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Newton's Early Optical Theory and its Debt to Chymistry

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Introduction[*]

In the years immediately preceding Isaac Newton's experimental demonstration that sunlight is actually a composition of heterogeneous spectral rays rather than being perfectly homogeneous, a sophisticated methodology based on the analysis and resynthesis of gross matter had decisively shown that chemical compounds were also made up of heterogeneous components. Although modern scholars tend to associate the experimental approach of seventeenth-century corpuscular matter theory with mechanical philosophers such as Pierre Gassendi and Robert Boyle, an extensive alchemical tradition extending from the High Middle Ages up to Boyle's immediate predecessors had long used the analytic retrievability of the constituents of compounds to argue for the permanence of the ingredients that went into them. Boyle, in particular, was the direct heir of this lengthy alchemical tradition, especially in his use of the atomistic writings of the Wittenberg medical professor Daniel Sennert. It is a well known fact that the young Newton was heavily influenced by Boyle, but no one up to now has argued in detail for a transfer from Boyle's work on "chymical" analysis and synthesis to the optical analyses and syntheses that formed the bases of Newton's early optical work.[1] Elsewhere I have argued that alchemical experimentation helped to bring a decisive end to traditional scholastic theories of mixture in the seventeenth century, thus setting the stage for the mechanical philosophy.[2] In the present paper I will show that a consideration of alchemy, or rather "chymistry," also adds an important new dimension to Isaac Newton's early optical discoveries and their presentation.

Although a widespread school of alchemical argumentation had long opposed the scholastic theory that mixture produces a homogeneous material product in which the ingredients no longer remain as such, the fruits of this tradition had only entered the mainstream of British natural philosophy in the early works of Robert Boyle. The peripatetic theory of "perfect mixture" had held sway among Aristotle commentators for almost two millenia when Newton was born in 1642.[3] Yet during Newton's years as an undergraduate in the early 1660's, Boyle employed existing alchemical arguments to wage a successful war against the Aristotelian theory of mixture, culminating in a series of publications that appeared almost exactly at the time when Newton first argued that white light too was heterogeneous. Within five years of Boyle's first publications on the corpuscular nature of matter, Newton had arrived at his own theory, also based on implicitly corpuscular presuppositions, that white light is composed of immutable rays of differing refrangibility. The congruence of these discoveries is a striking fact, but in and of itself, their timing could of course be coincidence. The second part of the present essay will therefore explore the similarities between Newton's demonstrations that white light is a mixture of unchanged colorfacient rays and Boyle's demonstrations that seemingly homogeneous mixtures are really composed of unchanged corpuscles. I will restrict myself here to cases where Newton was explicitly borrowing from Boyle's written work. In addition, I will provide linguistic evidence that Newton was in fact applying Boylean terminology about chymical compounds to the mixture of light. Although Newton employed this terminology in a cautious and heuristic fashion, it provides evidence, nonetheless, of his debt to the newly triumphant chymical corpuscularism of the seventeenth century.

The Theory of Perfect Mixture in Scholasticism

Chymistry in the seventeenth century comprehended a wide variety of activities and theories ranging from such technological pursuits as the making of alcoholic beverages, pigments, and salts, to the manufacture of drugs and the performing of iatrochemical cures, and finally, to the attempted transmutation of metals. One thing that characterized the theory espoused by almost all alchemists from the Middle Ages onwards, however, was a belief that the metals were composed of two principles, mercury and sulfur, to which Paracelsus in the mid-sixteenth century added the third principle, salt. By and large, alchemists had long believed that analytical processes such as calcination, sublimation, and dissolution in solvents could resolve minerals and metals into their preexistent components, namely their sulfur and mercury, or after Paracelsus, their mercury, sulfur, and salt.

It is not commonly appreciated by historians that this traditional alchemical emphasis on the analytic retrievability of the principles put alchemists at odds with a range of scholastic positions arguing for the nonretrievability of ingredients from a genuine mixture. In a word, the most widespread interpretations of Aristotelian matter theory in this period stated that it was not possible to re-isolate the initial constituents of a homogeneous substance once those constituents had combined to form a mixture, and such homogeneous mixts were widely thought to include materials as commonplace as metals, flesh, wood, milk, and wine. During the Late Middle Ages and the early modern period, this theory came increasingly into conflict with a host of empirical examples supplied above all by chymistry, a field where corpuscular theories of matter had been circulating in the Latin West since the thirteenth century. Indeed, alchemical writers were the first, I believe, to provide matter theories of any sort, including optical theories, based on experimental demonstrations of paired analysis and resynthesis. It was no accident that Robert Boyle, the famous seventeenth-century popularizer of the mechanical philosophy and debunker of Aristotelian mixture, was himself a chymist. He was, in fact, giving further articulation and modifications to the views of alchemists as expressed over a period of several hundred years. To make matters short, it was the field of chymistry that supplied Boyle's primary ammunition against early modern scholastic matter theory as taught in the universities. For chymistry provided a way out of the impasse resulting from a strict interpretation of substance and mixture first promulgated by Thomas Aquinas and later adopted by other scholastic schools that had forbidden the persistence and retrievability of ingredients within a mixture.

The degree to which early modern scholasticism was committed to the position that ingredients could not be retrieved from a genuine mixture has been largely overlooked by historians of science. By a "genuine mixture," of course, I refer to the Aristotelian concept of *mixis* – an absolutely homogeneous combination of ingredients, often called a "perfect mixture" by the scholastics. In order to understand the meaning of Aristotelian *mixis,* the contemporary reader must make a conscious effort to forget the terminology of modern chemistry, which refers to mechanical juxtapositions of particles as “mixtures” and distinguishes such uncombined ingredients from those that have entered into a “chemical compound” joined by “chemical bonds.” The language employed by chemists today reverses the terminology of Aristotle, for whom “mixture” meant a homogeneous combining of ingredients and “compound” or “composition” meant a mere juxtaposition of uncombined parts. Aristotle had claimed in Book I, Chapter 10 (328a10-12) of his *De generatione et corruptione* that genuine *mixis* occurred only when the ingredients of mixture acted upon one another to produce a state of absolute homogeneity. Otherwise, he asserted, a sufficiently keen-sighted person, such as the classical hero Lynceus, would be able to see the heterogeneous particles that made up what had seemed to be a genuinely uniform substance. Aristotle's predecessor Empedocles had of course espoused precisely the sort of theory that Aristotle was here debunking. Empedocles had maintained a century before Aristotle that the four elements were composed at the micro-level of immutable particles, which lay side-by-side to form compounds (what chemists today would call “mixtures”). Aristotle argued that such corpuscles could only form an apparent mixture, like wheat and barley in a jar: he dubbed such illusory mixture *synthesis* - literally "setting-together." Aristotle himself did not believe that the ingredients of a genuine mixture were incapable of retrieval. At *De generatione et corruptione* I 10 327b27-29 he argues the contrary, and his ancient followers, especially John Philoponus, spoke of separating mixtures by means of oiled sponges, river lettuce, and the like.[4] We are not speaking of the ancient commentators here, however, but rather of the scholastics of the Middle Ages and their early modern heirs.

The Jesuits, to name one early modern current, had adopted Thomas Aquinas as their master in theology, at the urging of Roberto Bellarmino in the 1590's.[5] Hence it is no surprise to find that the great Jesuit *De generatione et corruptione* commentaries, such as those of Franciscus Toletus and the Coimbrans, assume an explicitly Thomistic position on the subject of mixture. Even before the Jesuits appeared on the scene, the Thomistic view had become, as Anneliese Maier argued, the majority view among scholastics.[6] Like all scholastic Aristotelians, Thomas viewed matter as consisting of the four elements, fire, air, water, and earth. These in turn contained four "primary qualities" – hot and dry in fire, wet and hot in air, cold and wet in water, and dry and cold in earth. Although the pairs of these qualities along with an undifferentiated "prime matter" (*materia prima*) constituted the fundamental stage of material analysis, the primary qualities were not immutable, for the hot could pass away and be replaced by cold, just as the wet could pass away and be replaced by dry. This opened the door to the possibility of elemental transmutation: if, for example, the hot and dry in a sample of fire were replaced by cold and wet, that portion of fire would be transmuted into water.[7]

But the situation was still more complicated than this, for Thomas's hylomorphism insisted that Aristotelian *mixis*, the one type of mixture that led to a genuinely homogeneous product, could only occur if a new substantial form, called the "form of the mixture" (*forma mixti*), was imposed on the four elements.[8] This process occurred in a well-defined series of steps. First the four primary qualities of the elements produced, as a result of their mutual action and passion, a single medial quality preserving something of the extremes; this medial quality then provided the disposition necessary for the induction of the new substantial form, the form of the mixture. Yet in such a case, Thomas insisted, the imposition of the new form of the mixture meant that the four antecendent elements would be destroyed – the generation of the one entailed the corruption of the other. All that remained of the fire, air, water, and earth would be the primary qualities, the hot , cold, wet, and dry that had been paired within the elements before their destruction, and which were somehow responsible for the dispositive medial quality that prepared the way for the form of the mixture. Even here it is not clear that the four qualities that remained were the original ones underlying the elements or rather similar ones that had been newly generated, for in general Thomas insisted that the primary qualities were accidents of the substantial form. If the substantial form itself had been newly introduced to the ingredients, then how could its accidents be the same ones that had been present before in the preexistent elements (which had now been destroyed)? As for the elements themselves, they were now present within the mixture only *in virtute* or *virtualiter* – "virtually" – as a result of the said primary qualities.[9]

To employ a distinction made in many later scholastic treatments of mixture (though not in that of Thomas), one could not get the original ingredients back out again in number (*in numero*), since they had been destroyed by the very act of mixing. If one could perhaps retrieve fire, air, water, and earth that were the same as the original elements in species (*in specie*), there was no guarantee that they would return in the same relative quantities in which they had entered the mixture.[10] After all, the original fire, air, water, and earth had been destroyed by the process of mixture, and there was no reason to think that the primary qualities would reassemble into exactly the same pairings in proportions identical to those that they originally possessed. Hence the empirical correlation between input and output had been severed – mixture was effectively a black box linking substances with no shared material identity.

Newton, Boyle, and the Chymical Tradition of the Reduction to the Pristine State

Having given this overview of scholastic mixture-theory, I now want briefly to consider the period from about 1664 up to the publication and responses to Newton's famous "New theory about light and colors" published by Oldenburg in the *Philosophical Transactions* of the Royal Society in 1672. Here I will try to be very exact in my claims. What I want to argue here is that chymistry provided the young Newton with an important heuristic in his unfolding theory that white light is a heterogeneous mixture composed of immutable spectral colors. I do not mean to say that Newton found anything approximating this optical theory in his chymical sources, or even that the earliest phases of his discovery owed a significant debt to chymistry. To the contrary, Newton's early and serendipitous discovery that different colors are produced by rays of different refrangibility owes no obvious debt to chymical theory or practice. What is incontestable, however, is that the earliest descriptions of Newton's theory occur imbedded among extensive notes on chymistry taken by Newton from Robert Boyle, found in a portion of Newton's Cambridge notebook (now CU Add. 3996) entitled *Certain Philosophical Questions*, probably from around 1664, and in his more developed treatise found in Cambridge University Additional MS. 3975, probably from 1665-1666. Newton labelled both of these short treatises "Of Colours." For the sake of simplicity, I will call the version in *Certain Philosophical Questions* "Of Colours I" and the version in CU Add. 3975 "Of Colours II."[11] The appearance of chymistry in these tracts is in itself is not surprising, for Newton is known to have owed an important debt to Boyle's *Experiments Touching Colours*, a work on the colors of bodies, published in 1664. Boyle there tentatively proposes a theory that white light is modified by reflection and refraction to produce colors, performs experiments in color mixing by projecting one prism's spectrum upon that of another, and advises future researchers to carry out more extensive experiments with prisms.[12] While Boyle does not arrive at anything resembling Newton's bold claim that white light is actually a mixture of unaltered heterogeneous colors, the bulk of *Experiments Touching Colours* is in fact taken up with chymical processes that lead to color change as a result of minute corpuscles aggregating with one another and separating from one another. Boyle's other treatises of the period, such as *Certain Physiological Essays* (1661) and *The Origin of Forms and Qualities* (1666), employ extensive use of analysis and resynthesis to demonstrate the corpuscular nature of matter, a feature that is less prominent in *Experiments Touching Colours*.

It is further significant that Newton's early optical theory underwent major changes between "Of Colours I" and "Of Colours II." In the first treatise, Newton relied solely on observations of the colors produced when one looks at bodies through a prism. He interprets the differing refrangibility of the red and blue rays as being due to a difference in the speed of the light corpuscles. Furthermore, in "Of Colours I" he thinks that this speed can change, so that color mutation remains a possibility. All of this has changed by the time of "Of Colours II." In this treatise, Newton has begun experimenting with sunlight projected through prisms. He has observed the oblong shape of a prism projected on a wall about 21 feet distant, he has devised several experiments for resynthesizing the white light divided by the prism, and he has observed that a body of a given color will appear brighter when illuminated by a ray of the same color, whereas a body of a different color will appear fainter. Most importantly, in "Of Colours II" there is no more discussion of light corpuscles that change their speed, and indeed the evidence is that Newton had by this time come to the view that colors are immutable, though without stating this as a formal principle.[13]

There is another very significant feature of CU Add. 3975, the manuscript in which "Of Colours II" is found. This manuscript, unlike *Certain Philosophical Questions,* contains important notes explicitly taken from Boyle's *Certain Physiological Essays* and *The Origin of Forms and Qualities*, works in which Boyle described chymical analysis and synthesis at great length. Is it not then possible that Newton's research on light, which he considered from the time of his earliest recorded optical experiments to consist of material globules, transported some of Boyle's matter theory into the realm of optics? Can one perhaps even argue that Boyle's treatment of chymical analysis and synthesis encouraged Newton to move from a semi-Cartesian view of light corpuscles that can change their speed and hence the color that they produce to his mature position that colors are immutable, like the corpuscles arrived at by chymical analysis?

These questions are particularly significant in the light of recent research, which has revealed that Boyle was not so much the father of modern chemistry, as he is often depicted, as he was a committed Helmontian chymist with a powerful and lifelong interest in chrysopoeia, the transmutation of base metals into precious ones. Additionally, new work has revealed alchemical sources behind Boyle's famous corpuscular theory of matter. According to Boyle's corpuscular theory, particles of the smallest sort called *prima naturalia* combine to form larger aggregate corpuscles called *prima mixta* or "primary clusters," which can in turn recombine to form still larger clusters called "decompounded" or twice compounded particles - resembling what we would today call molecules. The odd term "decompounded" – having the sense of "further compounded" rather than "uncompounded" - is borrowed via Latin from the Greek grammatical term *parasynthetos*, which means "formed or derived from a compound word." Hence "to decompound" meant "to compound further," as in the case where the preposition *super* is added to the Latin noun *exaltare* (which already contains the preposition *ex*).[14] Boyle's hierarchical matter theory was heavily dependent on traditional alchemical theories with roots that lie in the medieval author Geber, who conceived of elementary corpuscles combining to form larger particles of sulfur and mercury, which in turn recombined to make up the minute corpuscles of metals per se. These theories were transmitted to Boyle by a variety of sources, but chief among them seems to have been Daniel Sennert, who was the direct source for Boyle's term *prima mixta.*[15]

Sennert embedded his corpuscularism within a sustained attack on the Aristotelian theory of perfect mixture, as it had been transmitted by the medieval and early modern scholastics. At this point, chymistry entered the picture in a highly significant way. As Sennert and Boyle argued, some of Aristotle's so-called perfect mixtures – such as blood and wine – could be subjected to distillation to yield their components. Even more importantly, the chymist could himself make seemingly perfect mixtures by dissolving metals in acid – after the violent dissolution of the metal, the perfectly clear solution could even be poured through filter paper without leaving any residue. Surely such a mixture of metal and acid was at least as homogeneous as Aristotle's examples of wine and blood. And yet, after dissolving his metal in acid, the chymist could then precipitate the metal out unchanged merely by adding an alkali, such as salt of tartar (potassium carbonate). These so-called reductions to the pristine state provided direct evidence against the Thomistic claim that the ingredients of a mixt could not be recaptured intact – the obvious conclusion to draw was that the bits of metal had simply been hidden within the solution all along in the form of indissoluble corpuscles or atoms. Hence the homogeneity of a host of seemingly uniform material substances was called into question by means of chymical experimentation. Indeed, it is no exaggeration to say that defeating the Aristotelian theory of perfect mixture in favor of corpuscularism with its emphasis on heterogeneity was an *idée fixe* with Boyle, which occupied an important place in his mechanical philosophy from his earliest works on natural science until his death in 1691. It is highly significant, I believe, that Boyle's most important works debunking scholastic mixture theory, the *Certain Physiological Essays* of 1661, the *Sceptical Chymist* of 1661, and the *Origin of Forms and Qualities* of 1666, were all in print in the years when Newton was formulating his theory that white light is a compound of immutable spectral colors. In fact, the first and last of these three works definitely served as sources for Newton in CU Add. 3975, the manuscript that contains the important second draft of his early treatise *Of Colours*.

Indeed, CU Add. 3975 contains an extract that recounts one of Boyle's most important reductions to the pristine state, where Boyle explicitly uses it to criticize the Thomistic theory of mixture.[16] The passage describes the dissolution of camphor in nitric or sulfuric acid. If sulfuric acid is used, the camphor forms a deep reddish solution, and loses its odor. Hence the camphor becomes unrecognizable as camphor, and seems to be perfectly mixed in the solution. But the mere addition of water will cause the camphor to return to its former state, including the reacquisition of its powerful scent. Boyle points out that this experiment throws considerable doubt on the scholastic theory that mixture entailed the loss of the initial ingredients. As he puts it,

> This Experiment may serve to countenance what we elsewhere argue against the Schools, touching the Controversie about Mistion. For whereas though some of them dissent, yet most of them maintain, that the Elements alwaies loose their Forms in the mix'd Bodies they constitute; and though if they had dexterously propos'd their Opinion, and limited their Assertions to some cases, perhaps the Doctrine might be tolerated: yet since they are wont to propose it crudely and universally, I cannot but take notice, how little tis favour'd by this Experiment; wherein even a mix'd Body (for such is Camphire) doth, in a further mistion, retain its Form and Nature, and may be immediately so divorced from the Body, to which it was united, as to turn, in a trice, to the manifest Exercise of its former Qualities.[17]

Hence Boyle views the camphor as having remained intact within the sulfuric acid, which merely caused it to alter its texture. The addition of water weakened the sulfuric acid, making it release the camphor, upon which the latter regained its usual qualities of whiteness and penetrating smell. Let us step back for a moment and consider the general form of Boyle's demonstration. First, one substance is mixed with another so that it loses its perceptible qualities – that is, the camphor loses its whiteness and its smell when mixed with the sulfuric acid. Then the camphor is reduced to its pristine state by adding water, whereon it regains its original qualities. To Boyle, this demonstrates that the camphor was present all along in the mixture, in the form of intact corpuscles. The mixture, in Aristotelian terms, was not a true mixture at all, but a compounding or juxtaposition of corpuscles.

There are many interesting features to Boyle's argument, and several that are pertinent to Newton. But for the moment I want to focus on Boyle's assumption that just because the camphor can be retrieved intact, it follows that the camphor was present in unaltered form all along in the sulfuric acid. Nowhere does Boyle explain why this must be the case. Why could the camphor not be regenerated from its ingredients rather than lurking in the mixture all along, in unchanged form? One needs no reminder of the fact that similar problems dogged Newton in his oft-repeated claim that white light consisted of unaltered and immutable colorfacient rays, which were merely separated by the prism on account of their unequal refrangibility. This problem was already raised by Robert Hooke in a letter to Oldenburg written only a week after Newton first presented his *New Theory About Light and Colours* in February, 1672. Hooke argues that there is no more reason to suppose that white light consists of immutable colorfacient rays than there is to suppose that the sounds made by an organ already exist in the air of its bellows.[18] Even though Newton had described the recombination of spectral colors to regain the white light from which they had been divided, Hooke felt no compulsion to accept that the rays responsible for the colors retained their integrity within the seemingly homogeneous white light before its refraction by a prism. Instead, he argued that the colors could have been manufactured by the initial act of refraction, as was the case in his own theory.

This makes one wonder why Hooke did not raise similar objections about Boyle's reductions of metals and camphor to the pristine state. Boyle's arguments for the permanence of metals and of camphor in acid solutions were structurally identical to those of Newton for the persistence of colorfacient rays in white light. In each case analysis provided evidence for the persistence of the ingredients within a mixture. Shouldn't Hooke have evinced the same skepticism towards Boyle's demonstrations that he did toward Newton's? Whatever Hooke's position should have been, the reality is that he did not doubt Boyle's claims about the persistence of ingredients dissolved in powerful solvents. Hooke's 1665 *Micrographia* is full of comments about the particles of metals that he believes to remain intact in acids, even though they are disguised within the solution until they are precipitated. Hooke in fact goes so far as to argue that because the compounds crystallized out of metallic solutions are transparent, therefore the individual metallic particles themselves must be transparent.[19] So why, then, did Hooke and others give analysis and synthesis such credence for determining the nature of the ingredients of a mixture in the case of material bodies and yet deny its validity in the case of light?

One could perhaps argue that the phenomena themselves were much better known in the case of metals than in that of light. Every metallurgist knew that one can recapture the dissolved metals from acids unchanged, but phenomena such as the elongated dispersion of a projected spectrum or the resynthesis of white light from spectral colors were, to put it mildly, not widely known before Newton. Nonetheless, the commonplace nature of acid solutions does not in itself address the issue. Even if one knew that the metal could always be regained intact from the solution, it did not automatically follow that the metal was in the solution all along rather than being regenerated from more primitive ingredients. Although one could detect the bitter taste of dissolved silver or the blue color of the solution that it typically made, the only way one had of knowing that these properties were ordinarily associated with silver was by comparing the solution either with the initial silver before it was dissolved or with the silver precipitated out of the solution. The properties of silver dissolved in acid are no more properties of ordinary undissolved silver than the spectral colors are perceptible properties of unrefracted white light.

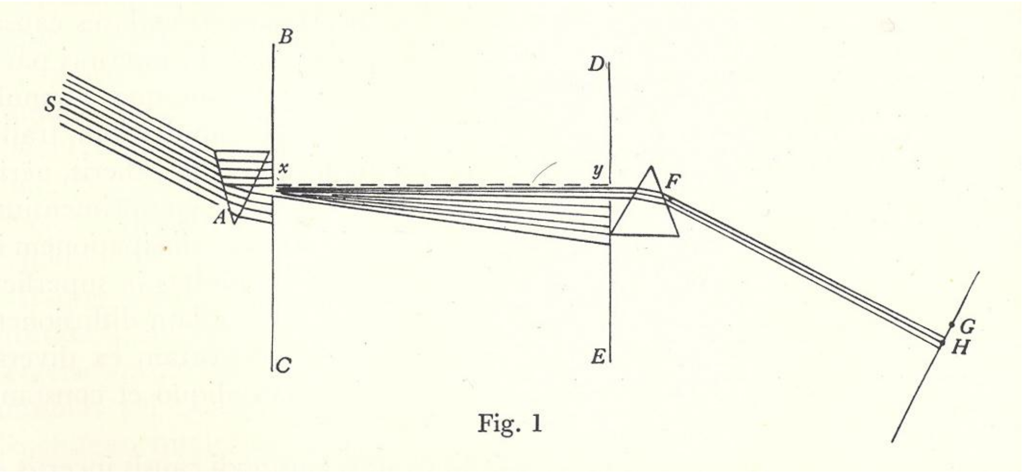
In their argument that metals and other substances retained their nature in compounds and solutions, however, Boyle and his predecessor Sennert had one great advantage over Newton. They were arguing against scholastic authors who had accepted as a matter of faith that the ingredients had been destroyed in the process of mixing them. Hence it was possible to turn the scholastics' own arguments against them. How could one reasonably argue that the dissolved silver had been regenerated *de novo* by the mere addition of potassium carbonate if one was committed to an Aristotelian theory that all metals had to be generated out of fumes beneath the surface of the earth? The scholastic authors would have had to abandon one important peripatetic theory in order to accommodate the other. And furthermore, if potassium carbonate could generate silver out of a silver solution, why could it not generate silver out of a solution of dissolved copper or iron? For that matter, since the initial ingredients had been destroyed, why should a powdered metal emerge from the solution instead of aardvarks or artichokes?

Scholastic authors had no satisfactory answers to these or a number of other, more technical objections raised by the reduction to the pristine state.[20] This was entirely unlike the situation with white light, where Newton's experiments with analysis and synthesis had essentially no precedent. Although Aristotle had held a mutation theory of color, of course, there was no pre-existing body of scholastic literature arguing against the persistence of the colors in white light precisely because it had not occurred to scholastic authors that white light was a mixture at all, homogeneous or otherwise.

In addition, Newton's own strong claims made it possible for his main opponents, such as Hooke, to shift the burden of proof onto him. Hooke was particularly adept at this, for he was content to call his own theory of color a hypothesis so long as Newton would do the same for his. Here Newton balked, however, for he believed that he had proven beyond any doubt that white light is composed of colorfacient rays that remain unaltered in the mixture. Although Newton acknowledged that he could not prove the corpuscular nature of light, which was hypothetical, he asserted that he could prove with mathematical certainty that white light contained the spectral rays *in actu*. How did Newton go about doing this? I will argue that Newton turned once again to chymistry, but to a slightly different type of experiment from that of the reduction to the pristine state. The reduction to the pristine state usually proceeded by first synthesizing a mixture (such as the mixture of silver and nitric acid) and then isolating one of its components by means of analysis (as in the reduction of silver by means of salt of tartar). Newton, however, would follow another type of chymical demonstration that inverted this order by starting with analysis and then passing to resynthesis. Let us begin with Newton's analysis of white light.

Newton's Resynthesis of White Light and Chymical Redintegration

Newton's 1672 *New Theory About Light and Colors* is famous, of course, for its inclusion of the *experimentum crucis*, the experiment using two prisms with two pierced boards between them to demonstrate that the rays producing individual spectral colors are always refracted at the same angle (see illustration below).



Newton's *experimentum crucis* from his second letter to Pardies (taken from H. W. Turnbull, ed., *The Correspondence of Isaac Newton* (Cambridge: Cambridge University Press, 1959), vol. I, p. 166).

The unequal yet fixed refrangibility of the spectral rays led Newton to the claim, as he puts it, that "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."[21] A great deal has been written about the *experimentum crucis*, of course, but what I want to focus on here is another experiment that appears at the end of the *New Theory*. There Newton advises that sunlight be passed through a single prism so that the oblong spectrum is projected on the opposite wall. After one has observed the spectrum, a lens is interposed between the prism and the wall, so that the refraction induced by the prism is reversed. The result is that the spectral colors recombine to form white light again.[22] Although this experiment has not received the same degree of scrutiny as the *experimentum crucis*, it would serve an important role in Newton's subsequent arguments with Hooke and Huygens.

Various passages in Newton's responses to his critics, as well as in the *Lectiones opticae* and the *Optica*, the extensive optical treatises that Newton composed after his appointment to Lucasian professor in 1669, but before the "New theory about light and colors" submitted to Oldenburg in 1672, reveal the function that Newton intended resynthesis to serve in his argument. The *experimentum crucis,* as Alan Shapiro has pointed out, was intended primarily to demonstrate the unequal refrangibility of the colorfacient rays, not to demonstrate color immutability.[23] Already in the early *Optica*, however, Newton had devised an experiment for proving the proposition that the spectral colors were immutable, by interposing a lens immediately after the first prism, which allowed one to focus the spectrum onto the second prism and thereby obtain a clearer separation of the spectral colors than the *experimentum crucis* allowed. The purer spectral colors that emerged from the second prism were incapable of analysis into more basic colors, did not act upon one another, and could not be changed by reflection from colored bodies, so Newton viewed them as absolutely immutable (see illustration below).

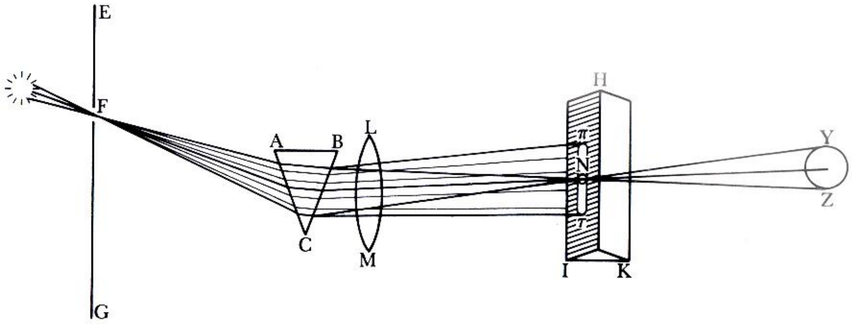


Figure II, 9

Newton's method of isolating the individual spectral colors by means of a lens placed before a second prism (from Alan Shapiro, The Optical Papers of Isaac Newton (Cambridge: Cambridge University Press, 1984), p. 456).

Once immutability was demonstrated to Newton's satisfaction, he then passed to his next proposition, that white light is a compounding of immutable spectral colors. It is important to understand how this proposition was linked in Newton's mind with the issue of immutability.[24] As Newton conceived it, if one grants that the colorfacient rays are unconditionally immutable, they must continue to be immutable once they are reassembled to form white light. Since they cannot be altered by any means, they must remain in act within the compound that we perceive as uniform white light. This point is worth reiterating in a slightly different way. Suppose that a critic argued the opposite of Newton's position, asserting that the prism's refraction does not merely separate the pre-existing colorfacient rays, but actually generates them out of white light that is itself homogeneous and uniform. Then let the critic concede that the newly generated colorfacient rays, once generated, are absolutely immutable. Here Newton's opponent would have made a potentially fatal concession. If he further admitted that the combined spectral rays could now generate white light, in accordance with the phenomena displayed by Newton’s experiments, he would be conceding the fact that he first denied, namely that the spectral rays exist unchanged within white light. Once unconditional immutability is granted, even if it is induced by refraction, the resynthesis of white light can only lead to the conclusion that the colorfacient rays exist in act within the white light that is produced.[25] One can therefore see the critical role that the resynthesis of white light, easily effected by means of a lens placed at a point where it could capture the analyzed spectral colors, played in Newton’s thought (see illustration below).

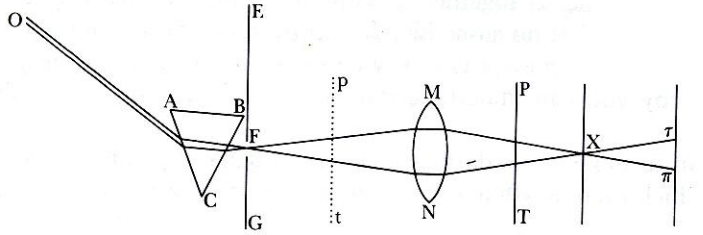


Figure II, 14

Newton’s resynthesis of white light from the spectral colors by means of a lens (from Shapiro, *Optical Papers,* p. 476).

This, then, was the general argumentative role that Newton allocated to resynthesis. If one allowed that the spectral rays separated by a prism were indeed immutable, then the production of white light from those unchangeable rays would show that that white light is a mere compounding of them. Unfortunately for Newton, however, the argument required that his opponents first admit the immutability of the spectral colors, a condition that some refused to acknowledge. As Shapiro has shown at length, Newton’s obscure comments about the production of pure spectral colors in the *New Theory* led to considerable confusion that undercut his expectations of immediate success. Because Newton did not describe a clear method of separating the spectral colors there in pure form, his opponents were able to devise methods that seemed to reveal that further colors could be derived from them.[26] Even before such demonstrations had been formulated, however, Hooke had already shown his unwillingness to take the bait. Already in his initial response to Newton’s “New Theory,” which appeared only a week after Newton presented his paper to the Royal Society, Hooke compared the generation of spectral colors from white light to the production of musical tones from strings and from the air within the bellows of a pipe organ. Hooke did not deny Newton’s claim that the prism divides light into its spectral colors, of course, but he saw no necessity to grant the existence of heterogeneous colorfacient rays already existent in white light before it encounters a prism.[27] In his second response to Newton’s theory, written a few months later, Hooke elaborated further on the string and pipe-organ comparisons –

> I have only this to say that he doth not bring any argument to prove that all colours were actually in every ray of light before it has sufferd a refraction, nor does his *experimentum Crucis* as he calls it prove that those proprietys of colourd rayes, which we find they have after their first Refraction, were Not generated by the said Refraction. for I may as well conclude that all the sounds that were produced by the motion of the [?strings] of a Lute were in the motion of the musitians fingers before he

> struck them, as that all colours wch are sensible after refraction were actually in the ray of light before Refraction. All that he doth prove by his *Experimentum Crucis* is that the colourd Radiations doe incline to ye Ray of light wth Divers angles, and that they doe persevere to be afterwards by succeeding mediums diversly refracted one from an other in the same proportion as at first, all wch may be, and yet noe colourd ray in the light before refraction; noe more then there is sound in the air of the bellows before it passt through the pipes of ye organ – for A ray of light may receives such an impression from the Refracting medium as may distinctly characterize it in after Refractions, in the same manner as the air of the bellows does receive a distinct tone from each pipe, each of which has afterwards a power of moving an harmonious body, and not of moving bodys of Differing tones.[28]

It is noteworthy that neither in his first response nor in this short elaboration did Hooke address the issue of resynthesis. He simply refused *ab initio* to accept that Newton had provided evidence for the immutability of the colorfacient rays before their initial exposure to a prism, while ignoring the fact that the rays could be reassembled to form white light. In this fashion Hooke managed to evade the conclusion that would follow from acknowledging that white light had been resynthesized from immutable spectral rays. One can begin to understand Newton’s frustration with Hooke and his other opponents when one considers their unwillingness to consider both the analytic and synthetic halves of his demonstration that white light is composed of heterogeneous rays.

But there were other ways for Newton's opponents to respond, even if they did take resynthesis into account, assuming that they did not accept the absolute immutability of the spectral rays. One response, quite simply, could have been that the light that one produces by resynthesis is not the same light that comes from the sun. Why was it necessary to assume that the resynthesized white light was identical to the original sunlight that entered the prism? Could it not simply have been regenerated from spectral rays that coalesced and lost their individual identity once thay came into contact with one another? In such a case, both the resynthesis of the white light and the repeated analysis of the spectral rays from it would yield products that were at best identical in *specie*, like the transmutable elements of Aristotelian natural philosophy. The resynthesized white light would in fact be regenerated from ingredients that were themselves generated *de novo* upon each successive analysis. A similar concern about the force of arguments based on resynthesis clearly occurred to Newton, for in his 1672 response to Hooke he described a method of excluding the possibility of a transmutation "wrought in the colours by their mutuall acting on one another, untill, like contrary Peripatetic Qualities, they become assimilated."[29] Newton's evidence consisted of a rotating wheel that allowed only one spectral color to be perceived at a time. By turning the wheel rapidly and letting the spectral colors fall in swift succession on the eye of the viewer, the illusion of whiteness inevitably ensued. Since the spectral colors were never simultaneously perceptible to the viewer, Newton was able to decouple the production of whiteness from the necessity of mixture in a conclusive fashion.

Despite the cleverness and demonstrative force of Newton's color-wheel experiment, he had still not proven that the white light resynthesized from refracted sunlight was identical to white light *tout court*. The very fact that our perception of whiteness on the strength of Newton's own theory was somehow illusory could weaken the claim that it must always be caused in the same way and by the same factors. As if to acknowledge this fact, Huygens suggested in 1673 that a light perceived as white might well arise from the combination of blue and yellow alone. Huygens' suggestion would lead Newton eventually to modify his theory, and to admit that he had not synthesized white light *simpliciter*, but merely sunlight.[30] Even before this, Newton had himself been aware of the fact that the green produced from the refraction of sunlight was not the same as the green made by mixing blue and yellow, since the former green was indecomposable.[31] The inability of human vision to distinguish such composite and simple colors clearly made an approach based on "maker's knowledge," where the production of an effect acted as a warrant for the correct knowledge of its principles, suspect at best.[32]

But this argument, when extended to the resynthesis of sunlight, would fly in the face of the empiricist principles that Newton's major early source, the arch-mechanical philosopher Robert Boyle, held most dear. In a very important passage of the *Optica*, Newton responds to this type of objection at some length. After pointing out that sunlight itself is constantly refracted by the atmosphere and reflected by clouds, not to mention the refraction that it must suffer upon entering our eyes, Newton says the following –

> Yet, since the sun's direct light is perceived to be white, and that color is not one of the primitives but may be shown to be generated by a mixture; and since there is no sensible difference between original light and that

> which is compounded from diversely colored rays, it must not be doubted that both are of the same nature.[33]

In short, the perceptible identity of the whiteness of sunlight and of the resynthesized white light acts as a warrant of their real identity. The fact that both the direct white light of the sun and the artificially recompounded white light color bodies with the same colors, refract into the same spectrum, and cannot be sensibly distinguished from one another provide sufficient evidence that they are indeed identical.[34] To dispute this position would be to argue explicitly against principles that lay at the basis of the mechanical philosophy, at least in the form that Robert Boyle enunciated it. Consider, for example, Boyle's comments, without doubt of alchemical origin, about the possibile identity of natural and artificial gold –

> And therefore not onely the Generality of Chymists, but diverse Philosophers, and, what is more, some Schoolmen themselves, maintain it to be possible to Transmute the ignobler Mettals into Gold; which argues, that if a Man could bring any Parcel of Matter to be Yellow, and Malleable, and Ponderous, and Fixt in the Fire, and upon the Test, and indissoluble in *Aqua Fortis*, and in some to have a concurrence of all those Accidents, by which Men try True Gold from False, they would take it for True Gold without scruple. And in this case the generality of Mankind would leave the School-Doctors to dispute, whether being a Factitious Body, (as made by the Chymists art,) it have the Substantial Form of

> Gold…. And indeed, since to every Determinate *Species* of Bodies, there doth belong more then One Quality, and for the most part a concurrence of Many is so Essential to That sort of Bodies, that the want of any of them is sufficient to exclude it from belonging to that *Species*: there needs no more to discriminate sufficiently any One kind of Bodies from all the Bodies in the World, that are not of that kind."[35]

Newton's early argument that natural sunlight and resynthesized sunlight make the same colors appear in bodies, refract the same spectral colors, and cannot be otherwise distinguished from one another finds its analogue in the various metallurgical tests that Boyle suggests should be used to determine the identity of natural and artificial gold. Just as Newton was content to argue that the white light produced by resynthesis was identical to natural sunlight before its analysis, so Boyle was happy to claim that a synthetic gold that passed all the assaying tests for natural gold would be identical to that natural gold. To argue otherwise would have been to invite back the imperceptible substantial forms of the scholastics, unknowable entities that were responsible for the different species into which natural things fell. Substantial forms underwrote the distinction between artificial and natural entities in a way that no mechanical philosoper could tolerate. To Boyle, on the contrary, it made no difference whether a substance had been broken down into its primitive constituents and then built back up again artificially, so long as the substance retained those properties that were deemed to be essential to it. This principle permeates Boyle's works, particularly *The Origin of Forms and Qualities* and *Certain Physiological Essays,* the very works that Newton was extracting while devising his own experiments to demonstrate color immutability and the mixing of the colorfacient rays to make white light.

Now I want to return briefly to another feature of Boyle's experimentation that may well have served as Newton's inspiration for his important experiments with the resynthesis of white light. This method of decomposition followed by recomposition, I submit, is precisely the method that Boyle called "redintegration" of a body by chymical means, only here Newton has transferred this chymical method to the analysis and synthesis of sunlight. The classic Boylean description of redintegration had appeared already in his *Certain Physiological Essays* of 1661, where Boyle describes the dissolution of saltpeter into its ingredients and the subsequent recombination of those ingredients to arrive once more at saltpeter.[36] In simplest terms, Boyle's experiment worked by injecting burning charcoal into molten saltpeter, and thus igniting it. This resulted in the release of nitrogen and carbon in combination with oxygen, leaving a non-volatile residue of "fixed niter" that resembled salt of tartar (potassium carbonate – in reality it *was* potassium carbonate). Knowing that spirit of niter (nitric acid) could be produced by the thermal decomposition of niter, Boyle then added spirit of niter to the tartar-like residue, and acquired a product that resembled the original saltpeter in all its significant properties. Employing the principle of substantial identity based on identity of sensible properties that we encountered in the case of gold, Boyle argued that the product was genuine niter. He was then able to conclude that niter itself is merely a compound of two very different materials, namely spirit of niter and fixed niter, which we would today call an acid and a base.[37] In *The Origin of Forms and Qualities*, Boyle would elaborate on this redintegration further, and also describe experiments aimed at redintegrating turpentine and stibnite, the ore of antimony.

Now let us return to Newton. The fact that Newton was thinking about the composition of white light in Boylean terms is not just borne out by the structural similarity of his prism experiments and Boyle's redintegration of saltpeter, but also by the terminology that Newton employs when describing this series of experiments in his optical lectures. Both in the *Lectiones opticae* and the *Optica*, Newton speaks of the sunlight reconstituted from spectral colors as being an *albedo redintegrata* - quite literally a redintegrated whiteness.[38] In the *Optica*, as I have pointed out, he explicitly argues that it is the redintegration of the white light that proves beyond any reasonable doubt that it is actually composed of a mixture of colorfacient rays.[39] Although one might argue that this agreement of Newton's terminology with that of Boyle is mere coincidence, there is direct evidence that Newton had already read about Boyle's experiments with redintegration before composing either the *Lectiones opticae* or the *Optica.* In the same year as Newton's famous *annus mirabilis*, 1666, the year in which he claimed to have discovered the heterogeneity of white light, Boyle had published his *Origin of Forms and Qualities.* Indeed, the very manuscript in which Newton recorded his first experiments with the resynthesis of white light from the spectral colors, CU add. 3975, also contains extensive notes drawn from Boyle's *Origin of Forms* on the redintegration of stibnite and turpentine.[40] It is clear, then, that chymical redintegration was a phenomenon that interested Newton, and one that he could easily have adapted to his optics from his reading in Boyle's chymistry.

If we now briefly consider Newton's April 1673 reply to his critic Huygens, we will find other important clues, also of a terminological nature, that reveal a Boylean influence. Shapiro has argued in a persuasive article that Newton's conception of white light as a mixture of immutable color-producing rays owes an important debt to comments that Boyle made in his *Experiments Touching Colors* about the so-called painters' primaries – blue, red, and yellow.[41] The theory that all other colors originate from these three was not old in Newton's day, and he seems to have derived it partly from a direct reading of Boyle's work. The mixing of pigments acquired particular significance for Newton in the response to Huygens.

What is interesting in this for us is Newton's use of Robert Boyle's peculiar corpuscular terminology. In arguing against Huygens' view that only yellow and blue may be responsible for the production of white light, Newton says that even if experiment revealed this result it would not be significant. The yellow and blue would themselves have to be compound colors, or as Newton says -

> But what Mr. Hugens can deduce from hence I see not. For the two colours [i.e. yellow and blue] were compounded of all others, & so the resulting white to speake properly was compounded of them all & onely decompounded of those two.[42]

As we can see, Newton has borrowed Boyle's unusual terminology whereby preliminary mixtures are "compounded" from simple ingredients and these compounds are in turn recombined or “decompounded” to make more complex mixtures. Huygen’s white can be produced from blue and yellow only if the blue and yellow are already compounds rather than simple colors, so that the white is actually a decompounded color containing all the spectral primaries. Newton then goes on to demonstrate the force of his argument by analogy between the composition of white light from the spectral colors and the making of a grey powder by mixing variously colored powders. Here too he employs Boyle’s compositional stages of mixture, saying that a decompounded grey can be made from an orange and blue that are themselves compounded colors composed of simpler ones.

Conclusion

Let me conclude, finally, by summarizing my claims as follows. Newton’s principal object of attack in much of the “New theory about light and colors” and the optical lectures was the idea that white light is “transmuted” into the spectral colors by refraction. Instead of this being the case, he wanted to show that the colorfacient rays are themselves immutable, and retain their “form” or “disposition” to produce the sensation of distinct colors within the eye.[43] At the same time, he wished to show that white light itself is a mixture of these immutable spectral rays, which do not affect one another at all when they are compounded, but only act on the sense of sight to produce the sensation of whiteness. Newton’s principal way of demonstrating this was by means of repeated analyses and syntheses of light – exactly the method that Boyle used in the chymical realm for showing that saltpeter, stibnite, turpentine, and other substances were produced out of unchanging corpuscles that could be dissassembled and reassembled like the parts of a watch. Boyle's redintegration experiments in turn derive from the Sennertian tradition of the reduction to the pristine state and from the increased emphasis on analysis and synthesis that one sees in the chymistry of Joan Baptista Van Helmont.[44] The origins of this analytic-synthetic tradition in chymistry lie in the Geberian alchemy of the late Middle Ages, which attempted to demonstrate that metals and minerals are composed of heterogeneous particles retaining their substantial identity while undergoing the separation and recombination that results in phenomenal change. Viewing Newton's major chymical source, Robert Boyle, in the light of contemporary practice rather than presenting him anachronistically as the father of modern chemistry therefore opens considerable vistas. It now becomes possible to see Newton's experimental decomposition and redintegration of white light as owing a significant debt to a practical and theoretical tradition of alchemical analysis and synthesis whose origins recede well into the Middle Ages. Although Newton was of course deeply influenced by the optics of Descartes and Hooke, we must not ignore his transformation of paired chymical analysis and synthesis, long used to reveal the heterogeneity of material substances, into a tool for demonstrating the same fact in the realm of light and color.

Notes

[*] The author would like to offer his thanks to Alan E. Shapiro and Jed Buchwald, both of whom read the paper and offered very constructive criticisms. Thanks are also owed to Domenico Bertoloni Meli for his encouragement.

[1] This is not to say that no other scholars have noticed the parallelism between Newton's analyses and syntheses of white light and chemical analysis and synthesis. See for example Noretta Koertge, "Analysis as a Method of Discovery during the Scientific Revolution," in Thomas Nickles, ed., *Scientific Discovery, Logic, and Rationality* (Dordrecht: Reidel:, 1980), pp. 139-157; see pp. 151-152.

[2] For a full account of this tradition up to the time of Boyle, see William R. Newman, *Atoms and Alchemy: Chymistry and the Experimental Origins of the Scientific Revolution* (Chicago: University of Chicago Press, 2006).

[3] As I argue in *Atoms and Alchemy*, it is important to distinguish between the views of Aristotle himself on mixture and the tradition inaugurated by Thomas Aquinas in the thirteenth century. Although Aristotle believed that "perfect mixture" implied homogeneity, he did not deny that the ingredients of such mixture could be regained

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intact. Thomas, and his followers in this matter, such as John Duns Scotus, held that the forms of the initial ingredients were destroyed by the process of mixture itself; hence the ingredients as such (i.e. numerically identical ingredients) could not be recaptured.

[4] Aristotle, *De generatione et corruptione* at I 10 327b27-29 that "it is clear that the ingredients of a mixture first come together after having been separate and can be separated again" (in the translation of E. S. Forster). For Philoponos, see de Haas, 1999, 26, n. 22.

[5] Matton, Sylvain , "Les théologiens de la Compagnie de Jésus et l'alchimie," in Frank Greiner, ed., *Aspects de la tradition alchimique au XVII*^{e} *siècle* (Paris: *S.É.H.A.,* 1998), pp. 383-501; see p. 383.

[6] Anneliese Maier, *An Der Grenze Von Scholastik Und Naturwissenschaft* (Roma: Edizioni di Storia e Letteratura, 1952, 2. Auflage), p. 89.

[7] Aristotle points out that this process has a cyclical character: if the dry in fire passes away and is replaced by wet, the fire will become air; if the hot in air is replaced by cold, the air will become water; if the wet in water is replaced by dry, the water will become earth; and if the cold in earth is replaced by hot, the earth will become fire. See Aristotle, *De generatione et corruptione* II 3-4 330a30-332a2, especially II 4 331b2-4.

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[8] Maier, *An Der Grenze,* pp. 31-35 *et passim.* A much inferior study to Maier's, though still useful on certain points, is Xaver Pfeifer, *Die Controverse über das Beharren der Elemente in den Verbindungen von Aristoteles bis zur Gegenwart, Programm zum Schlusse des Studienjahrs 1878/79* (Dillingen: Adalbert Kold, 1879). Thomas's discussion of mixture may be found in Thomas Aquinas, *De mixtione elementorum* in *Sancti Thomae de Aquino opera omnia,* (Rome: Editori de San Tommaso, 1976), vol. 43, 127-130.. As Maier points out, the corresponding section of Thomas's *De generatione et corruptione* commentary is interpolated. See Maier, 1952, 31-32.

[9] Maier, *An der Grenze*, pp. 33-35. Thomas's position on mixture fit very nicely with his view that every substance could have only one substantial form (the so-called "unity of forms" theory). Nonetheless, the "unity of forms" theory did not follow necessarily from Thomas's theory of mixture, since many scholastic authors who upheld the *opinio modernorum* on mixture believed that one substantial form could be subordinated to another, even in a single substance. Those authors who maintained a plurality of substantial forms in a given substance often invoked the human body and soul as a case of such subordination. Although the soul was the substantial form of man *per se*, the body had its own subordinate form, which accounted for its ability to resist decomposition into the elements for some time after death. See Roberto Zavalloni, O.F.M., *Richard de Mediavilla et la controverse sur la pluralité des formes. Textes inédits et étude critique. [Philosophes medievaux. Tome II.*] (Louvain: Éditions de l'institut supérieur de philosophie, 1951), 303-381.

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[10] A good account of the *in numero/in specie* distinction is found in the *De generatione et corruptione* commentary of Franciscus Toletus. Toletus makes it clear that the scholastic distinction hinged on the absence or presence of substantial corruption. See Toletus, *Commentaria, una cum quaestionibus, in duos libros Aristotelis, de generatione et coruptione* (Venice: Juntas, 1603), fol. 93v.

[11] Both "Of Colours I" and "Of Colours II" have been edited with valuable commentary in J.E. McGuire and Martin Tamny, eds, *Certain Philosophical Questions: Newton's Trinity Notebook* (Cambridge: CUP, 1983), pp. 431-442 and 466-489. The reader who wishes to see the chymical text in which "Of Colours II" was imbedded by Newton, however, will have to consult the edition of CU Add. 3975 at http://www.webapp1.dlib.indiana.edu/newton/mss/norm/ALCH00110/.

[12] For Boyle's influence on Newton's optics, see Alan E. Shapiro, *The Optical Papers of Isaac Newton, Volume I, The Optical Lectures 1670-1672* (Cambridge: CUP, 1984), pp. 4-7 and Shapiro, *Fits, Passions, and Paroxysms* (Cambridge: Cambridge University Press, 1993), pp. 99-102, 120.

[13] A detailed discussion of Newton's evolving optical theory between "Of Colours I" and "Of Colours II" may be found in McGuire and Tamny, *Certain Philosophical Questions*, pp. 241-274.

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[14] See the *Oxford English Dictionary*, online version, *sub voce*, consulted 17 September 2007. "Superexaltare" means "to exalt further."

[15] Robert Boyle, *The History of Particular Qualities,* in Michael Hunter and Edwad B. Davis, *The Works of Robert Boyle*, 14 vols. (London: Pickering and Chatto, 1999-2000), vol. 6, p. 274.

[16] Newton, CU Add. 3975, 32v-33r, from *The Chymistry of Isaac Newton*, http://webapp1.dlib.indiana.edu/newton/mss/norm/ALCH00110/. .

[17] Boyle, *The Origine of Formes and Qualities*, in Hunter and Davis, *Works*, vol. 5, p. 396.

[18] Hooke to Oldenburg, responding to Newton's *New Theory* , 15 February 1671/2, H. W. Turnbull, ed. *The Correspondence of Isaac Newton* (Cambridge: Cambridge University Press, 1959), vol. 1, letter 44, p. 111.

[19] Robert Hooke, *Micrographia* (London: Royal Society, 1665), c[2v] (where Hooke discusses the taste of metals disolved in acids), and pp. 72-3 (where Hooke argues that the particles of metals are transparent since their solutions and crystals are transparent).

[20] For these objections, see Newman, *Atoms and Alchemy*, pp. 106-123. The precipitate would actually be silver carbonate rather than powdered metallic silver, but since silver

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carbonate reduces to silver upon simple heating, Sennert reasonable supposed that the precipitate was merely finely divided silver.

[21] Newton to Oldenburg, 6 February 1671/2, *Correspondence*, vol. 1, letter 40, p. 97.

[22] Newton to Oldenburg, 6 February 1671/2, *Correspondence*, vol. 1, letter 40, p. 101.

[23] Alan E. Shapiro, "The Evolving Structure of Newton's Theory of White Light and Color," *Isis* 71(1980), pp. 213-214.

[24] The situation is actually more complicated than Newton envisioned it, if we take into account more modern wave-theories of light that rely on Fourier analysis and other techniques unavailable to either Newton or his opponents. See A.I. Sabra, *Theories of Light from Descartes to Newton* (Cambridge: Cambridge University Press, 1981), pp. 261, 280-281.

[25] These points have already been made, albeit in briefer form, by Alan E. Shapiro in his magisterial article "The Gradual Acceptance of Newton's Theory of Light and Color, 1672-1727," *Perspectives on Science* 4(1996), pp. 59-140; see pp. 106-107.

[26] Shapiro, "Gradual Acceptance," pp. 73-80, 107-119, *et passim.*

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[27] Hooke to Oldenburg, 15 February 1671/2 responding to Newton's *New Theory*, in Turnbull, *Correspondence*, vol. 1, letter 44, p. 111.

[28] Hooke, apparently to Brouncker, c. June 1672, in Turnbull, *Correspondence*, vol. 1, letter 71, pp. 202-203.

[29] Newton to Oldenburg, 11 June 1672, in Turnbull, *Correspondence,* vol. 1, letter 67, p. 182.

[30] Oldenburg to Newton, 18 January 1672/3, in Turnbull, *Correspondence*, vol. 1, letter 99, pp. 255- 256. See Shapiro, "Evolving Structure," pp. 211-235, pp. 215-216, 222.

[31] Newton to Oldenburg, 11 June 1672, in Turnbull, *Correspondence,* vol. 1, p. 181. See Shapiro, "Evolving Structure," p. 222.

[32] For "maker's knowledge," see Antonio Pérez-Ramos, *Francis Bacon's Idea of Sciece and the Maker's Knowledge Tradition* (Oxford: Clarendon Press, 1988).

[33] Shapiro, *Optical Papers*, vol. 1, p. 505.

[34] Shapiro, *Optical Papers,* vol. 1, p. 143: "Any one falling upon the same body, whatever it be, colors it with the same colors; any one, if it is transmitted through a prism, shows the same colors and peforms the same way in every respect."

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[35] Boyle, *Origin of Forms and Qualities*, in *Works*, vol. 5, pp. 322-323.

[36] See William R. Newman and Lawrence M. Principe, *Tried in the Fire,* Chapter Five, for Worsley. See also John T. Young, *Faith, Medical Alchemy and Natural Philosophy: Johann Moriaen, Reformed Intelligencer and the Hartlib Circle*, (Brookfield, VT: Ashgate, 1998), pp. 183-216, esp. 198-200.

[37] The experiment is clearly described by Boyle, *Certain Physiological Essays*, Hunter and Davis, *Works*, vol. 2, pp. 92-96.

[38] Shapiro, *Optical Papers*, vol. 1, p. 162, line 9; and 516, line 16. .

[39] Shapiro, *Optical Papers*, vol. 1, p. 504: "Et eadem ratione constat reflexam albedinem similiter compositam esse, siquidem (ut dixi) redintegrata est...."

[40] Newton, CU add. 3975, fol. 32v, from *The Chymistry of Isaac Newton*, http://webapp1.dlib.indiana.edu/newton/mss/norm/ALCH00110/:
"The purenesse of this redintigrated Antimony
seemed to proceede from the recesse of so much Sulphur
which is not at all necessary to the constitution of Antimony
though perhaps too the vitrum a top might proceede from
the avolation of two much Antimony from the superficciall

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parts. pag 265<.> But redintegration of Bodys succeded best in Turpentine
for a very cleare liquor being distilld from it was againe
put to the caput Mortuum (which was very dry brittle Transparent
sleeke & red but purely yellow when poudered)
it was immediatly dissolved part of it into a deepe red
Balsome. And by further disgestion in a large well
stopt Glasse became perfect Turpentine againe
as all men judgd by the smell & Taste. pag 268 of for<ms>"

[41] Alan E. Shapiro, "Artists' Colors and Newton's Colors," *Isis* 85(1994), pp. 600-630; see pp. 614-615.

[42] Newton to Oldenburg, responding to Huygens, 3 April 1673, in Newton, *Correspondence*, vol. 1, letter 103, p. 265.

[43] For the term "transmutation," see Shapiro, *Optical Papers*, vol. 1, p. 472. For "forms" and "dispositions," see p. 505.

[44] For the influence of Van Helmont on Boyle, see William R. Newman and Lawrence M. Principe, *Alchemy Tried in the Fire: Starkey, Boyle, and the Fate of Helmontian Chymistry* (Chicago: University of Chicago Press, 2002).