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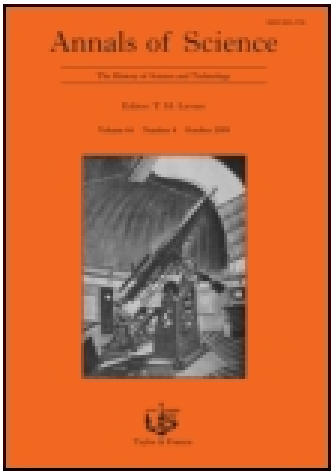

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Two kinds of modification theory of light: Some new observations on the Newton-Hooke controversy of 1672 concerning the nature of light

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Two Kinds of Modification Theory of Light: Some New Observations on the Newton–Hooke Controversy of 1672 Concerning the Nature of Light

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Summary

It has not been sufficiently emphasized that there existed two kinds of modification theory of colours, *Aristotle's modification theory* and *Descartes–Hook's modification theory*. This seems to have caused some confusion in the interpretation of the optical controversy between Newton and Hooke in 1672. The aim of the present paper is to prove that these two kinds of modification theory really coexisted, and on that basis to present a new interpretation of the optical controversy of 1672. The characteristics and the historical role of each of these theories will be described. Newton's colour theory was formed under the influence of Aristotle's modification theory, which had been disseminated through the work of an English Gassendist, Walter Charleton. Newton's optical theories were created not only under the influence of Descartes, as we have been often told, but also under the conspicuous influence of corpuscular philosophers.

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1. Introduction

In Newton's time, the nature of light and colours was explored in two kinds of modification theory of light: Aristotle's on the one hand and Descartes–Hooke's on the other. Historians of science have not sufficiently emphasized the coexistence of these two theories, and this seems to have caused some confusion in the interpretation of the optical controversy between Newton and Hooke in 1672.[1] Some historians assume that

[1] T. S. Kuhn noticed that more than one version of modification theories existed before Newton. But he did not argue their role in Newton's time. T. S. Kuhn, 'Newton's Optical Papers', in *Isaac Newton's Papers and Letters on Natural Philosophy* [hereafter *Papers and Letters*] edited by I. B. Cohen (Cambridge, Massachusetts, 1978), pp. 27–45 (pp. 30–1).

Hooke maintained Aristotle's modification theory and Newton opposed it, while others consider that Hooke adopted Descartes–Hooke's modification theory and met with Newton's refutation.

The first aim of the present paper is to prove that these two kinds of modification theory really coexisted, and on that basis to present a new interpretation of the optical controversy of 1672. The second aim is to describe the characteristics and the historical role of each of these theories and to inquire into the contribution of Aristotle's modification theory to the formation of Newton's optical theory.

Part I will treat Newton's controversy with Hooke (1672) and indicate the inadequacies of the interpretations thus far made by the historians of science. Then, by taking Newton's student notebook into consideration, the coexistence of the two kinds of modification theory will be proved. The characters of the two theories will also be discussed.

Part II will describe the formation of Newton's theory of light and colours and the contribution of Aristotle's modification theory which has been generally supposed to be incompatible with Newton's theory.

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PART I

2. What was the modification theory of colours?

Newton sent his famous paper 'New Theory about Light and Colours' to the Royal Society in 1672, which caused a controversy between himself and Hooke. It has been generally maintained that the controversy was due to to their different attitude toward the modification or qualification theory of colours.[2] Newton wrote in his paper:

> Colours are not *Qualifications of Light*, derived from Refractions, or Reflections of natural Bodies (as 'tis generally believed,) but *Original* and *connate properties*, which in divers Rays are divers.[3]

But Hooke could not assent to this proposition.[4] He backed the modification theory of colours, while Newton rejected it.

What was this modification theory of colours? It is surprising to find that even the two famous historians of Newtonian optics, Professor R. S. Westfall and Professor A. I. Sabra, hold different interpretations at this point. Therefore, I shall start my argument by examining the different interpretations of the two historians of science.

2.1. *The modification theory as Aristotle's conception of colours: Westfall's interpretation of the Newton–Hooke controversy*

According to Westfall, Aristotle's modification theory was widely accepted before Newton's time, and in connexion with this theory arose the controversy between Newton and Hooke. Aristotle's conception of colours supposed white to be the original colour of light, with other colours to be made by the admixture of darkness (or black) to light (or white). This modification theory of Aristotle was accepted during the Middle

[2] Professor Zev Bechler suggests that their difference in methodology was another root of their controversy. Zev Bechler, 'Newton's Optical Controversies: A Study in the Grammar of Scientific Dissent', in *The Interaction Between Science and Philosophy*, edited by Yehuda Elkana (Atlantic Highland, N.J., 1974), pp. 115–42. This aspect of their controversy will not be discussed in the present paper, though it seems to me very important.

[3] *Papers and Letters*, p. 53. Also in *The Correspondence of Isaac Newton*, edited by H. W. Turnbull (Cambridge, 1959), I, 97. See also *The History of the Royal Society*, edited by Thomas Birch (London, 1756–7), III, 9.

[4] *Papers and Letters*, pp. 112–3. As for Newton's answer to Hooke's criticism see ibid., pp. 116ff.

Ages, as in the cases of Grosseteste, Albertus Magnus, Witelo, and Theodoric of Freiberg, and it was later accepted by Descartes.[5] Westfall writes:

> 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. ... The fundamental assumption of this conception of colors, stated from the point of view of the *Meteorologica* [of Aristotle], 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... namely, that all of the colors fall on a scale between the contrary extremes of black and white.[6]

And Robert Hooke, an adversary of Newton,

> 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.[7]

Thus, 'It remained for Isaac Newton to challenge the traditional concept of modification'.[8] Hooke defended this traditional theory, while Newton opened 'a reasoned attack on the doctrine of modification'.[9] Westfall continues:

> 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.[10]

In his books Westfall repeats the same view.[11]

[5] R. S. Westfall, 'The Development of Newton's Theory of Color', *Isis*, 53 (1962), 339–58 (pp. 342–3).
[6] Ibid.
[7] Ibid., p. 347.
[8] Ibid., p. 348.
[9] Ibid., p. 353.
[10] Ibid., p. 354.
[11] R. S. Westfall, *The Construction of Modern Science: Mechanism and Mechanics* (New York, 1971), p. 56; *Never at Rest* (Cambridge, 1980), p. 166. S. I. Vavilov, a famous Russian scholar of Newtonian optics, is almost of the same opinion as Westfall. S. I. Wawilow [Vavilov], *Isaac Newton* (Leipzig, 1951), translated from Russian to German by J. Gruen, Chapters 3 and 5. He wrote, 'Die Physik übermittelte Newton die traditionellen Anschauungen des Aristoteles in fast unveränderter Form. Man nahm, dass die Farben aus einer Vermischung des Lichts mit der Dunkelheit in verschiedenen Proportionen entstehen'. (p. 20.) In Japan, the late T. Hirosige adopted Westfall's interpretation in his *History of Physics* (*in Japanese*), 2 vols (Tokyo, 1968).
Westfall, in his 'Newton and his Critics on the Nature of Colors' (*Archives internationale d'Histoire des Sciences*, 15 (1962), 47–58) presented another view that the root of the controversy between Newton and his critics (including Hooke) consisted in the critics' misunderstanding that Newton supported the peripatetic conception of real qualities. Against this view, A. I. Sabra wrote, 'This seems to me to lay the emphasis on the wrong place. The suspicion of peripatetic conceptions in Newton's doctrine of colours was only a false start'. (See Sabra's book cited in footnote 27, pp. 232–3.) I agree with Sabra.

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If Westfall's view was the case, Hooke was a defender of Aristotle's modification theory, and must have accepted the following criteria of Aristotle's conception of colours:

(*a*) White is the original colour of light and other colours are produced by the modification of it.

(*b*) The modification is raised by the admixture of darkness to light, and colour of light is determined by the quantity of darkness it contains. Red is the nearest approach to white. It contains the least darkness. As the admixture of darkness increases and the strength of light declines, there appear first green and finally violet etc.

Did Hooke admit the above? Probably he admitted (*a*), because he wrote:

> *white* is nothing but a pulse or motion, propagated through an homogeneous, uniform, and transparent medium: and... colour is nothing but the disturbance of that light.[12]

For Hooke, white was the colour of the undisturbed original light. How about (*b*)? He never admitted (*b*). He did not consider that all of the colours were made from the admixture of darkness to light or that they fell on a scale between the contrary extremes of black and white.

Westfall, however, assumes that Hooke admitted (*b*) as well. He takes up 'Hooke's explanation' of the spectrum of the sun and writes:

> According to Hooke's explanation the forward angle of the oblique pulse [*BO*] 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 [*BA*], 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, meanwhile, 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.[13]

It must be noted here that this is not Hooke's own explanation of the spectrum of the sun, but is merely Westfall's interpretation of Hooke's explanation, which is not representing Hooke's theory correctly. The basis of my criticism consists in the following discussion, presented under three subtitles.

(1) *Hooke's explanation of the spectrum*

Hooke explained the phenomenon of the spectrum of the sun from his own definition of colours which is different from Aristotle's modification theory. Hooke's 'definition of Colours' was given in his *Micrographia.*

> That Blue is an impression on the Retina of an oblique and confus'd pulse of light, whose weakest part precedes, and whose strongest follows. And, that Red is an impression on the Retina of an oblique and confus'd pulse of light, whose strongest part precedes, and whose weakest follows.[14]

[12] *Papers and Letters*, p. 111.
[13] Westfall (footnote 5), pp. 347–8.
[14] R. Hooke, *Micrographia* (London, 1665), p. 64.

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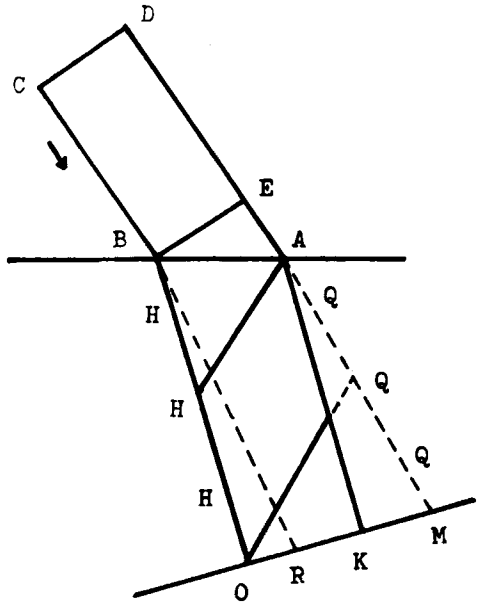

Figure 1.

Hooke's explanation of the spectrum of sun. BOR is blue and AKM is red.

He never said that red was the impression of the strongest pulse and blue of the weakest pulse, but the colour of light was determined by the order of the strong and weak pulses. Red, for example, was not the impression of light which contained the least darkness, but was the impression of the oblique pulse of light 'whose strongest part precedes, and whose weakest part follows'.

The production of the spectrum of the sun was explained according to this definition of colours in the same *Micrographia.* Although Hooke did not give a full explanation, we can reconstruct it easily. In Figure 1 a pulse of light *BCDE* falls obliquely on the surface *AB*. After refraction, the pulse is made oblique to the progressive because of the difference of the speeds of light in different mediums. The end *B* which precedes the other end *E* must, Hooke wrote, necessarily be somewhat more obtuned, or impeded by the resistance of the transparent medium, than the other end *E*, and the ray 'have its side *HH* more deadened by the resistance of the dark or quiet medium'.

> Whence there will be a kind of deadness superinduc'd on the side *HHH*, which will continually increase from *B*, and strike deeper and deeper into the Ray by the line *BR*; Whence there all the parts of the triangle *RBHO* will be of a dead *Blue* colour, and so much the deeper, by how much the nearer they lie to the line *BHH*, which is most deaded or impeded... [15]

It is apparent that *BO* is more deadened than *BR*, and that *BO* precedes *BR* because of the obliqueness of the pulse to the progressive. In the triangle *BOR*, therefore, the weakest part of the pulse *BO* precedes and the strongest part *BR* follows. Then *BOR* must be blue according to Hooke's definition of colours.

[15] Ibid., p. 63.

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> Next on the other side of the Ray, the end *A* of the pulse *AH* will be promoted, or made stronger, having its passage already prepar'd as 'twere by the other parts preceding, and so its impression will be stronger; And because of its *obliquity* to the Ray, there will be propagated a kind of a faint motion into *QQ*..., whence all the triangle *AKM* will be tinged with a *Red*.[16]

In the triangle *AKM*, *AK* precedes *AM*, and *AK* is stronger than *AM*. The strongest part *AK* precedes and the weakest *AM* follows. So *AKM* must be red.

If Hooke had accepted the Aristotelian conception of colours, *AK*, the strongest part of the whole pulse, should have been red. But 'the *Red* will be the deeper the nearer it approaches the line *MA*'.[17] Hooke's theory resembled Aristotle's modification theory in the point that it took account of the dark medium bordering the beam. But the two theories were quite different. Hooke did not suppose that colours were produced by the admixture of darkness to light in contrast with Aristotle's modification theory. Colours were produced by the resolution of the pulse of light to the row of weak and strong pulses, which was caused by the dark medium.

(2) *Hooke's explanation of the colours of thin transparent bodies*

In order to explain the phenomenon of colours which appear on thin transparent bodies, Hooke pointed out that 'in this Production of Colours there is no need of a terminating shadow',[18] while such a shadow was essential for Aristotle's modification theory. This phenomenon was very important for Hooke and the experiment on it was to be

> such a one as our *thrice exellent Verulam* calls *Experimentum Crucis*, serving as a Guide or Land-mark, by which to direct our course in the search after the true cause of Colours.[19]

Hooke's theory ought to explain this phenomenon if it be a correct theory. Hooke wrote:

> Which properties, as they have been already manifested, in the Prisme and falling drops of Rain, to be the cause of the colours there generated, may be easily found to be the efficients also of the colours appearing in thin *laminated* transparent bodies...[20]

The colours of thin plate and the colours of the spectrum of the sun were explained from the same theoretical basis, that is, from the order of the weak and strong pulses. For the production of colours on laminated body, the body must neither be too thick nor too thin and it must be transparent. Moreover, there must be a considerable reflecting body adjacent to the under side of the lamina.[21] When a pulse of light falls on the laminated body *AB*, a part of it is reflected on the upper side and the other part is reflected on the lower side of the body (Figure 2). The pulse *ef*, which is reflected from the lower side, is weaker not only by reason of the two refractions in the surface *AB*, but

[16] Ibid.
[17] Ibid.
[18] Ibid., p. 53.
[19] Ibid., p. 54.
[20] Ibid., p. 64.
[21] Ibid., p. 65.

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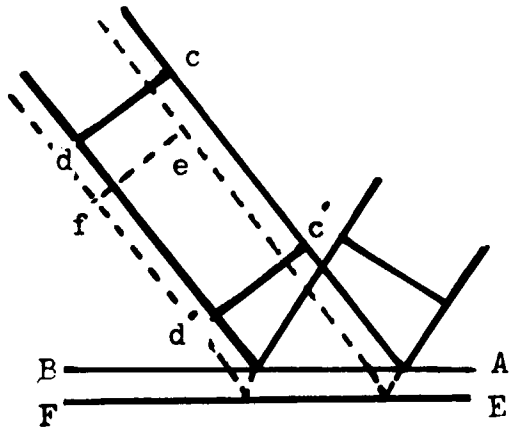

Figure 2.

Hooke's explanation of colours of thin transparent bodies.

by reason of the time spent in passing and repassing between the two surfaces *AB* and *EF*, than the pulse *cd*, which is reflected from the upper side *AB*. The pulse *ef* goes behind the pulse *cd*.

> this confus'd or *duplicated* pulse, whose strongest part precedes, and whose weakest follows, does produce on the *Retina* the sensation of a *Yellow* [Red].[22]

If the laminated body is thicker, the pulse *ef* goes further behind.

> And in this case it will rather seem to precede the following stronger pulse [*c*'d'], then [than] to follow the preceding one [*cd*] and consequently a *Blue* will be generated.[23]

If the laminated body is much thicker, the pulse *ef* eventually goes behind the pulse *c'd'*. Then the strong pulse *c'd'* precedes the weak pulse *ef*, and there appears red. Thus colours appear periodically as the thickness of the plate increases.

It is apparent from this explanation:

> that for the production of Colours there is not necessary either a great refraction, as in the Prisme; nor Secondly, a determination of Light and shadow, such as is both in the Prisme and Glassball.[24]

Only the disposition of strong and weak pulses determines the colour of light. Shadow does not play any essential role for the generation and determination of colours of light.

(3) *The immutability of the colours of light*

Each of the colours of a ray of light, generated by a prism, cannot be changed into any others by its passing through the second prism, as Newton demonstrated in his

[22] Ibid., p. 66.
[23] Ibid.
[24] Ibid., p. 54.

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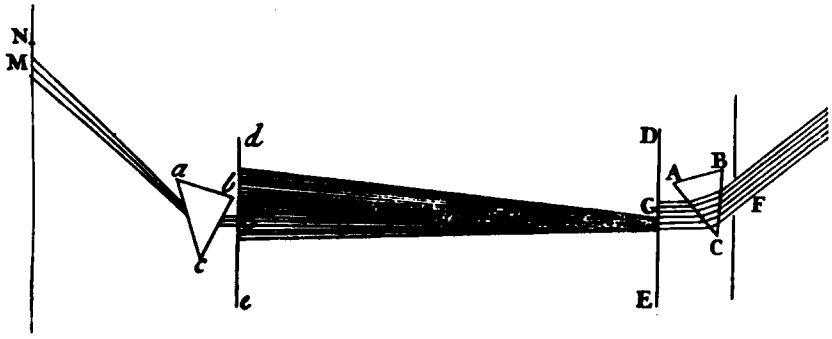

Figure 3.

Newton's *experimentum crucis.*

experimentum crucis (Figure 3). Newton wrote in his 1672 optical paper under proposition 3:

> The species of colour, and degree of Refrangibility proper to any particular sort of Rays, is not mutable by Refraction, nor by Reflection from natural bodies, nor by any other cause, that I could yet observe.[25]

This statement evidently contradicts Aristotle's modification theory, which expounded that the first prism produced colours by mixing the light with darkness. According to this theory, then, the second prism, by mixing more darkness and making the rays less brilliant, should shift the whole spectrum toward blue.

Hooke admitted this immutability of the colours of light. He wrote:

> the third proposition, to which I do readily assent in all cases, except where the split ray is made by another refraction, to become intire and uniform, again to diverge and separate...[26]

Colours of rays of light are immutable except when they are rejoined to produce white light.

The above discussion (1), (2), (3), at tests that Hooke did not accept the criterion (*b*). He was not a defender of the Aristotelian theory of colours, although he admitted criterion (*a*).

Thus, the controversy between Newton and Hooke in 1672 did not depend on Aristotle's modification theory, and Westfall's interpretation, which regards Hooke as a defender of Aristotle's conception of colours, does not fit the case. We should now examine the alternative, Sabra's interpretation of the modification theory.

2.2. *The modification theory as the pulse theory of light: Sabra's interpretation of the Newton–Hooke controversy*

A. I. Sabra presents his own interpretation of the 'modification theory' in his *Theories of Light from Descartes to Newton*, which is regarded, against his will, as a standard history of seventeenth-century optics. He supposes that the controversy between Newton and Hooke can be interpreted as the antagonism between the

[25] *Papers and Letters*, p. 53.
[26] *Papers and Letters*, p. 113.

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defender of the corpuscular theory of light and that of the pulse theory of light. He writes:

> Before him [Descartes] writers on the subject were content to explain colours as a result of the mixture of light and darkness, or of a finite number of 'primary' colours, in various proportions.[27]

This implies that, though the modification theory did exist before Descartes, Descartes did not adopt it and that Hooke, a follower of Descartes, was not a defender of Aristotle's modification theory of colours. As to the cause of the controversy between Newton and Hooke, Sabra writes:

> Newton concluded, colours were not 'qualifications', or modifications suffered by light upon reflection or refraction, as it was generally assumed; they were '*Original* and *connate properties*' of the rays just as their respective degrees of refrangibility were.[28]

And

> It was this interpretation of the constitution of white light and the role which Newton assigned to the prism in the production of colours that occupied the greatest and most important part of the controversy between Newton and the critics of his theory, Hooke, Pardies and Huygens. They all suspected from Newton's expressions that he was inclined towards an atomistic interpretation of light which they found disagreeable.[29]

> Hooke in particular envisaged a new formulation of his pulse hypothesis which would have fully taken the experimental results into account without conceding the original heterogeneity of white light.[30]

When Newton sent his 'New theory about light and colours', Hooke 'was not a little pleased with the niceness and curiosity of his [Newton's] observation' on light and 'wholly agree[d] with him as to the truth of those he hath alledged'.[31] But he could not assent to Newton's hypothesis explaining the phenomena of colours.

> But grant his first proposition, that light is a body, and that as many colours as degrees thereof as there may be, so many sorts of bodies there may be, all which compounded together would make white; and grant further, that all luminous bodies are compounded of such substances condensed, and that whilst they shine, they do continually send out an indefinite quantity thereof, every way in orbem, which in a moment of time doth disperse itself to the utmost and most indefinite bounds of the universe; granting these, I say, I do suppose there will be no great difficulty to demonstrate all the rest of his curious theory... If my supposition be granted, that light is nothing but a simple and uniform motion, or pulse of a homogeneous and adopted (that is a transparent) medium,... I believe Mr. Newton will think it no difficult matter, by my hypothesis, to solve all the phaenomena...[32]

[27] A. I. Sabra, *Theories of Light from Descartes to Newton* (London, 1967), p. 67.
[28] Ibid., p. 241.
[29] Ibid., p. 242.
[30] Ibid., p. 233.
[31] *Papers and Letters*, p. 110.
[32] *Papers and Letters*, p. 114.

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Newton made a counter-attack.

> To me, the Fundamental Supposition [of Hooke's theory] it self seems impossible; namely, That the *Waves* or Vibrations of any Fluid, can, like the Rays of Light, be propagated in *Streight* lines, without a continual and very extravagant spreading and bending every way into the quiescent Medium, where they are terminated by it.[33]

If the general acknowledgement by historians of science that the modification theory caused the controversy between Newton and Hooke is correct, and, at the same time, if Sabra's interpretation that the two men disputed about the pulse theory of light is correct, it is the logical consequence that that modification theory which Hooke defended is equivalent to the pulse theory of light or, rather, to the colour theory which is based on the pulse theory of light. Thus the controversy between Newton and Hooke was the one between the corpuscular theory and the pulse theory of light.[34]

Newton supposed that white was the aggregate of the rays of different colours, which were differently refrangible. It is clear that Newton adopted the corpuscular theory of light, though he hesitated to state it explicitly. Therefore, white was the aggregation of all kinds of corpuscles and was originally heterogeneous. Hooke adopted, on the contrary, the pulse theory of light. For the pulse theory white was the colour which an original uniform pulse of light exhibited. Colours were generated when this uniform pulse was disturbed and destroyed. Hooke called this disturbance 'the modification of light'. It should be noted that this modification was caused not by the admixture of darkness to light, but by the split of a pulse of light into strong and weak pulses at prisms or at thin transparent bodies. The order of strong and weak pulses determined the colour of light.

It was impossible for the pulse theory of light to suppose any kind of light be originally heterogeneous, because respective elements of the undulatory motion of ether in space, such as direction, amplitude, and frequency, could not be two or more at a given point and time. The motion must be a definite one because there was only one kinetic ether in space. Hooke could not understand why it was necessary that rays which exibit various colours should originally exist in the uniform pulse of white prior to the prismatic dispersion.[35] Colours were procured from white at the prism. Hooke, however, admitted that

> It is true, I can, in my supposition, conceive the white or uniform motion of light to be compounded of the compound motions of all the other colours, as any one strait and uniform motion may be compounded of thousands of compound motions, in the same manner as DESCARTES explicates the reason of the refraction; but I see no necessity of it.[36]

It was possible for Hooke, as Sabra summarizes, to *imagine* white to be heterogeneous, though it was not heterogeneous in a real or physical sense.[37]

[33] *Papers and Letters*, p. 121.

[34] Shapiro also assumes that the basis of the controversy between Newton and his critics lay in the conflict between emission (corpuscle) theory and wave (pulse) theory of light. A. E. Shapiro, 'Newton's Definition of a Light Ray and the Diffusion Theories of Chromatic Dispersion', *ISIS*, 66 (1975), 194–210 (p. 194).

[35] *Papers and Letters*, p. 111.

[36] *Papers and Letters*, p. 114.

[37] Sabra, (footnote 27), p. 280.

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When white light, consisting of uniform motion, passes through a prism, Hooke considered, it is resolved into component pulse motions of various colours of which it was imagined to be composed. But once split, *a* component motion was never able to be split or modified again by another refraction. Rays of light were immutable by refraction. It was, however, possible to reduce the component motions to one simple and uniform pulse as it was at first. This explanation of Hooke's reminds us of the Fourier analysis, as Sabra points out.[38] Sabra's explanation is not entirely irrelevant, though many historians of science may feel it is somewhat unhistorical.

The modification theory of colours for Hooke was the colour theory which was based on the pulse theory of light. Here, the modification was not caused by the admixture of darkness. Let me call this type of modification theory 'Descartes–Hooke's modification theory'.[39]

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2.3. *The modification theory of colours in Newton's period: the theory reconsidered*

The preceding discussion demonstrated that the optical controversy in 1672 between Newton and Hooke was concerned not with Aristotle's modification theory, but with Descartes–Hooke's modification theory. However, there remains one problem to be solved.

Sabra supposes that Aristotle's conception of colours had been annihilated by Descartes and had no influence on Newton. But this interpretation contradicts Newton's own description in his student notebook where he wrote:

> Coulors arise either from shaddows intermixed with light or or [*sic*] stronger and weaker reflection.[40]

This is a description apparently indicating the influence of Aristotle's conception of colours on Newton. The difficulty of Sabra's interpretation here may be easily removed if we only suppose that two kinds of modification theories coexisted in Newton's period: Descartes–Hooke's modification theory and Aristotle's modification theory.

At first, Newton adopted Aristotle's modification theory, but he gradually abandoned it. When he disputed against Hooke in 1672, he only attacked Descartes–Hooke's modification theory. He never attacked Aristotle's modification theory, to which Hooke in reality did not subscribe at all.

Aristotle's modification theory was known in Newton's period and had been already described in the work of an English natural philosopher Walter Charleton. Charleton was a mechanical philosopher in the seventeenth century and introduced Gassendi's corpuscular philosophy to England. Charleton wrote his work *Physiologia*

[38] Ibid., pp. 280–1.

[39] Though Westfall supposed that Descartes adopted Aristotle's modification theory, his view is not appropriate. Because Descartes wrote:

> But I do acknowledge that shadow and refraction are not always necessary to produce them [colours]; and that instead of these the size, shape, situation, and movement of the particles of bodies we call colored can variously compete with light, in order to increase or diminish the rotation of the particles of the fine material.
>
> (*Oeuvres de Descartes*, edited by C. Adam and P. Tannery, 12 vols, Paris, 1897–1913, IV; *Discourse on Method, Optics, Geometry and Meteorology*, translated by Paul J. Olscamp, Indianapolis, 1965, pp. 338–9).

We should note that Descartes refused to admit the distinction between true and apparent colours. Shadow was no longer essential for the production of any colours. Colours were generated not by the admixture of darkness to light but by the rotation of ether particles.

[40] Cambridge University Library, MS. Add. 3996, f.105v.

Epiculo-Gassendo-Charltoniana in 1654,[41] and Newton did read this book in his younger days. Newton's statement quoted in the above is assumed to have originated in Charleton's *Physiologia*.[42] There, Charleton wrote that white colour was caused by the atoms of light which came directly from the luminous body and black was the negation of light.[43] Therefore, white was the original colour of light. Intermediate colours as red, blue and green,

> are but the off-spring of the Extreme, arising from the intermission of Light and shadow, in various proportions; or, more plainly, that the sense of them is caused in the Retina Tunica, according to the variety of Reflections and Refractions, that the incident Light suffers from the superficial particles of objects...[44]

Colours were, thus, created 'by a certain *Modification*' of light.[45]

Charleton also gave an explanation of prismatic colours:

> the Rayes of Light arriving at the *Base* of the Triangle, are trajected through it by a longer tract or way, than those arriving at or nearer to the *Top* thereof: and therefore, the Glass being in that part most crass, there must be more impervious particles obsistent to the Rayes of Light; each one whereof repercussing its raye back again into the medium from the Glass, causeth that the number of shadowes is multiplyed in that part of the object, which the Base of the Triangle directly respecteth; and consequently produceth a Caerule Tincture thereon.[46]

He supposed that colours were generated by the admixture of darkness to the original white light. The light, which contained most darkness, is blue. His theory was a mechanical version of Aristotle's modification theory. Aristotle's conception of colours was in this way passed on to Newton's period.

Furthermore, the coexistence of Aristotle's and Descartes–Hooke's modification theories is confirmed in a work of Robert Boyle. Boyle wrote:

> I encline to take Colour to be a Modification of Light... But whether I think this Modification of the Light to be perform'd by Mixing it with Shades, or by Varying the Proportion of the Progress and Rotation of the *Cartesian Globuli Caelestes*, or by some other way which I am not now to mention, I pretend not here to Declare.[47]

Here, Cartesian modification is distinguished from Aristotle's modification. The coexistence of two kinds of modification theories is also suggested in Newton's own

[41] W. Charleton, *Physiologia Epiculo-Gassendo-Charltoniana* (London, 1654; reprinted New York, 1966). Concerning Charleton, see H. Rolleston, 'Walter Charleton, D.M., F.R.C.P., F.R.S.', *Bulletin of the History of Medicine*, 8 (1940), 403–16, and the introduction to the reproduced *Physiologia* by R. H. Kargon. See also Kargon's, 'Walter Charleton, Robert Boyle, and the Acceptance of Epicurean Atomism in England', *ISIS*, 55 (1964), 184–92, and *Atomism in England from Harriot to Newton* (Oxford, 1966), Section 8; Lindsay Sharp, 'Walter Charleton's Early Life 1620–1659, and Relationship to Natural Philosophy in Mid-seventeenth Century England', *Annals of Science*, 30 (1973), 311–40.

[42] J. Hendry, 'Newton's Theory of Colour', *Centaurus*, 23 (1980), 230–51 (pp. 233–34).

[43] Charleton (footnote 41), p. 191.

[44] Ibid., pp. 191–2.

[45] Ibid., p. 190.

[46] Ibid., p. 194.

[47] R. Boyle, *Experiments and Considerations Touching Colours...the Beginning of an Experimental History of Colours* (London, 1664; reprinted New York, 1964) p. 90.

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writings. In his *Lectiones Opticae*, Newton criticized the peripatetic conception of light and colours, and then he wrote:

> As far as the opinions of other philosophers are concerned, they said that colours were generated either from variously mixed shadow and light; or from the rotation of globules or, rather, their various pressures; or, finally, from various modes with which some etherial medium was vibrated, while standing light was produced from the impulse of vibrating ether which was carried in Retina Tunica.[48] (Translation, mine.)

Here, he cites three theories of colours: a revised (perhaps mechanical) version of Aristotle's conception of colours, Descartes conception of colours, and Hooke's. As Hooke adopted the Cartesian theory of light, we may regard him as a follower of Descartes. And by Newton, Descartes–Hooke's modification was distinguished from Aristotle's modification theory.

But, then, why were both Aristotle's conception of colours and Descartes–Hooke's conception of colours called 'the modification theory'? It is because these theories both supposed that white was the original colour of light. Such theories that regarded white as the original colour of light and that supposed colours to be generated by manufacturing white, have been called 'the modification theory', whether the modification was caused by the admixture of darkness or by the split of the pulse of light. (Criterion (a).)

Newton, who defended the corpuscular theory of light, supposed that white was the aggregation of all kinds of corpuscles of light and that it was originally heterogeneous. He could not allow Aristotle's conception of colours nor Descartes–Hooke's conception of colours, because both supposed that white was not heterogeneous but uniform and that white was the colour which the original light exhibited.

Though Newton adopted Aristotle's modification theory when he started his optical research, by degrees he abandoned it. He criticized Hooke not because of Aristotle's modification theory but because of Descartes–Hooke's modification theory.

PART II

3. Newton and Aristotle's modification theory of colours

As has been shown in Part I there existed two kinds of modification theory in Newton's time: Aristotle's and Descartes–Hooke's. The former was adopted and revised by Charleton, while the latter was a colour theory based on the pulse theory of light, with which Newton did not agree. When Newton started his optical research in his student years, he adopted Aristotle's modification theory. This theory, in reality, was to play a positive role in the formation of Newton's revolutionary theory of colours. I shall here analyse Newton's student notebook called *Quaestiones*,[49] and try to elucidate the positive role of Aristotle's modification theory in Newton.

[48] I. Newton, *Lectiones Opticae*, in *Isaac Newtoni Opera Quae Exstant Omnia*, edited by S. Horsley (London, 1782), III, (reprinted, Stuttgart and Bad Connstatt. 1964) p. 351.

[49] Cambridge University Library, MS. Add. 3996, ff. 88–135. The following papers treat Add. 3996 in detail: A. R. Hall, 'Sir Isaac Newton's Note-Book, 1661–65', *Cambridge Historical Journal*, 9 (1948), 239–50; R. S. Westfall, 'The Foundations of Newton's Philosophy of Nature', *British Journal for the History of Science*, 1 (1962), 171–82; J. A. Lohne, 'Isaac Newton: The Rise of a Scientist 1661–1671', *Notes and Records of the Royal Society of London*, 20 (1965), 125–39. Concerning the optical aspect of the notebook, see Westfall, footnote 5, and Hendry, footnote 42.

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3.1. *The development of Newton's theory of colours in his 'Quaestiones'*

As stated in the preceding sections, Newton started his research with a mechanical version of Aristotle's modification theory. He wrote:

> Coulors arise either from shaddows intermixed with light, or or [*sic*] stronger and weaker reflection, or parts of the body mixed with and carried away by light.[50]

But Newton gradually came to abandon Aristotle's conception of colours which he had learned from Charleton's work.

> No colour will arise out of the mixture of pure black and white for then pictures drawne with inke would be coloured or printed would seeme coloured at a distance and the verges of shadows would be coloured and lamb black and spanish whiteing would produce colours whence they cannot arise from more or lesse reflection of light or shadows mixed with light.[51]

Here Newton ruled out (*b*) (Part I, §2.1), one of the criteria of the Aristotle's modification theory.

His original theory of colour appeared in the later entries of the same *Quaestiones*. There he made a description of an experiment. He painted a square plate with two colours and looked at it through a prism. (Figure 4.)

If abdc be white and cdsr black then eodc is red.
If abdc be black and cdsr white then eodc is blew.
If abdc be blew and cdsr white then eodc is blewer.

If (abdc) be	white	and (cdsr) be	blew	then eodc is	Red
	black		blew		blewer.
	blew		black		Greene or Red.
	black		red		blew.
	red		black		redder.
	red		white		blew.
	white		red		redder.
	white		whiter		blew.
	whiter		white		redd.
	black		blacker		Greene or Darke red.
	blacker		black		blew.

Newton assumed the following to explain this experiment.

> The more uniformely the globuli move the optick nerves, the more bodys seeme to be coloured red, yellow, blew, greene etc. But the more variously they move them, the more bodys appeare white black or Greys.[52]

White is assumed to be an impression made by the aggregation of variously moving globules of light. By the time when Newton made this description, he recognized the heterogeneity of white light and abandoned (*a*), another criterion of Aristotle's modification theory.

[50] MS Add. 3996, f.105v. The third alternative that 'colours are parts of the body mixed with and carried away by light' seems also derived from Charleton's *Physiologia* (see p. 185). Charleton attributed it to Epicurus. This alternative, however, had no virtual influence on Newton's later development.

[51] MS Add. 3996, f.105v.

[52] Ibid., f.122r.

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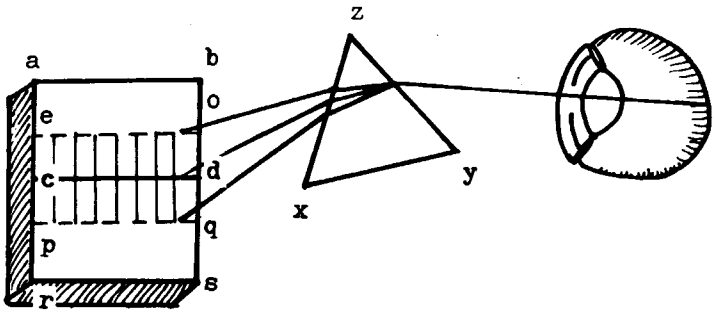

Figure 4.

Newton's 'plate experiment'. (From his *Quaestiones.*)

He went on to explain the cause of the production of the observed colour fringes. He supposed that light globules, which constructed white, moved with different speeds respectively. And,

> 1 Note that slowly moved rays are refracted more then swift ones. 2ndly If adbc be shaddow and cdsr white then the slowly moved rays coming from cdqp will be refracted as if they had come from eodc soe that the slowly moved rays being seperated from the swift ones by refraction, there ariset 2 kinds of colours viz: from the slow ones blew, sky colour, and purples. from the Swift ones red, yellow and from them wich are neither moved very swift nor slow ariseth greene but from the slow and swiftly moved rays mingled ariseth white grey and black.[53]

He associated the colour with the speed of light and then with its refrangibility. A globule that makes red, moves fastest and is least refrangible. A globule that makes yellow, moves less fast and is more reflangible. A globule that makes green, moves slower and is much more refrangible, and a globule that makes blue, moves slowest and is most refrangible.[54]

By the time when he made this entry, Newton abandoned both criteria of Aristotle's modification theory. Newton's description, nevertheless, preserved an important feature of Aristotle's conception of colours. According to the modification theory of light, red is the strongest light because it contains least darkness, and blue is the weakest light because it contains most darkness. Newton associated red with the fastest globules, and blue with the slowest ones. Therefore, red was the impression made by the strongest globules of light and blue was the impression made by the weakest. Newton's theory and Aristotle's modification theory both supposed that red was the strongest

[53] Ibid., f.122v.

[54] The experiment on the colour fringes observed with a prism was not original with Newton. We can find a similar experiment in Charleton's *Physiologia*:

> let us here observe; that the Colours created by Light, reflected from objects on the Prism, and therein twice refracted, are Geminated on both sides thereof. For, insomuch as those Colours are not appinged but on the Extremes of the Object, or where the superfice is unequal (for if that be Plane and Smooth, it admits only an Uniform Colour, and the same that appears thereon, when beheld without the Prism): therefore are two Colours alwayes observed in that Extreme of the Object, which respecteth the Base of the Triangle in the Glass, and those are a Vermillion and a Yellow; and two other Colours in that extreme, which respecteth the Top of the Triangle; and those are a Violet blew, and Grass green. (p. 189)

I think it is possible that Newton's 'plate experiment' was done under the influence of this experiment. He tried it with more exquisite accomodation, that is, with the coloured plates.

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Mass			Remaining Motion After Reflection		
Particle in the body	Greater rays	Lesser rays	Greater rays	Lesser rays	Colour of the body
12	9	2	1/7	5/7	Blue
2	9	2	7/11	0	Red

Table.

light and blue was the weakest.[55] In this respect, Newton's theory of colour had something common with Aristotle's conception of colours.

Red, the strongest light in Aristotle's theory, consisted of globules with the fastest speed, according to Newton. Furthermore, red, the fastest and the strongest was the least refrangible, and blue, the weakest and the slowest was the most refrangible. Thus each ray has its own refrangibility according to its strength or its speed.

Newton first associated colours with speeds of light globules. But he changed his position later in his *Quaestiones* and related colours to the masses of globules (Table).

> 8. Though 2 rays be equally swift yet if one ray be lesse than the other that ray shall have so much lesse effect on the sensorium as it has lesse motion than the others etc. Whence supposing that there are loose particles in the pores of a body bearing proportion to the greater rays, as 12:9[56] and the less globules is in proportion to the greater as 2:9, the greater globulus by impinging on such a particle will loose 6/7 parts of its motion the less glob: will loose 2/7 parts of its motion and the remaining motion of the glob: will have almost such a proportion to one another as their quantity have viz 5/7 : 1/7 : : 9 : $1\frac{4}{5}$ wich is almost 2 the lesse glob. And such a body may produce blews and purples. But if the particles on which the globuli reflect are equal to the lesse globulus it shall loose its motion and the greater glob: shall loose 2/11 parts of its motion and such a body may be red or yellow.[57]

When a body deprives more motion of greater rays than of lesser rays, it exhibits blue. Namely, a body, which reflects more of lesser rays than greater rays, exhibits blue. On the contrary, a body, which reflects more of greater rays than lesser ones, exhibits red. Therefore, blue is the impression of lesser rays and red is that of greater rays. Here again, Newton linked colours with the strength of light, a feature of Aristotle's theory remaining.

It is known that in his later works (for example *Lectiones Opticae*) Newton related colours with mass or velocity of the globules of light.[58] Even after he reached his

[55] On account of his theory of colour, Newton also explained colours on the surface of bodies.

> 4 Hence redness yellownes etc. are made in bodys by stoping the Slowly moved rays without much hindering of the swifter rays. and blew greene and purple by diminishing the motion of the swifter rays and not of the slower. Or in some bodys all these colours may arise by diminishing the motion of all the rays in greater of lesse geometricall proportion, for then there will be lesse difference in theire motions than otherwise.

[56] It is not 12:9 but 9:12 in Newton's original writing. But the transposition seems reasonable, or else it contradicts the following argument. See Hendry (footnote 42), pp. 240–2.

[57] MS Add. 3996, f.123r.

[58] Zev Bechler, 'Newton's Search for a Mechanistic Model of Colour Dispersion: A Suggested Interpretation, *Archive for History of Exact Sciences*, 11 (1973), 1–37.

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original and revolutionary theory of light and colours, he still preserved an important feature of Aristotle's modification theory, though he discarded the latter's uniformity of white light.

3.2 *Newton's position in seventeenth-century optics*

The relation of Newton's optics to that of Descartes has been much discussed by historians of science.[59] According to them, Newton, a mechanical philosopher, read Descartes's works, adopted Descartes' sine law, and wrote to the Royal Society that, when he found his new theory, he applied himself to 'the grinding of Optick glasses of other figures than Spherical' following Descartes.[60] In other words, it was supposed that Newton had succeeded to the Cartesian research programme of optics.

It is true that Newton accepted Descartes's achievements in geometrical optics. But Descartes regarded light as a pulse or action in the ether as Hooke did, while Newton regarded it as moving corpuscules. This difference has not been taken seriously. Therefore, I want to set forth a hypothesis that there were two different programmes of optics going in the seventeenth century. Though they were both mechanical and shared the same geometrical optics, they differed in their models of light.

One was the pulse programme of light, which supposed light to be pulse or motion in the ether and explained colours according to Descartes–Hooke's modification theory. Descartes, Hooke and Pardies subscribed to this. The other was the corpuscle programme of light, which supposed light to be corpuscles and explained colours according to Aristotle's modification theory. Charleton, young Newton and others accepted this programme. Newton learned Aristotle's modification theory from Charleton and partly under its influence he formed his new theory. Incidentally, it is probable that Gassendi himself belonged to this programme, under whose influence Charleton wrote his books.[61]

Now it is quite apparent that Newton was strongly influenced by non-Cartesians of the time, among whom the English Gassendist, Charleton, wrote that Descartes' theory of light was

> never to be conceded by any, who fears to ensnare himself in many inextricable Difficulties, Incongruities, and Contradictions, in the deducement of it through all the Phaenomena of Light, Colours, and Vision...[62]

Therefore it is no longer possible to regard Newton only as a successor of Descartes in relation to his optical theories.

4. Conclusion

The modification theory of colours was the theory which regarded white to be the primary original colour of light. There were two versions of the modification theory in Newton's period. One was Aristotle's modification theory, according to which colours were generated by the admixture of darkness to light. Charleton and young Newton subscribed to this theory, and its features are somewhat preserved even in Newton's mature theory. The other was Descartes–Hooke's modification theory, which supposed that colours were produced by the split of white light while darkness did not play

[59] Sabra, (footnote 27) p. 13. He suggests here the strong influence of Descartes on Newton. Also see A. R. Hall, 'Further Optical Experiments of Isaac Newton', *Annals of Science* 11 (1955), 27–43 (p. 36).

[60] *Papers and Letters*, p. 47.

[61] Gassendi, like Charleton, supposed that colours arose from the mixture of shadow and light: *Syntagma Philosophicum* (*Opera Omnia*, Lyons, 1658, I, p. 434). See Westfall, (footnote 49) p. 175, note 10.

[62] Charleton, (footnote 41) p. 197.

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any essential role. The former was the colour theory incorporated with the corpuscular theory of light and the latter was that with the pulse theory of light.

Earlier studies of seventeenth-century optics have overlooked the coexistence of the two kinds of modification theory. Notably, Westfall, conscious only of Aristotle's modification theory in Newton's time, failed adequately to interpret the optical controversy, while Sabra successfully explained the controversy but could not have consistently dealt with Newton's discussion in his student notebook, *Quaestiones.*

The demarcation of the two kinds of modification theory of light proposed in this paper presents a new comprehensive interpretation of Newton's *Quaestiones* as well as of his controversy with Hooke. It may also suggest a new historiography of seventeenth-century optics.

Acknowledgment

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