibility. To increase the distance would have been especially difficult; he was using a beaker two feet deep at is was. But Hooke apparently felt no need to press the investigation further; the experiment had served its purpose for him.

It remained for Isaac Newton to challenge the traditional concept of modification. The earliest of his considerations of light and color of which we know is recorded in one of his notebooks.[31] At the time Newton made the notes he had read Descartes' *Dioptrique* and almost certainly his *Meteores* as well. He had read Boyle's *Experimental History of Colours,* the influence of which is perceptible from almost the first notes and citations from it which appear frequently. The notes reflect the state of opinion on colors at that juncture perfectly. They contain a brief refutation of Descartes' conception of light, in which Newton laid bare the difficulties inherent in a conception of light as pressure. Meanwhile the Cartesian influence continued to dominate his approach to colors as his first discussion of them reveals.

> Of Colours.
>
> That darke colours seeme further of y^n light ones may be from hence y^t the beames loose little of theire force i nreflecting from a white body because they are powerfully resisted thereby but a darke body by reason of y^e loosenes of its parts give some admission to y^e light & reflects it but weakly & so y^e reflection from whitenes will be sooner at y^e eye. or else because y^e whit sends beams w^{th} more force to y^e eye & givs it a feircer knock.[32]

As the passage indicates, Newton, like Grimaldi, like Boyle, and like Hooke, was searching for a mechanical explanation of colors — a mechanical explanation, as Descartes had demanded, but a satisfactory mechanical explanation, as Descartes had not supplied. One other thing the passage suggests, and later passages suggest more strongly, that Newton would insist on the rigorous application of mechanical principles. What a quantity of half-baked mechanizing had been generated in the name of science, imaginary frictions producing imaginary rotations, imaginary obliquities imaginatively blunted!

29 *Ibid.,* p. 58.

30 *Ibid.,* p. 64.

31 *Add. 3996,* Univ. Lib., Cambridge; extensive passages from the notebook are cited in A. R. Hall, " Sir Isaac Newton's Note-book, 1661-65," *Cambridge Historical Journal, 9* (1948), 239-50.

32 *Add. 3996,* f. 105v.

The novel feature of Newton's discussion is the serious application of the principles of mechanics on a microscopic scale. Instead of constructing imaginary models, for example, he suggested that colors may appear in prisms because some rays, moving more slowly than others, are refracted at a greater angle. The suggestion might be extended beyond prismatic colors to explain the colors of bodies.

> Hence rednes yellownes &c are made in bodys by stoping y^{e} slowly moved rays wthout much hindering of y^{e} motion of y^{e} swifter rays. & blew greene & purple by diminishing y^{e} motion of y^{e} swifter rays & not of y^{e} slower. Or in some bodys all these colours may arise by diminishing y^{e} motion of all y^{e} rays in greater or lesse geometricall proportion, for y^{n} there will be lesse difference in theire motions y^{n} otherwise [33]

A few sentences later he tried another hypothesis. Supposing the rays of equal velocity but their particles of unequal size, he concluded that they would strike the eye with different impacts.

> Whence supposeing y^{t} there are loose particles in y^{e} pores of a body bearing proportion to y^{e} greater rays, as 9:12: & y^{e} less globulus is in proportion to y^{e} greater as 2:9. y^{e} greater globulus by impringing on such a particle will loose 6/7 ptes of its motion y^{e} less glob: will loose 2/7 parts of its motion & ye remaining motion of y^{e} glob: will have almost such a proportion to one another as their quantitys have. viz. 5/7:1/7::9:1 4/5 w^{ch} is almost 2 y^{e} lesse glob. & such a body may produce blews and purples. But if y^{e} particles on w^{ch} y^{e} globuli reflect are equall to y^{e} lesse globulus it shall loose its motion & y^{e} greater glob: shall loos 2/11 parts of its motion and such a body may be red or yellow [34]

While he was searching for a mechanical explanation of color, Newton had been carried by his own mechanical genius to substitute a new assumption in the discussion. The first of his steps in optics, as the notebook reveals it, saw him break with the conception of modification to try, however tentatively, analysis. That is, he considered the idea that white light may be a mixture out of which the individual colors are separated. In this insight was contained, as it finally proved, the whole of his work in optics.

Of what suggested the idea Newton did not say a word. Nevertheless, the tenor of his entire scientific career pervades the notebook so definitely that conjecture appears reasonable. Instinctive preference for quantitative treatment and insistence on mathematical rigor, where unchecked imagination in model building had held sway, seem to have prompted the suggestions in the notebooks. Mechanical explanations were demanded. Very well, let mechanical principles be employed instead of empty counterfeits in the form of imaginary machines. Would a slow ray and a swift ray be equally refracted by a constant refracting force? Would a small and a large corpuscle rebound with equal force from particles of the same size? The obvious parallel between Newton's final conception of color and the principle of inertia, suggesting the application of mechanics to color, renders this

[33] *Ibid.*, f. 122v.

[34] *Ibid.*, f. 123v.

conjecture more plausible. In a word, the new idea he employed appears hand in hand with more rigorous mechanical and mathematical treatment.

Whatever the cause, Newton had hit upon a new idea. As yet it was only an idea. He treated it as a tentative hypothesis to which he had not committed himself; the examples cited above show him trying a combination of analysis and modification. He tried to apply the idea to the explanation of colored fringes around bodies seen through a prism. Conjecturally he placed two rectangles side by side (abcd and cdsr) and on both he designated the fringe areas next to the common edge (eodc in the rectangle abcd, and cdqp in cdsr). He attempted to compile a chart of the colored fringes when various pairs of colors, generally pairs of contrasting light and dark colors, are placed in abcd and cdsr. An explanation followed:

> 1. Note y^{t} slowly moved rays are refracted more then swift ones
> 2^{dly} If adbc be shaddow and cdsr white then y^{e} slowly moved rays comeing from cdqp will be refracted as if they had come from eodc soe y^{t} y^{e} slowly moved ray being seperated from y^{e} swift ones by refraction, there ariset 2 kinds of colours viz: from y^{e} slow ones blew, sky colour, & purples. from y^{e} swift ones red yellow & from them w^{ch} are neither moved very swift nor slow ariseth greene but from y^{e} slow & swiftly moved rays mingled ariseth white grey & black. whence it is y^{t} cdqp will not appeare red unless qsrp be darke because as many slow rays as come from cdqp & are refracted as if they came from eodc; soe many slow rays come from qsrp & are refracted as if they came from dqpc unless qsrp be darker y^{n} dqpc [35]

Nothing in the passage suggests actual experimentation; Newton seems to be trying merely to explain commonly observed fringes. If the explanation proves anything, it is that simplification and clarity were not to be reached down this road. Evidently Newton found the going as rough as the modern reader does; he did not attempt to follow this approach again.

Rather Newton turned in a different direction and took the second major step in his optical work, condensing the dismaying complexity into a simple experiment.

> 3^{dly} That y^{e} rays w^{ch} make blew are refracted more y^{n} y^{e} rays w^{ch} make red appeares from this experim^{nt} If one hafe of y^{e} thred abc be blew & y^{e} other red & a shade or black body be put behind it then lookeing on y^{e} thred through a prism one halfe of y^{e} thred shall appeare higher y^{n} y^{e} other. & not both in one direct line, by reason of unequall refractions in y^{e} differing colours.[36]

Apparently the colored thread and not the prismatic spectrum was Newton's first observation of differential refraction. Certainly he made a practice of citing the thread experiment with the spectrum in support of his theory. Years later, when Anthony Lucas wrote from Liege challenging Newton, he cited several experiments in support of his case, including a variant of the one with thread. Newton commented in his reply that one of Lucas' experiments, duly performed, was the most conspicuous experiment he

[35] *Ibid.*, f. 122v.

[36] *Ibid.*, f. 122v.

knew, next to the *experimentum crucis,* for demonstrating the differential refraction of light.[37]

If it later took on this importance in his mind, the experiment did not do so at once. Newton had taken up a new idea of major importance. He had confirmed it by an ingenious experiment. He had not, apparently, realized its significance. Following the experiment in the notebook are some of the speculations cited above in which he returned partially to the idea of modification. Finally the discussion trails off into a series of notes on color taken from Boyle. If Newton had discovered " the oddest if not the most considerable detection wch hath hitherto beene made in the operations of Nature," he did not know it.[38]

Newton himself has told us what occasioned a new look at the significance of the thread experiment. He was trying to grind non-spherical lenses to perfect the telescope. It is not hard to imagine the scene when full realization struck. As he pondered the difficult task of generating a non-spherical surface, his mind would have roamed over the problems of optics. Suddenly the significance of the thread experiment for the work he was engaged in would have flashed before him. There is no refracting surface that can bring all of the rays to a focus — that is, there is no such surface if light is a heterogeneous mixture of rays with different refrangibilities. At this point Newton would have begun a systematic investigation. Another notebook records that investigation.[39] It begins with some observations taken from Boyle. Gold leaf, pieces of colored glass, an infusion of lignum nephriticum, each appears of different colors when seen from opposite sides. Newton included the same observations in the paper sent to the Royal Society in 1672 as further examples of the process of analysis by which colored phenomena are produced. In all of them, Newton argued, some rays are transmitted while others are reflected, so that different colors appear on opposite sides. From Boyle's observations he moved on to the thread experiment. Then — his third significant step — he saw the relevance of the prismatic spectrum for his idea.

Newton could hardly have failed to try the projection. Boyle had done it and had called the prism " the usefullest instrument men have yet employed about the contemplation of colours . . ." [40] Descartes and Hooke, among those he had read, and Marci and Grimaldi among the others, had made the prismatic spectrum the central evidence for their theories of color. Newton now perceived that the same experiment must either confirm or deny his new theory, and if it confirmed it, overthrow those of his predecessors. Not the same experiment, however; as others had tailored the experiment to their needs, so also Newton tailored it to his. The first recorded instance of his prismatic projection involved two specific modifications of previous experiments. When earlier investigators had observed

[37] Newton to Oldenburg, 18 August 1676; *The Correspondence of Isaac Newton*, ed. H. W. Turnbull, 6 vols. projected (Cambridge, 1959-continuing), *2*, 80.

[38] Newton to Oldenburg, 18 January 1671/2; *Correspondence*, *1*, 82-3.

[39] *Add. 3975*, pp. 1-20, Univ. Lib., Cambridge; Extensive passages are cited in A. R. Hall, " Further Optical Experiments of Isaac Newton," *Annals of Science*, *11* (1955), 27-43.

[40] *Works*, *I*, 738.

dispersion, they had referred it to the apparent diameter of the sun. When Pardies sent his intelligent comments on Newton's paper to the Royal Society in 1672, he seized upon the same point. Newton was fully aware of this possible explanation of dispersion. He calculated that when the angles of incidence and refraction of the median rays at the two faces of the prism are equal, the effect of the apparent diameter of the sun is neutralized. If the prism is placed at the proper angle with respect to the incident rays, the image ought to be round if all of the rays have the same refrangibility. In the first recorded instance of the experiment Newton stated that the prism was placed so that the rays were " equally refracted " at the two faces of the prism.[41] He also allowed the spectrum enough space to spread out, a trajectory of twenty-two feet where Descartes had permitted a few inches and Hooke two feet. In his paper to the Royal Society Newton wrote that " applying my self to consider them [the colors of the spectrum] more circumspectly, I became surprised to see them in an oblong form; which, according to the received laws of Refraction, I expected should have been circular." [42] The words should be taken as a rhetorical device which is not to be understood literally. The development of his argument in the *Lectiones Opticae* works for the identical effect. First he stated the concept of differential refraction as a premise. He asked then what the shape of the image should be given equal refrangibility (i. e., " according to the received laws of Refraction ") and calculated that it should be round. Finally he introduced the experiment revealing that it is not round and thus upheld the premise originally stated. Newton did not observe an elongated spectrum by accident. He had carefully designed an experiment, convinced, in the light of his earlier observations, that such a result would occur.

Newton's investigations of color had begun within the framework of Cartesian ideas; that is, he too was searching for a mechanical explanation. His deliberations had led him to the discovery of a new property of light which was inextricably interwoven with a complete reformulation of the question of color. At least half of his genius lay in his ability to recognize the distinction between the property and mechanical explanations. Whereas Descartes and Hooke would have broken off the investigation to imagine a mechanical model, Newton was able to keep the two processes separate and to explore the property to its fullest extent. Of course, Newton had an explanation from the very beginning. He held a corpuscular theory of light, and the old tradition of strong and weak colors led him to identify blue with small particles and red with large. In an inattentive moment as he wrote the paper of 1672 he included a reference to the materiality of light, and was as a result plunged into an exchange with Hooke. Various passages in letters following the paper refer to his corpuscular hypothesis, and in 1675 he submitted a version of it to the Royal Society. The paper anticipates his future statements on ether. Newton never surrendered the

[41] *Add. 3975*, p. 2. Newton conducted further experiments in which he narrowed the incident pencil down to 7′ in order to demonstrate differential refraction. On one occasion he performed the experiment with the beam from Venus.

[42] Cohen, ed., *Newton's Papers*, p. 48.

Cartesian vision of a mechanical explanation. But he did see that the new property he had discovered was something entirely distinct. He refused correctly to mix his experimental demonstrations of the property with discussions of its source.

Newton's argument in Part II of the *Lectiones*, and in the popularized version which he sent to the Royal Society, constitutes a reasoned attack on the doctrine of modification. If the fact of differential refraction takes a leading position in the argument, its function is to support more fundamental concepts—that white light (that is to say, normal sunlight) is a heterogeneous mixture, and that the phenomena of color are produced by a process of analysis, whether through refraction or reflection. Thus the observations taken from Boyle that he included in the 1672 paper depend on analysis without refraction. Similarly the ingenious experiments with the colors of thin plates, begun in the notebook investigation, completed in the unpublished *Discourse of Observations* (1675), and ultimately published in the *Opticks*, were intended to demonstrate that analysis explains the colors of bodies as well as it explains the prismatic spectrum. Newton's theory was expounded specifically in refutation of those with which he was most familiar, the theories of Descartes and Hooke. Individual passages in the *Lectiones* and in the paper of 1672 reveal that both men were very much in mind as Newton wrote. The discussion of the prismatic spectrum refers explicitly to their insistence on the necessity of a dark medium limiting the beam, and of course denies it. Newton asked if dispersion might be due to a spinning motion acquired by the corpuscles in refraction which would cause their paths to curve; the reference to Descartes is evident. In a curious passage Newton inquired if dispersion could result from "contingent irregularities" in the glass. Obvious means of eliminating that possibility spring to mind; he could have shifted the prism a little, used another angle, used another prism. Instead he refracted the dispersing beam through a second prism set in reversed position immediately beyond the first; by this means he restored the round white beam and demonstrated that dispersion is the regular product of an ordered cause and not an accidental phenomenon.[43] The experiment was important in the necessary demonstration that white light can be recomposed, but the discussion of it is couched entirely in terms of irregularities in the glass. Passages in Descartes and Hooke, which exploit a similar idea, help to illuminate Newton's procedure. Descartes' explanation of a comet's tail hinges upon the hypothesis that light reflected from the comet is dispersed by a surface in the sky where corpuscles of different sizes meet.[44] Hooke developed a theory

[43] Cohen, ed. *Newton's Papers*, p. 48.

[44] *Le monde*, Chap. xv; *Principles of Philosophy*, Part III. In his early notebook Newton entered a paragraph headed, "Of ye Sunn Starrs & Plannets & Comets" which contained a number of questions about vortices including the following: "Whither Cartes his reflexion will unriddle ye mistery of a Comets bird [beard]." (*Add. 3996*, f. 93v.) Newton's reply to Hooke's criticism of his paper referred explicitly to this point. "Amongst other irregularities I know not what is more obvious to suspect then a fortuitous dilating & spreading of light after some such manner as Des-Cartes hath described in his aethereall refractions for explicating ye Tayle of a Comet . . ." (Newton to Oldenburg, 11 June 1672; *Correspondence, 1*, 178.)

of what he called the inflection of light as it passes through a medium of varying density. He argued that bubbles of heated, rarefied air act as concave lenses, causing beams to diverge. This led him on to suggest that lenses might be perfected to achieve a true focus by varying the density of the glass instead of their figure.[45] Undoubtedly his immoderate claims, in the face of Newton's reflecting telescope, of what he could achieve by refraction were based on this idea. In the light of these passages Newton's discussion of " contingent irregularities " in the prism begins to make sense. Furthermore the famous phrase, *experimentum crucis,* which became almost synonymous with the Newtonian theory, was coined by Hooke in his optical writings. Francis Bacon had referred to an *instantia crucis;* Hooke employed the phrase in his *Micrographia* and extended the notion with the phrase *experimentum crucis.*[46] Newton borrowed it and applied it to the climactic experiment in the paper of 1672. Thus many passages indicate that Newton wrote with Descartes and Hooke in mind. The most important reference to them, however, is not an isolated passage. It is Newton's argument in its entirety, his reasoned refutation of the concept of modification.

In Part II of the *Lectiones Opticae* Newton stated a complete theory of colors. Perhaps the full dimensions of his genius are as visible here as in any of his work. Before any critic had challenged his conclusions, he had foreseen the objections they would raise and provided his answers. In the exchanges that followed publication Newton did achieve a higher degree of clarity and concision in stating the essentials of his theory, at the cost of considerable psychic attrition. But almost all of the material that he now brought forward to support his position had been stated already in the lectures. In many ways the paper of June, 1672, sent in reply to Hooke, displays Newton's experimental power in fuller play than the original paper sent in February. With perfect surety he seized the central issues Hooke had raised and devised brilliant experiments to settle them. Or rather he seemed to devise experiments, for they had all been expounded beforehand in the *Lectiones.* Having thought through the problem completely, Newton had been able to present a fully elaborated theory of color.

Whereas the modification theory held ordinary sunlight to be simple and homogeneous, Newton demonstrated that it is a heterogeneous mixture of what he called difform rays, rays differing in refrangibility, in reflexibility, and in the color they exhibit. One of his clearest statements of the point occurs in a reply to Huygens in 1673.

1. The Sun's light consist of rays differing by indefinite degrees of refrangibility.
2. Rays wch differ in refrangibility, when parted from one another do

[45] *Micrographia,* pp. 220-1, 232-3. Newton's notes on *Micrographia* contain this point. (*Add. 3958.1,* f. 4.)

[46] *Novum Organum,* Bk. ii, Aph. xxxvi; *The Works of Francis Bacon,* ed. James Spedding, Robert Leslie Ellis, and Douglas Denon Heath, 14 vols. (London, 1858-62), *1,* pp. 294 ff. Hooke, *Micrographia,* pp. 54, 59. Perhaps some of Hooke's pique stemmed from the realization that his own phrase had been attached to a demonstration refuting him.

proportionally differ in the colours wch they exhibit. These two Propositions are matter of fact.

3. There are as many simple or homogeneal colours as degrees of refrangibility. For to every degree of refrangibility belongs a different colour by Prop: 2. And that colour is simple . . .
4. Whiteness in all respects like that of the Sun's immediate light & of all ye usuall obects of our senses cannot be compounded of two simple colours alone. . . .
5. Whiteness in all respects like that of the Sun's immediate light cannot be compounded of simple Colours, without an indefinite variety of them.[47]

Men of the seventeenth century did not find this an easy conception to grasp. In 1676, for example, after the issue had been discussed before them over a space of four years, members of the Royal Society could still ask whether rays of light might not owe their exhibition of different colors to their several degrees of velocity "rather than, as Mr. Newton thought, to the several connate degrees of refrangibility in the rays themselves?"[48] In replying to the question Newton tried to settle the matter once and for all.

> *That in any Hypothesis whence ye rays may be supposed to have any originall diversities, whether as to size or figure or motion or force or quality or any thing els imaginable wch may suffice to difference those rays in colour & refrangibility, there is no need to seek for other causes of these effects then those original diversities.* This rule being laid down, I argue thus. In any Hypothesis whatever, light as it comes from ye Sun must be supposed either homogeneal or heterogeneal. If ye last, then is that Hypothesis comprehended in this general rule & so cannot be against me: if the first then must refractions have a power to modify light so as to change it's colorifick qualification & refrangibility; wch is against experience.[49]

All the phenomena of colors are produced, not by the modification of simple light, not by the mixture of light with anything else, but through analysis, by whatever means, of the heterogeneous mixture into its components. Newton maintained that the rectilinear propagation of light can be inflected by two general means, refraction and reflection. When Hooke brought diffraction forward, Newton claimed that it was merely a special case of refraction. Because rays differ in their connate degrees of refrangibility, they are separated by refraction. The experiment with the prismatic spectrum was the principal demonstration of this fact. "And what is said of their refrangibility," he added at the end of his *Discourse of Observations*, in which he investigated the colors in thin plates, "may be understood of their reflexibility: that is, of their dispositions to be reflected, some at a greater, and others at a less thickness of thin plates or bubbles, namely, that those dispositions are also connate with the rays, and immutable . . ."[50]

47 Newton to Oldenburg, 23 June 1673; *Correspondence*, *1*, 293.

48 Thomas Birch, *History of the Royal Society*, *3*, 295; cited in Cohen, ed. *Newton's Papers*, p. 225.

49 Newton to Oldenburg, 15 February 1675/6; *Correspondence*, *1*, 419-20.

50 Cohen, ed. *Newton's Papers*, p. 224.

> For I apprehend [he stated in a letter] that all ye Phaenomena of colours in ye world result from nothing but separations or mixtures of difform rays & that different refrangibility & reflexibility are only ye means by wch those separations or mixtures are made.[51]

In the hypothesis of light Newton reduced reflection and refraction to a single process, the inflection of a rectilinear ray passing through a medium (ether) of varying density. All the phenomena of colors, then, can be traced back to the size of corpuscles constituting the various rays.

> I suppose, that as bodyes of various sizes, densities, or tensions, do by percussion or other action excite sounds of various tones & consequently vibrations in the Air of various bignesse so when the rayes of light, by impinging on the stif refracting Superficies excite vibrations in the aether, those rayes, what ever they be, as they happen to differ in magnitude, strength or vigour, excite vibrations of various bignesses; the biggest, strongest or most potent rayes, the largest vibrations & others shorter, according to their bignesse strength or power, And therefore the ends of the Capillamenta of the optique nerve, wch pave or face the Retina, being such refracting Superficies, when the rayes impinge upon them, they must there excite these vibrations, wch vibrations (like those of Sound in a trunk or trumpet,) will run along the aqueous pores or Crystalline pith of the Capillamenta through the optic Nerves into the sensorium (wch Light itself cannot doe,) & there I suppose, affect the sense with various colours according to their bignesse & mixture; the biggest with the strongest colours, Reds & Yellows; the least with the weakest, blews & violets; the midle with green, & a confusion of all, with white, much after the manner, that in the sense of Hearing Nature makes use of aerial vibrations of severall bignesses to generate Sounds of divers tones, for the Analogy of Nature is to be observed.[52]

Since he agreed that all rays of light have a common velocity, differences in "magnitude, strength or vigour," could only mean differences in the first of these.

One facet of this theory on which Newton insisted is its relation to the law of sines. Once the dispersion of light in refraction was established, the orderly procedure of nature was called into question unless the difform nature of light were admitted. If the contention asserted by Hooke after the paper of 1672 were true, that dispersion is generated in refraction, then refraction is a fortuitous process not governed by law. By applying the law of sines to each species of ray, Newton reaffirmed it.

A necessary consequence of the new theory of color is the immutability of rays. By refraction and reflection they can be mixed and separated, but in their connate properties of refrangibility, reflexibility, and propensity to exhibit a certain color they remain unchanged. The full realization of this consequence, as the argument in Part II of the *Lectiones* reveals, led to the conception of the *experimentum crucis*. The *experimentum crucis* in turn

[51] Newton to Oldenburg, 15 February 1675/6; *Correspondence, 1*, 418.

[52] Newton to Oldenburg, 7 December 1675; *Correspondence, 1*, 376.

became the very anchor of the Newtonian position, which his critics could neither budge nor ignore.

> And therefore, [he concluded] if by refraction, or any other of the aforesaid causes, the difform Rays, latent in such a mixture, be separated, there shall emerge colours different from the colour of the composition. Which colours are not New generated, but only made Apparent by being parted.[53]

Stated in this way, Newton's theory appears as the application of the principle of inertia to the theory of color, especially when it is read in conjunction with the hypothesis of light. Change is merely change of velocity according to the strict rule that F equals ma. Properties of a particle are indifferent to its state of motion, and undergo no changes with it.

The argument of two millenia's standing as to the number of primary colors was terminated with the unexpected answer of infinity. As many degrees of refrangibility as there are between the extreme cases, so many colors there are. And the angle of dispersion is infinitely divisible. Newton designated the individual species of rays, and the single colors they exhibit, with a variety of adjectives — primary, primitive, uncompounded, simple, original, homogeneal.[54] Infinite in number, they fall between the extremes of purple and red on an ordered scale — a discontinuous scale in that each color is a single discrete and immutable entity, a continuous scale in that the steps between them are indefinitely small.

Still more surprising was the treatment of white and black. Formerly the two extremes of the color scale, they were now removed from the scale entirely — and identified. Whereas white had been associated with pure light and colors with mixtures, Newton reversed the positions. White (that is, pure white) can be produced only by a heterogeneous mixture of all the rays. "This I believe hath seemed the most Paradoxicall of all my assertions," he commented, "& met with the most universall and obstinate Prejudice."[55] The *Lectiones* indicate that perhaps Newton himself had found this a difficult conclusion to accept; the longest, most thorough, and most brilliant section of Part II is devoted to it, as though Newton felt obliged to convince himself beyond any possible doubt. By various ingenious methods he analyzed sunlight into its components; by equally ingenious means he reconstituted the original composition. The latter step was mandatory; Newton had to demonstrate that a mixture of the separated rays appears as white if he were to establish his position. In the paper of 1672 he included one of these experiments. He intercepted the rays diverging from a prism with a lens and brought them to a focus. A screen between the lens and the focus displayed the spectrum in reduced form; beyond the focus it displayed the spectrum with the order of colors reversed; at the focus it displayed white. When Hooke challenged this position, Newton added various elaborations to the experiment. If he observed the white focus through a prism, he saw the colors of the spectrum again. When he intercepted one color at the lens, the same color disappeared from the image

[53] Cohen, ed. *Newton's Papers*, p. 54.

[54] *Correspondence, 1*, 180, 287, 291, 293.

[55] Newton to Oldenburg, 7 December 1675 (*Discourse of Observations*); *Correspondence, 1*, 385. Newton deleted this sentence from the final version of the *Discourse*.

seen through the prism. In one of his most beautiful experiments he arranged a cogged wheel between the lens and the focus so that, as it turned, the cogs intercepted some of the converging rays. As the wheel turned slowly, a succession of colors flicked on the screen. When the speed of rotation increased until the succession could no longer be distinguished, the focus again appeared white. White, that is to say, is not to be identified with any single physical entity; it is the sensation produced by a heterogeneous mixture of all the rays. Grey and black differ from it in intensity alone; considered as colors they are identical to white. To demonstrate this point Newton reflected beams of sunlight from colored surfaces onto a white paper. In each case the paper displayed the color of the surface, that is, the color exhibited by the rays that the surface reflected most copiously. When a black surface was used, granting of course that it reflected very little light, the paper displayed white.

In shattering the conception of color as a scale of gradation between opposing qualities, Newton made possible their mathematical treatment. Once again the affinities of his theory with the new philosophy of nature is evident. Light and heavy were no longer considered as opposites, but as degrees of the same quality; the same was true of hot and cold. Newton now identified colors with given rays possessing other objective, measurable qualities. Degrees of refrangibility could be arranged on a single absolute scale, whereas a scale stretching from white to black necessarily lacked an absolute reference. The subjective sensation of color became little more than a convenient symbol to signify the measureable entity.

In both mechanics and mathematics Newton's achievement represents the culmination of earlier work. No predecessor, however, made straight the way for a new theory of color. In the face of a long tradition sanctified by its seeming embodiment of common sense, he was able to recognize its assumptions, conceive of others, and in the end maintain them victoriously. To realize that familiar objects may be conceived in wholly unfamiliar terms is not an easy matter. How difficult an intellectual feat it was is revealed by the case of Descartes, who consciously rejected tradition but was unable to recognize that the dictates of common sense concerning color belonged to the tradition as well. It is revealed also by the reaction to Newton's theory, especially on the part of men like Hooke and Huygens. Even with the theory spread before them supported by experimental proofs they were unable to dispense with the familiar objects of intellectual furniture. Huygens never did accept the new theory. Perhaps it was necessary that Newton should take the initial step, the hardest step, at the very outset of his scientific career, before the tradition had become a part of his nature too intimate to be recognized and considered objectively. Be that as it may, he did take the step, and turned the theory of colors upside down by employing a wholly novel idea. More clearly than anything else in his career, Newton's work in optics reveals his power of original thought.