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CAN THERE BE COLORS IN THE DARK?

PHYSICAL COLOR THEORY BEFORE NEWTON

BY HENRY GUERLAC†

Isaac Newton's first scientific paper, setting forth his epoch-making theory of light and colors, appeared in the *Philosophical Transactions* of the Royal Society of London in February 1672.[1] Newton was barely thirty years old, a young don at Trinity College, Cambridge, where he was destined to remain immured for the next quarter century. Yet several years before submitting his classic paper he had been investigating the problem of colors using what one scholar has called his "instrument of choice," the triangular glass prism. Indeed, not long after his appointment, in the autumn of 1669, as Mr. Lucas's Professor of Mathematics, he devoted his first university lectures to these optical discoveries.[2] Only a sampling of the experiments described in these lectures, or recorded in his earlier notebooks, was drawn upon for his first published paper.

A central thrust of this "New Theory of Light and Colors"[3] was to show that color is derived from light which is not a simple entity but appeared to Newton as composed of, or could be analyzed into, different "colorific" rays. These rays, however one might envisage them, differ in refrangibility, i.e., in the degree to which they are bent in passing from a thin transparent medium like air into a denser medium like water or glass. Having established this fact, Newton then set forth in thirteen numbered propositions his "doctrine" of the origin of colors. As the rays differ in "refrangibility" (a word that Newton here introduced into the English scientific vocabulary), so they differ in their disposition to exhibit this or that color. The relation or "analogy," as he calls it, between colors and the degree of refrangibility he described as "very precise and strict." Colors, Newton clearly recognized, have no extra-mental existence, but are internal sensations of our sensory apparatus evoked by the light from luminous or illuminated bodies.

[1] *Philosophical Transactions of the Royal Society,* No. 80, February 19, 1671/72, 3075-3087. Facsimile repr. in I. Bernard Cohen et al., *Isaac Newton's Papers & Letters on Natural Philosophy* (Cambridge, Mass., 1958; 2nd ed. 1978), 47-59.

[2] The Latin Manuscript (ULC MS. Add. 4002) was published in facsimile by the Cambridge University Library, as *The Unpublished First Version of Isaac Newton's Cambridge Lectures on Optics 1670-1672* (1973). Recently it has been included, with annotations and an English trans., in Alan E. Shapiro, ed., *The Optical Papers of Isaac Newton,* Vol. I (Cambridge, 1984) 46-279.

[3] Newton's communication was a letter to Henry Oldenburg, Secretary of the Royal Society, who in effect gave it a title by describing it as a "New Theory about Light and Colors." The last word used what is now American spelling.

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In his "New Theory" the propositions setting forth Newton's doctrine of color are followed by a curious paragraph that could well puzzle a modern reader. Here Newton wrote: "These things being so, it can no longer be disputed, whether there be colours in the dark, nor whether they be the qualities of the objects we see." The second clause is easily interpreted, for the word "qualities" was a technical term of peripatetic philosophy, a subject Newton had endured as a Cambridge undergraduate and from which, like his more enlightened contemporaries, he was seeking to free himself.[4] Indeed, he was soon to avoid the word "qualities" altogether because of its Aristotelian overtones, favoring instead the word "properties" in replying to the critics of his first paper; more than thirty years later he used it in the opening sentence of his long-delayed *Opticks* (1704).

But what are we to make of the first clause where he asks whether there can be colors in the dark? This has the ring of some earlier philosophical disagreement, and further inquiry will show this to have been the case. Compared to the copious literature on the history of optics, surprisingly little attention has been paid to physical theories of color before Newton and to the role of light in its production. This, presumably, is because color was not considered part of optics, which, from classical antiquity to Newton's day was—like theoretical astronomy, mechanics, and geodesy—considered a branch of the "mixed," or as we would say, "applied," mathematics. Color theory was left to the painters and to the speculative vagaries of philosophers. Newton, with his discovery of the strict relation between color and the degree of refrangibility of solar rays, was the first to show that numbers could be assigned to colors, in a word that color could be quantified and treated with a rigor justifying its inclusion as a part of optics. Indeed, Newton was fully aware of his temerity, for when he delivered the first of his Lucasian lectures early in 1669/70, he felt obliged to explain to his auditors why he planned to discuss in mathematical lectures the nature of colors, "which is considered to have no relation to mathematics."

An introduction to a forthcoming edition of Newton's *Opticks* clearly calls for some background on traditional geometrical optics, and it was not long before I discovered how rich is the rapidly growing literature on the subject, yet how little, and that limited in scope, has been written about the *physical* theories of light and color before Newton.[5] And with good reason. This I shall try in some degree to remedy.

[4] For this passage see E. A. Burtt, *The Metaphysical Foundations of Modern Science* (New York, 1925), 232-233. Burtt concentrated on the second clause, which I believe he misinterpreted, and ignored the first.

[5] For Antiquity see Arthur Erich Haas, "Antike Lichttheorien," in *Archiv für Geschichte der Philosophie,* 20 (1907), 345-386, and the article by David E. Hahm, "Early Hellenistic Theories of Vision and the Perception of Color," in Peter Machamer and Robert Turnbull, ed. *Studies in Perception* (Columbus, Ohio, 1978), 60-95. Useful back-

I. Ideas held by the earliest Greek philosophers concerning light and colors can be traced only in a fragmentary and conjectural way before the extended treatments by Plato and Aristotle. The first theory of vision, which left traces well into the early eighteenth century, has been called the "extromission" or "visual ray" theory. It assumed that we see external objects by virtue of a fire-like emanation from the eye. An early supporter of this theory was the Pythagorean, Alcmeon of Croton (5th century B.C.), who gave as evidence the flashes of light and color seen when the eye is struck.[6] For Empedocles, who held this theory, we have good evidence, since Aristotle quotes ten lines from the former's poem *On Nature,* in which the theory is clearly invoked.[7]

Plato in the *Timaeus* elaborated this doctrine, describing a particulate fire-matter emitted from the eye as an even stream of a substance akin to the light of everyday life.[8] When daylight, a kind of gentle fire, meets this outstreaming substance, like encounters like, and the two coalesce to form the visual ray. Colors, for Plato, are particulate flames given off from every sort of body. These color-particles differ in size. If equal to the components of the visual effluence, they are imperceptible, and the color is called the "transparent" or the "diaphanous," a term that Aristotle was soon to adapt for his own purposes. Larger particles from these bodies contract the compound, yielding the sensation of black, while smaller particles dilate it, producing white. Here would seem to be the origin of Aristotle's doctrine to be described below.

In his *De Sensu,* Aristotle rejects any extromission theory[9] and in so doing makes some interesting and (in some cases, alas, perdurant) assertions. Each of the five senses has its appropriate object; that of our sense of sight is color; color is what we see,[10] just as flavor is the object of our sense of taste. Color is not an effluence from the seeing eye or from the objects we perceive but an incorporeal "form" or "quality"

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ground for color theory in the Middle Ages is in William A. Wallace, O.P., *The Scientific Methodology of Theodoric of Freiberg* (Fribourg, Switzerland, 1959), esp. 132-248, to be cited henceforth as Wallace (1959). For the seventeenth-century, A. I. Sabra's *Theories of Light from Descartes to Newton* (London, 1967) is valuable, but color is treated only in passages devoted to Descartes and Robert Hooke.

[6] The theory has sometimes been credited to other early Pythagoreans.

[7] Aristotle's *De Sensu,* 437b-438a. For English versions see William A. Hammond, *Aristotle's Psychology* (London, 1902), and G.T.R. Ross, ed., Aristotle, *De Sensu and De Memoria* (Cambridge, England, 1906), the translation I have used. For references to light and color in Aristotle's works see H. Bonitz, *Index Aristotelicus* (Berlin, 1870).

[8] *Dialogues of Plato,* trans. Benjamin Jowett, 2 vols. (New York, 1937), II, 26.

[9] Aristotle is not consistent throughout his works. In the *De Caelo* (II, viii, 290a) he writes: "The planets are near, so that our vision reaches them with its powers unimpaired; but in reaching to the fixed stars it is extended too far, and the distance causes it to waver." Similar views are invoked in the *Meteorologica,* III, iv, 373b, 374b.

[10] Modern psychologists agree that what we see is color.

inhering in colored bodies. Light, in some mysterious way, makes colors visible.

But what is light? Light—if you will bear with me, or rather with Aristotle—is not a material entity but the *activity* of a fire-like substance, similar to the aether that pervades the outermost sphere of the heavens. When light enters the transparent medium, the *diaphanous,* the result is color. In the bodies of our daily experience color "is the limit of the transparent medium in a definitely bounded body." This is a definition unlikely to illuminate the modern reader, and I give it only to suggest the veil that Aristotle cast over conceptions of the role of light for nearly two millennia.

There are, nevertheless, some comprehensible, if incorrect, things to put down about Aristotle on color. There are two "fundamental" or "primary" colors, black and white, and all the other chromatic colors we commonly distinguish are derived from these primaries. Note that black and white are *opposite* qualities, just as among flavors sweet and bitter are opposite.

Here, we might mention in passing, are two examples of Aristotle's practice of explaining physical phenomena, and much else, in terms of a polarity of antithetical qualities or powers.[11] This basic approach he sets forth in the *Physics,* citing his Pre-Socratic predecessors who spoke of the wet and the dry, the hot and the cold, and (with Democritus) the full (the atoms) and the empty (the void).[12]

How many colors did Aristotle distinguish? The answer would be seven: white, yellow, red, violet, green, blue, and black. But we should not be deluded into thinking that Aristotle ranked colors in a chromatic sequence like that of a prismatic or diffraction spectrum. His listing does, however, seem to represent a rough scale of brightness or luminosity: from white and yellow at one end to the "dark" colors blue and black at the other.[13] It is evident that Aristotle had in mind the colors of familiar opaque objects, or colored liquids, what the schoolmen were later to call "true" or "genuine" colors, distinguishing them from the ephemeral colors displayed by the rainbow, by the spray of a fountain or waterfall, by prismatic crystals or glass with bevelled edges: the so-called "apparent," "emphatical," "false," or "phantastical" colors. Until the seventeenth century this dichotomy proved a real obstacle to attempts at understanding the physical origin of color and its relation to light.

[11] Harold Cherniss, *Aristotle's Criticism of Pre-Socratic Philosophy* (Baltimore, 1935), 12.

[12] Aristotle, *The Physics,* trans. Wicksteed and Cornford (Loeb Classical Library, I, v. 188a, 19-26). Farther on (188b) we read: "And since the intermediates are compounded in various degrees out of the opposite couple (colors, for instance, out of white and black) it follows that all things that come into existence in the course of nature are either opposites themselves or are compounded of opposites."

[13] Hammond, *Aristotle's Psychology,* 160, n.1.

The only "emphatical" colors mentioned by Aristotle are those of the rainbow which, in his *Meteorologica,* he was the first to study in some detail. He reports (incorrectly) that only three colors—red, green, and blue—are readily distinguished, although yellow can sometimes be seen, but he did note the secondary bow in which the same three colors are in reverse order.

In the corpus of Aristotle's writings, to which the Latin West fell heir, are included several works which, although they possess some marked Aristotelian features, cannot, scholars generally agree, be attributed to the master himself. One of these, the *De Coloribus,* deserves, because of its later influence, more than passing attention. That this treatise on colors is not by Aristotle himself was clear to J. G. Schneider, who in 1818 included excerpts from it in his edition of the works of Theophrastus of Eresus, adding the cautionary subheading: *Vulgo Aristoteli Adscripta.* The careful analysis of Prantl (1849) left little doubt that Aristotle could not have been the author.[14] Recent scholarship has somewhat gingerly attributed it to Theophrastus of Eresus or to one of his devoted pupils.[15]

De Coloribus is a strange agglomeration, containing some astute observations, dubious inferences drawn from meteorological color phenomena, and remarks about the color changes in maturing plants, fruit, the hair of animals, and the plumage of birds.[16] There are major departures from Aristotle's opinions, as when, for example, the author asserts that the "primary" colors are the colors of the four traditional elements: Earth, Air, and Water are white, whereas Fire, like sunlight, is yellow. All other colors are derived from the simple ones by mixing.

It is in treating light, a subject central to our discussion, that *De Coloribus* markedly departs from Aristotle's doctrines. For Aristotle, light is immaterial and without color, whereas our Peripatetic author considers it a material substance that can mix with other substances, force its way through air because of its greater "density," and is reflected from solid surfaces. In *De Coloribus* light has the color of fire, which is the only element visible without the help of any other agency, and it makes all other substances visible. Black or darkness (*schotos*) is not a color but only the privation of light; bodies appear black through the paucity or absence of reflected light. Yet bodies derive their chromatic colors from the "primary" colors when their particles mix with each other or with light.

[14] Carl von Prantl, *Aristoteles über die Farben, erläutert durch ein Uebersicht der Farbenlehre der Altern* (Munich, 1849).

→ H.B. Gottschalk, "The De Coloribus and its Author," *Hermes,* 92 (1964), 59-85. Gottshalk gives an admirable analysis of this treatise and translations of salient passages.

[16] For the Greek text and complete trans. of the *De Coloribus* see "Aristotle on Colours," in Aristotle, *Minor Works,* ed. W.S. Hett (Loeb Classical Library), 4-45. Hahm (1978), 83-84, points to the number of places where *De Coloribus* shows an affinity with Epicurean theory.

For the first time we perceive a suspicion that light must do more than make colors visible: it plays a mysterious part in modifying them, for we read (798b): things appear differently when they are seen in shadow or in sunlight, in a strong or weak light, and according to the angle at which they are seen. In this connection the author of the *De Coloribus* anticipates an observation we shall encounter with the Epicureans, that light striking a bird's plumage from different angles changes its color:

> Birds' feathers too when held to the light at a certain angle appear violet; if still less light falls upon them, they turn a dark greyish brown; but if much light is mixed with their natural black color they turn crimson, and this becomes the color of fire if it is vivid and glittering.[17]

II. In later Antiquity, Euclid and Ptolemy both revert to the older doctrine of extromission. In Euclid's *Optics,* which treated the geometry of the light ray, it made no difference whether the rays come *from* the eye or from the observed object. Color or the role of light did not concern him. But as an exception to my generalization that classical optics did not treat color, there is an *Optics* attributed, but not with certainty, to Ptolemy (Claudius Ptolemaeus), the great mathematical astronomer who flourished about 150 A.D. In this *Optics* color is the subject of a lost Book I. Something of its contents has been reconstructed from allusions to it in the surviving Books of the work.[18] Ptolemy follows Aristotle in many details of his theory of color. Colors are actually *in* the objects we see; they are inherent "qualities" of the things around us, actually *there.* And Ptolemy accepted and reinforced with his prestige the Aristotelian doctrine that there are two "primary" or "principal" colors, white and black, from which the others are derived by mixing. Ptolemy, however, differed from Aristotle's dominant doctrine by conceiving sight as resulting from visual rays emanating from the eye. More trivially, we learn from Olympiodorus in his commentary on the *Meteorologica* of Aristotle that Ptolemy claimed that seven colors, not just three, could be discerned in the rainbow.

There is little need to encapsulate the history of ancient atomism from Democritus to Lucretius, except to point out that for such thinkers, although the atoms themselves are colorless, their arrangement and physical interconnections, which make up the visible bodies, yield us our sensations of color. Yet as Aristotle wrote, colors for Democritus did not have real independent existence. Then how do we perceive colors? If we may adopt the terminology of Newton's friend, the philosopher John Locke, the classical atomists clearly made a distinction between the "primary qualities" (like shape and texture) and "secondary qualities"

[17] Gottschalk, 64. For a stiffer rendering see Aristotle, *Minor Works,* 11.

[18] Albert Lejeune, *Euclide et Ptolémée* (Louvain, 1948). A critical edition of Ptolemy's *Optics* was later published by Lejeune (Louvain, 1956).

like odor, color or taste. These were said to be the result of convention (*nomos*), apparently meaning "mind-dependent" or "in thought," or (as we would say) *subjective.*

This was a major clarification and eventually exerted a profound effect on speculations about color with the revival of Epicurean atomism in the Renaissance and later. But it still left open the question of what physical processes originate and affect our sense organs. One step lay in the abandonment of the "visual ray" theory of vision and the acceptance of an *intromission* theory. Indeed, one form of this was the atomists's well-known theory of visible emanations *from* objects, the *eidola* or *simulacra,* images that travel to the observing eye, conveying the object's shape, motion, and also its color or colors. The *eidola* were conceived as thin films that peel off objects but are constantly replaced; on reaching the eye the *eidola* retain the relative disposition (*rhythmos*), the interconnections of the atoms, and the colors at the surface of bodies.

If we ask what part light plays in all this, the fragments of Democritus tell us nothing, although from Aristotle we learn that Democritus attributed the whiteness of a body to the smoothness of its surface and black to its roughness or (to use a favored seventeenth-century term) its "asperity." There may be here a suggestion that white and black result when light is reflected diversely or absorbed from differently structured surfaces, which indeed was to be the theory of Pierre Gassendi and Robert Boyle. I know of no passage from the early atomists discussing how the intermediate or chromatic colors arise.

The only extended exposition of a theory of colors, relating it to the theory of the *eidola,* is to be found in the famous letter of Epicurus to his friend Herodotus (not, of course, the famous historian). It is a passage primarily concerned both with Aristotle's theory and that of Empedocles and Plato:

> For external things would not stamp on us their own nature of colour and form through the medium of the air which is between them and us, or by means of rays of light or currents of any sort going from us to them, so well as by the entrance into our eyes or minds . . . of certain films coming from the things themselves, these films or outlines being of the same colour or shape as the external things themselves.[19]

Though light is mentioned in passing (as an emanation from the eye), Epicurus is here primarily concerned to refute earlier theories. There is, however, something more interesting, although cryptic, in a surviving fragment from Epicurus's treatise *Against Theophrastus.* This signalized a problem destined to engage the curiosity of later writers. Here Epicurus makes clear that light in some way is involved in the origin of colors:

[19] Diogenes Laertius, *Lives of Eminent Philosophers,* trans. R. D. Hicks, 2 vols (London, 1925 and later reprints), II, 579, in The Loeb Classical Library. Another English version is in Whitney J. Oates, *Stoic and Epicurean Philosophers* (New York, 1940), 6.

"I do not know," the fragment says, "how one should say that things in the dark have colour."[20]

In Lucretius, the Roman popularizer in splendid verse of the Epicurean philosophy, there occurs a striking observation specifically linking our perception of different colors to the role of light rays. In a prose translation it reads:

> . . . since colours cannot exist without light and the first beginnings of things [*primordia rerum,* i.e. the atoms] do not come into the light, you may be sure that they are clothed with no colour. For what colour can there be in total darkness?

And Lucretius continued with an observation that the colors of the feathers of birds change when light is reflected to the observer from different angles:

> After this fashion the down which encircles and crowns the nape and throat of doves shows itself in the sun; at one time it is ruddy with the hue of bright pyropus; at another it appears by a certain way of looking at it to blend with coral-red green emeralds. The tail of a peacock when it is saturated with abundant light, changes in like fashion its colours as it turns about. And since *these colours are begotten by a certain strike of light, sure enough you must believe they cannot be produced without it.*[21]

This passage, although few classical scholars seem to have noted its portent, was later to be familiar to seventeenth-century investigators of the mysterious problem of color.

III. In the early Middle Ages in the West (where I do not propose to linger) the only available texts on the subject of the physics of color and vision were portions of Plato's *Timaeus* rendered into Latin in the 4th century A.D. by Chalcidius and some passages in St. Augustine. Aristotle's views on colors were not appreciated until the full corpus of his works, including the *De Anima* and the *De Sensu,* were translated, along with the classical commentators, in the 12th and 13th centuries, and when Thomas Aquinas produced, along with much else, a commentary on the *De Sensu.* It was much later that the writings of the Epicurean atomists gained currency.

At roughly the same time as the Greek writings were translated the optical studies by Arab scientists became available in Latin versions. For mathematical and experimental optics the single most important author was Ibn Al-Haytham, known in the West as Alhazen. His *Optics,* given its Latin titles of *Perspectiva* or *De Aspectibus,* was for the later Middle

[20] Epicurus, "Fragment against Theophrastus," in Oates, 45. For the notion that colors result from the mixing of light with air see Epicurus, "Letter to Pythocles," in Oates, 25.

[21] Oates, 106. Pyropus, or pyrope, is a deep red species of garnet. The emphasis in the last sentence is mine.

Ages the most influential stimulus for the mathematical and experimental study of light and vision. Alhazen was frequently cited by later optical writers, among them Roger Bacon. But on color Alhazen had little to offer beyond the prescient statement that the form of color "is always intermingled with the form of light,"[22] quoted by Roger Bacon, who derived from Alhazen and Avicenna the view that nothing is seen without light and that color does not have a real existence in darkness.[23] On this question scholars were divided. Averroës led the opponents of Avicenna and insisted that colors *do* exist in the dark. Albertus Magnus, invoking the distinction between material and formal causes which Aristotle had made, chose a middle path and urged that the material differences in bodies, which underlie their different colors, are present not only in light but in darkness; yet to supply the "form" of colors, that is, to actualize them, light is essential. Albert concludes therefore that colors can exist in the dark, but only potentially. A similar position was taken by Thomas Aquinas, who adhered to Aristotle's definition of color and reasoned "that since bodies have no actual surfaces in their interior (only potential ones), they are not colored on the inside except potentially." Yet light, as Thomas put it, is in a certain sense the "substance of color" (*substantia coloris*).

Dietrich of Freiburg (d. *ca.* 1310), one of the notable figures in the history of medieval optics, is perhaps best remembered for his study of the rainbow, his *De Iride.*[24] His small treatise on colors, the *De Coloribus,* was written as an explanatory appendix to the *De Iride.*[25] Aristotle was his principal authority, but he drew significantly from Alhazen, whom he cites as *auctor perspectiva,* to the effect that color does not affect vision without light, nor does light affect vision without color. His definition of light is essentially Aristotelian: it is a real quality or form of the diaphanous. Dietrich's *De Coloribus,* an introduction to the problem of color, opens by taking up the question "that has been greatly agitated among his predecessors and contemporaries: which is, whether colours can exist in the dark." Dietrich's debt to Aristotle and, closer at hand, to Albertus Magnus, is quite apparent, although veiled in his cumbrous terminology. For Dietrich, as Father Wallace puts it, "one can truly say that colors do not exist in darkness, in the sense that they have not been brought to actuality from their accidental potency, and yet one can maintain that they do exist in darkness in the sense that they are already

[22] Wallace (1959), 138 and n. 1. See note 5 above.

[23] *The Opus Majus of Roger Bacon,* trans. Robert Belle Burke, 2 vols. (Philadelphia, 1928), II, 473. But see note 27 below.

[24] For Dietrich (or Theodoric) of Freiberg see Wallace (1959) and the same author's account in the *Dictionary of Scientific Biography,* ed. Charles Coulston Gillispie Vol. IV (1971), 92-94, with bibliography.

[25] Dietrich's opuscule *De Coloribus* is analyzed, with appropriate background, in Wallace (1959), 163-173. The Latin text is in Appendix III, 364-376.

outside their essential potency, and need only an accidental mover [the light] to be actualized."[26]

If we turn to classical atomism, the only sources for the medieval scholar were the critical references to Democritus in Aristotle. Yet, in the 5th century, fragments of the ancient natural philosophy of atomism appeared in the treatise on the Seven Liberal Arts by Martianus Capella, a work very popular in the Middle Ages. In the listing of the philosophers assembled for the marriage of Mercury and Philology, the central and symbolic episode, there is a facetious reference to Democritus, described as "surrounded by atoms," and to Epicurus, about whom the Middle Ages remained largely ignorant until the translation into Latin, early in the 15th century, of the *Lives of the Eminent Philosophers* by Diogenes Laertius and its first printing in 1475.

As a popularizer of Epicurus's physical philosophy Lucretius was unknown to the Middle Ages, or so it has been generally believed. Yet he was often quoted (perhaps following Macrobius, a later Roman writer) as a poetic influence upon Virgil. Indeed Macrobius gives some forty citations where Lucretius is seen as anticipating, and probably influencing, Virgil's prosody. In Seneca, whose *Naturales Questiones* was familiar to the Latin Middle Ages, there is a passage that might ultimately derive from Lucretius on color. Seneca quotes from a poem, which he attributed to his patron, the Emperor Nero, in which the neck of a dove is said to "glisten" when the bird moves about. Seneca follows this with the remark that the *neck* of a peacock (no mention of the spectacular tail) also "gleams" when it moves. Of course these could have been everyday observations, but Lucretius might have been the source. There is no reference as in Lucretius, however, to changing colors.

A full acquaintance with the Lucretian poem is generally thought to have awaited the discovery by Poggio Bracciolini, about 1417, of a manuscript of the *De Rerum natura.* A corollary is that the lines referring to color which I have cited above from the great poem could not have been known before Poggio's discovery. Or so I believed on first noting their significance. But not long ago evidence, ready at hand, suggested that this was not the case. Roger Bacon's *Opus Majus,* written before 1267 (the year he sent a copy to the Pope), has some sentences strongly suggesting that the lines quoted above from Lucretius were known to him. Here, as in Lucretius, the intimate role of light in the production of the different chromatic colors is clearly suggested. Roger writes:

that in accordance with the diversity of the fall of the same light on the same object the aspect is changed, and the color appears different to the vision, as in

[26] Wallace (1959), 166. Elsewhere Wallace writes: "The existence of colors in darkness and at the interior of bodies were much discussed questions because they touched upon the mysterious and very intimate relation which apparently existed between light and color" (*ibid.,* 152).

the case of the dove's neck when it turns the neck in different positions to the light, and so too in the case of the peacock's tail.[27]

Roger goes on to remark that without light nothing is seen. No great discovery, to be sure, in view of the gradual approach by his scholastic predecessors to the true solution. But even more clearly than Lucretius he is telling us that light is somehow directly involved in the production of colors.

Needless to say, Aristotle's old theory of color, subject to various minor modifications, remained dominant during the sixteenth century, despite growing anti-Aristotelianism and the emerging popularity of corpuscular theories. René Descartes, a *chef de file* of the burgeoning anti-Aristotelian movement, was quite familiar with classical atomism, for the notion of a void is several times attacked in his correspondence. Yet as his theories of matter testify, he was, in a broad sense, a corpuscularian.

On the subject of light and color, as on other matters, Descartes was a revolutionary figure. He rejected both what he had learned from his conservative teachers at the school of La Flèche and from the atomists. He urged his readers to reject "those little flying images, called intentional species, which so torment the imagination of Philosophers," as well as the *simulacra* of the atomists. For them he substituted a view of light fitted to his mechanically conceived universe. The light (*lumen*) that originates in luminous or light-emitting bodies is simply a rapid circular motion which passes to us as an impulse through the globules of his "second element," reaching us from the sun or the stars "in an instant." This light (*lux*) is not a material entity but a "tendency to motion" passed along by the closely-packed globules. We can visualize these as a compact chain of tiny spheres connecting us, along our line of sight, with the source of light.

Descartes's contributions to optics are contained in two treatises appended to his famous *Discours de la méthode* (1637). The *Dioptrique* dealt with geometrical optics and the design of telescopic lenses and had little or nothing to say about color. But in the *Météores,* where Descartes works out the geometry of the sun's rays in producing a rainbow, he is obliged to confront the problem of the nature of light and color.[28] Here, as in other scattered texts, we find him an important precursor of, and doubtless to some degree an influence upon, Isaac Newton. In the first place, he appears as the earliest modern figure to recognize that light is

[27] Roger Bacon, *Opus Majus,* trans. Burke, II, 450. See also 557. Alhazen may have been an influence, for under a passage headed "Color varies according to the quality of light," we read that the feathers of a peacock and a silk cloth, where green is mixed with dark red, change color when seen at different times of day, according to the difference in the light striking them. See the Latin in Friedrich Risner, ed. *Opticae Thesaurus,* (Basel, 1572), 2-3.

[28] Both reprinted in *Oeuvres de Descartes,* eds. Adam and Tannery, VI, 1-228, 231-366.

not merely an auxiliary agent making colors visible to us but *the true source of color.* He is the first as well to insist that color is color and to attack the scholastic philosophers for their sharp distinction between "true" colors and those that are merely "apparent," "false," or "emphatical," like the colors of the rainbow.

In the *Météores,* accompanying his classic analysis of the rainbow's formation, Descartes reports two experiments to illustrate what happens in a raindrop. The first, whether or not he was aware of it, had been performed long before by Dietrich of Freiberg. Passing a beam of the sun's light through a transparent sphere of glass filled with water that acted as an isolated and magnified raindrop, Descartes, like Dietrich, was able to show that the beam suffered two refractions and one reflection in passing into and out of a raindrop. This, of course, did not explain how the colors originate.

Aware that "emphatical" colors like those of a rainbow could be produced by a triangular glass prism, Descartes was the first, so far as I can discover, to undertake *and publish* a serious prismatic experiment. If a beam of the sun's light after passing through a prism is admitted through a narrow aperture, it forms a colored image on a vertical paper, with the red appearing at one extremity of the image and blue or violet at the other. But this is true only if the aperture is small enough; if it was too wide, all Descartes obtained was a white image. Influenced by the still prevailing Aristotelian idea that colors are produced by a mixture of black and white (or light and shadow), he noted that quite different colors were seen at the extremities of the image, where the beam of light grazed the region of shadow. To explain this effect he had recourse to a mechanical model. For him, we recall, light is only an impulse or tendency to motion transmitted by the subtle second matter which itself has no translation motion. Colors, he imagined, could be produced by giving the subtle matter a rotation. The spin producing red is swifter than the spin yielding blue or violet. Intermediate rates of spin give the intermediate colors. Descartes was aware that refraction was somehow a cause of what the scholastics had called the "emphatical" colors, but he applied his theory also to explain the "true" colors of objects, where shadows and refraction were not involved. In their stead the size, shape, situation, and motion "of the parts of bodies we call colored can interact in diverse ways to increase or decrease the rotation of the subtle matter."[29]

IV. Three seventeenth-century scholars are specially important to us as forerunners of Newton and influences upon his thought about light and color: Pierre Gassendi (1592-1655), Gassendi's English disciple Walter Charleton, and Robert Boyle (1627-1691). Gassendi has not received his due from philosophers or historians of science, especially from de-

[29] *Oeuvres de Descartes,* VI, 335.

votees of Descartes, whose chief antagonist he was.[30] Gassendi was born in a small village a few miles from Digne, a dreary, sulphurous watering place in the Alps of upper Provence. He had his advanced education at the University of Aix-en-Provence and taught philosophy there with a wide-ranging curiosity and an independence of mind uncommon in the universities of his day. He became a canon and later (in 1634) Provost of the church at Digne.

As firmly anti-Aristotelianism as Descartes, Gassendi took a quite different route, becoming the first influential philosopher of atomism in the modern world. His early interest in Epicurus, with his hope of rehabilitating that Greek thinker's reputation (for Epicurus had been widely proscribed as a hedonistic materialist), was only an aspect of his anti-Aristotelian strategy. The first publication to reveal his conversion to atomism was a small tract published in 1642 on the apparent size of the sun when viewed near the horizon or near the zenith. In this early work, as Robert Boyle was to remark, "The most Learned *Gassendus*" has some passages towards "reviving the Atomical philosophy."[31] Gassendi's first Epicurean work, his *Observations on the Tenth Book of Diogenes Laertius,* published in 1649, treats the life, character, and ethical views of Epicurus, revealing in its title his chief literary source.

Gassendi's atomistic theories are fully set forth in his major work, the *Syntagma philosophicum,* which treats logic, physics (in the seventeenth-century meaning of the word), and ethics. It was published posthumously in the first two volumes of his collected works brought out by friends in 1658. His atomic theory adheres closely to the classical model, and I need not trouble you with it, except to note that he rejects, doubtless in the interest of piety, the notorious "swerve" (*clinamen*) with which Epicurus endowed his atoms.

His physical theory of color, on the other hand, is central to our story, since it indirectly influenced the young Isaac Newton through the works of Walter Charleton and Robert Boyle. Abandoning Aristotle, Gassendi conceived light as a material efflux streaming out of luminous bodies like the sun and the fixed stars, or from an earthly fire, and either propagated directly to us or reflected from other bodies. He rejects the *eidola,* those images that are propagated from luminous or illuminated bodies. For Gassendi they are nothing but light itself; for him light consists of a stream of very fine corpuscles transmitted to us with an incomprehensible speed (*pernicitate ineffabili*) to move our organ of vision. These

[30] As, for example, Alexandre Koyré's picture of Gassendi as "pas un grand savant" in *Actes du Congrès du Tricentenaire de Pierre Gassendi* (Digne, 1957), 175-190. The leading studies on Gassendi are by Bernard Rochot, *Les travaux de Gassendi sur Epicure et sur l'atomisme* (Paris, 1944) and his article in the *Dictionary of Scientific Biography,* V, 1972, with more up-to-date bibliography.

[31] Robert Boyle, *Experiments and Considerations Touching Colours* (London, 1664), 94-95.

fine corpuscles are tiny spheres which, unlike the second element of Descartes, have a translational motion through the void or through air.

Like Descartes, his illustrious opponent, whose support he was willing to invoke on this score, Gassendi firmly rejects the scholastic habit of distinguishing between "true" and "false" or "fantastical" colors. Color is color. And more bluntly than Descartes he states that the essence of color is from the light itself. Light as it originates (*in sua fonte*), undisturbed and unmodified, gives the sensation of white. Black is simply the absence of white light. What of the chromatic colors? To support his view that they are modifications of white light Gassendi cites at length the lines from the *De Rerum natura* already echoed, as we saw, in Roger Bacon, where Lucretius remarks upon the changing color of a dove's neck and of a peacock's tail as the position of the bird or the observer changes.

Gassendi could not accept, as did so many of his contemporaries, the Aristotelian view that the various colors arise from different mixtures of black and white or light and shade. The only result of such mixtures would merely be varying degrees of grey. But since in fact other colors exist, they must be accounted for. Here Gassendi is understandably vague. He invokes different reflections and refractions which affect the different greys and alter the motions or directions (*tenores*) of the rays, thereby confusing the sensorium and producing in us different color sensations.

We must now turn to the person who first brought Gassendi's speculations to England, the physician Walter Charleton. Shortly after taking his medical degree he received, at the onset of the civil war, the short-lived appointment of physician-in-ordinary to Charles I. After the King's execution Charleton turned his talents, such as they were, to writing on medical and other subjects. In the early 1650s, probably under the influence of Thomas Hobbes, he was attracted to the rival exponents of a "New Philosophy," Descartes and Gassendi. In 1654 appeared Charleton's major work, an attempt to present the views of Gassendi and his atomic theories to the English public. Entitled *Physiologia Epicuro-Gassendo-Charletoniana,* with the subtitle "A Fabrick of Science Natural, upon the Hypothesis of Atoms," the subject is further described on the title-page as "Founded" by Epicurus, "Repaired" by Petrus Gassendus, and "Augmented" by Walter Charleton.[32] The book is a hard read: the English is so dreadfully Latinized that it is almost difficult to tell, at some points, in which language he believed himself to be thinking.

Charleton introduces his section dealing with light and color with an account of early theories, remarking that most of the "sects" seem "as remote from each other, as the Zenith from the Nadir," so he had no need to justify his "Adherence to that more verisimilous Doctrine of

[32] Reprinted in facsimile, with an Introduction by Robert H. Kargon, as *The Sources of Science,* No. 31 (Johnson Reprint Corporation, New York and London, 1966).

Democritus and *Epicurus*,"[33] where the atoms are without color and bodies differ in color owing to their surface textures and their influence upon, or modification of, the rays of light. Those rays, Charleston clearly states, are streams of minute particles either emitted directly from their source or "fountain" or reflected from the surfaces of bodies where they are influenced by the excrescences and cavities found there.

At considerable length Charleton argues, as had Gassendi, against the "*Distinction of Colours* into *Real* or *Inhaerent,* and *False* or only *Apparent,* so much celebrated by the Schools" (*ibid.,* 187, Art. 4). The former are the colors of different opaque bodies; the latter are evanescent colors "such as those in the Rainbow, Parheliaes, Paraselens, the trains of Peacocks, necks of Doves, Mallards, &c." (188, Art. 4). To this category belong the colors produced "by *Prisms* or *Triangular Glasses,* vulgarly called *Fools Paradises,*" which sometimes appear less real than others reputed to be only apparent (188, Art. 5). All these must nevertheless be considered real, "being equally produced by Light and Shadow gradually intermixt."

Charleton sums up his discussion by affirming that the difference between evanescent and "durable" colors is that the former derive from light *refracted* by transparent bodies, while the latter are *reflected* from opaque ones whose surface particles "are of this or that Figure, Ordination, and Disposition." Colors, in any case, are not "inhaering" qualities of bodies (189, Art. 1).

At greater length than might seem necessary Charleton discusses that "so Paradoxical assertion" (those are his words) of Epicurus that there are no colors in the dark. Unaware of the complex nature of light, yet believing that in some fashion white light is "modified" to produce "intermediate" colors (i.e., the chromatic colors between the extremes of white and black), he sets forth his position in words that display, in their Latinate English, his inescapable debt to Aristotle. Since all colors vanish in the absence, "the Amotion or defection of Light," he continues, "we are to observe that it is one thing to be *Actually* Colorate, and another to be only *Potentially,* or to have a *Disposition* to exhibit this or that particular Colour, upon the access of the Producent, Light."

Although we agree that bodies are without color in the dark, yet they retain a capacity "whereby each one, upon the access and sollicitation of Light, may appear clad in this or that particular Colour, respective to the determinate ordination and Position of its superficial particles" (186, Art. 1).

Our disciple of Gassendi does not hesitate to advance his own theory of color. In speaking about what, after Newton's introduction of the word into our language, we call the prismatic *spectrum,* he struggles, not too successfully, to explain the production of color as the result of different

[33] Charleton, *Physiologia,* p. 184, Art. 6.

proportions of light mingled with shadow. He ends by confessing that the foundation of his theory of color is "not layed in the rock of absolute Demonstration . . . but in the softer mould of meer *Conjecture*" (196, Art. 10). He adopts, of course, the corpuscular theory of light that Gassendi had put forward but does not pretend to know what are the proper figures and essential qualities of the insensible particles of light, with what kind of motion they are radiated from a luminous source, what are the "determinate" positions and shapes of the reflecting and refracting particles at the surface of opaque or diaphanous bodies "which modifie the Light into this or that species of Colour," or "what are the precise proportions of shadows, interwoven with Light, which disguise it into this or that colour" (197, Art. 10).

Let me justify the space given to Charleton, a figure of far lesser worth than Descartes, Gassendi, and Robert Boyle, with whom I shall conclude. It is through Charleton and Boyle rather than from Gassendi's own writings that Newton was led to a corpuscular theory of light and an atomic theory of matter and—most important of all—the realization that light is the "producent," as Charleton put it, of all color. I do not doubt that it was from Walter Charleton that Newton learned of that "so paradoxical assertion" of Epicurus which was echoed in his first paper: that there are no colors in the dark.

The Honourable Robert Boyle, scion of a notable Anglo-Irish family, was one of the founding Fellows of the Royal Society of London and from the beginning a member of its Council. The year of the Society's foundation (1662) saw the appearance of the second edition of Boyle's *Spring of the Air,* to which was added an appendix with the experiments and table we summarize as "Boyle's Law," relating the pressure and volume of air (at constant temperature) and demonstrating quantitatively the elasticity or "spring" of the air. Two years later Boyle brought out a book that was soon to exert a profound influence upon the young Newton, the *Experiments and Considerations Touching Colours* (1664).

Boyle's book on color is something of a miscellany, a collection of his observations on the many different ways that colors can be observed. His chemical interest is very much in evidence, and there is a section on painter's pigments. Theoretical conjectures are widely scattered. He draws upon Gassendi in a number of places, notably for the corpuscular theory of matter and the corpuscular theory of light. The immediate cause of colors is "the modifi'd Light it self, as it affects the Sensory." Colors are not to be thought of as *inherent* in the object, although light can be influenced by the surface texture of objects and so appear colored when reflected to our eyes.

In Isaac Newton's earliest notebooks we find records of his reading of Boyle on colors, and these records, or at least some of them, are echoed in his classic paper of February 1672 and in the *Opticks* itself. Certain of Boyle's observations Newton adduced in support of his own radical

theory of the composite nature of white solar light, for example, the peculiar property of gold leaf (Boyle called it "foliated gold" such as apothecaries used to gild pills), or an infusion of that rare and exotic wood *lignum nephriticum* (nephritic wood), which had the curious characteristic of appearing a different color by reflected and by transmitted light. Boyle suggested that transmitted light was "so Temper'd with Shadow, and Modify'd, that the Eye discern'd no more a Golden Colour, but a Greenish Blew."[34] For Newton, on the other hand, these substances are "apt to reflect one sort of light," i.e., one sort of colorific ray, "and transmit another," as he reported in his paper of February 1672.

Perhaps the most important influence of Boyle on Newton was where the former, in one place, described a prism as "the usefullest Instrument Men have yet imploy'd about the Contemplation of Colours." Again he describes it as "the Instrument upon whose effects we may the most Commodiously speculate the Nature of Emphatical Colours (and perhaps that of others too)." Fully as significant is that he urges his reader to use his prism in a darkened room "not (as is usual) in an ordinary Inlightn'd Room."[35]

V. We may now summarize the state of knowledge of the relation of light to color when Newton came upon the scene. The more emancipated thinkers no longer believed that colors have an independent external existence or that they are inherent "qualities" or "forms" that light merely makes visible. The artificial distinction between "real" and "emphatical" colors has been abandoned. Light is increasingly thought to be material or the activity of a material substrate, as in the theories of Descartes and later of Robert Hooke, whose "wave" or pulse theory of light was set forth in his *Micrographia* (1665). Both recognized, as Newton too made clear in his *Opticks,* that color, in any case, was not an objective reality but a subjective response of our visual equipment. Light was increasingly understood to be the chief causative agent of our sensation of color. Aristotle's venerable explanation that the chromatic colors derived from a varied mixture of the two "fundamental" colors, black and white, was still very much alive, expressed most often as the mixture of light and shadow. The colors seen on the surface of bodies, or produced by refraction, result from an alteration or *modification* of the pure, homogeneous light of the sun, generally when the light is mixed with shadow. It will be one of Newton's chief objectives in his *Opticks* to show by various experiments that this hypothesis is untenable.

That light is the principal agent in the production of our color sensation was implied by the ancient atomists, as recorded in the fragment of Epicurus *Against Theophrastus* and in Lucretius's great poem when

[34] Boyle, *Experiments,* 198-99.
[35] *Ibid.,* 191.

writing of the color changes in the neck of a dove or the tail of a peacock. As we saw, this Lucretian passage left its imprint on Roger Bacon and was quoted by Pierre Gassendi and Walter Charleton. Robert Hooke, the first to publish careful observations on the rings of color observed in thin films and plated bodies—"Newton's rings" we call them—saw a similarity between these rings and "the Colours in Peacocks, or other Feathers," but recognized that these color phenomena could better be studied in the plates of "Muscovy glass" (mica), where he had observed them, since "this laminated body is more simple and regular . . . and more manageable, to be divided or joyned, then [*sic*] the parts of a Peacocks feather."[36]

Newton went further than mentioning a mere similarity between the colored rings observed in thin films and the spectacle of a peacock's tail. He would seem to have carried out experiments on the colored rings independently of Hooke and with an ingenuity and degree of precision that justifies our naming the rings after him. In one of his early notebooks Newton recorded that, in observing the colors produced by a thin film of air between two glasses, he found that the colored rings appeared greater the more obliquely he observed them. Later, when taking notes on Hooke's *Micrographia,* he recalled his earlier observation, adding the comment: "The more oblique position of ye eye to ye glasse makes ye coloured circles dilate."[37] Long after, Newton devoted the greater part of Book Two of the *Opticks* to the ring phenomenon in thin films or plates, and his early observation on the effect of the angle of vision was elaborated into Observations 7 and 19 of the first Part of that Book. In order to demonstrate that the explanation he put forward had wider applications and could apply to "the parts of all natural Bodies being like so many Fragments of a Plate," Newton gave an example, now familiar to my readers:

> The finely colour'd Feathers of some Birds, and particularly those of Peacocks Tails, do in the very same part of the Feather appear of several Colours in several Positions of the Eye, after the same manner that thin Plates were found to do in the 7th and 19th Observations, and therefore their Colours arise from the thinness of the transparent parts of the Feathers; that is, from the slenderness of the very fine Hairs, or *Capillamenta,* which grow out of the sides of the grosser lateral Branches or Fibres of those Feathers.[38]

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[36] Hooke *Micrographia,* 49.

[37] Newton's notes "Out of Mr. Hook's Micrographia" were published in Appendix IV of Geoffrey Keynes, *A Bibliography of Dr. Robert Hooke* (Oxford, 1960). See esp. 100, item 48 for Newton's comment, given also in A. Rupert Hall and Marie Boas Hall, *Unpublished Papers of Isaac Newton* (Cambridge, 1962), 403.

[38] *Opticks,* ed. 2, 1717/18, Book II, Part III, 226, where in this edition the bracketed words first appear in English. The Latin *Optice* (1706) had made the change: *et proinde Plumarum istarum Colores,* etc.