# A History of Optics

## *From Greek Antiquity to the Nineteenth Century*

OLIVIER DARRIGOL

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# 3

# NEWTON'S OPTICS

In a world still impregnated with the scholastic concept of light as the multiplication of intentional species through a medium, the most natural way to subsume the theory of light under mechanics was to adopt a mechanical medium similar to the air for sound propagation or to liquids for the transmission of pressure. This was indeed the choice of some of the greatest natural philosophers of the seventeenth century, as we saw in the previous chapter. Yet there was another option: a partial return to ancient Greek atomism, which could be reinterpreted as a kind of mechanical philosophy since it purported to deduce all phenomena and sensations from the collisions of immutable atoms. Although Newton's optics is far too complex to be reduced to a variety of atomism, its espousal of the corpuscular nature of light partly depended on the contemporary revival of this ancient philosophy.

The first section of this chapter briefly describes the new varieties of atomism. The second is devoted to Newton's early emissionist concept of light and to the accompanying insights into the nature of colors. The third section recounts the response of the main protagonists of the wave or pulse theory of light, with emphasis on a revealing polemics with Hooke. The fourth section describes Newton's public though unpublished hypothesis of an optical ether whose states affect the motion of the rays or of the light corpuscles. The structure and contents of the *Opticks* of 1704, as well as the queries appended to its successive editions, are described in the fifth and last section.

## 3.1 Neo-atomist theories

The chief protagonists of seventeenth-century atomism were Isaac Beeckman in the Netherlands, Pierre Gassendi in France, and Walter Charleton in England. Beeckman's variety of mechanical philosophy reduced all matter to arrangements of atoms and all sensations to the impact of atoms on the sensory organ. Although his interest in optics was mostly limited to the Dutch art of telescope making, he made clear that he espoused a neo-atomist doctrine in which light was a flux of atoms emitted by the luminaries. In his understanding of vision, the atoms of light were reflected by an illuminated object and impacted the retina to form a picture of it. That is to say: he rejected the flying effigies of the ancient atomists; he adapted his atomism to Alhazen's idea that light was responsible for vision; and he accepted Kepler's analysis of the eye. Beeckman's diary contains numerous allusions to this view. For instance, in 1616 he wrote: "[In the hearing process] the air itself … strikes our ear, in the same manner as the flame of a candle is dispersed through the entire room and [then] is called *light*." Thus, light and sound were equally material. In the same entry, Beeckman made clear that tiny particles of the air (torn off and projected by the sounding body) conveyed sound, and that air was much coarser than light. In an entry of 1618, he explained refraction by a differential adherence of the "globules of rays" with the globules of the refracting surface. In other occasions he used the expression "atoms of light."[1]

The French astronomer and philosopher Pierre Gassendi met Beeckman in the late 1620s, and judged him to be "the best philosopher I have yet encountered." Gassendi criticized Descartes's pretense to reach truth by introspection, and opted for a revised Epicurean atomism as the best hypothesis for interpreting our sensorial experience. In his turgid *Physica*, written toward the middle of the century, he defined light as follows:

> It appears that light in a luminous body is nothing but tiny corpuscles which, configured in a certain configuration, then transferred from this body with an extreme velocity, and received by the organ of vision, are able to move this organ and to create the sensation called vision.

Gassendi then defined rays as the rectilinear trajectory of the corpuscles, explained reflection and refraction by analogy with the motion of a ball at the border between two porous media with unequal amounts of pores, colors as an Aristotelian mixture of light and shadow. Regarding the process of vision, he accepted the essentials of Kepler's theory, although he had earlier speculated with his patron Nicolas-Claude Fabri Peiresc that the crystalline served to correct the inversion of the retinal image.[2]

In England, Walter Charleton's *Physiologia* of 1654 propagated Gassendi's ideas, with a few nuances. Charleton's definition of vision was slightly more Epicurean than Gassendi's, as Charleton hesitated to abandon the idea of particles ejected from the surface of luminous bodies:

> The SIGHT … discerns the exterior Forms of Objects, by the reception either of certain *Substantial*, or *Corporeal Emanations*, by the sollicitation of *Light* incident upon, and reflected from them, as it were Direpted from their superficial parts, and trajected through a diaphanous Medium, in a direct line to the eye: or, of *Light it self*, proceeding in streight lines from Lucid bodies, or in reflex from opace, in such contextures, as exactly respond in order and position of parts, to the superficial Figure of the object, obverted to the eye.

The analogy with sound induced him to favor the second alternative:

> As it is the property of *Light*, transfigured into colours, to represent the different Conditions and Qualities of bodies in their superficial parts, according to the different Modification and Direction of its rayes, either simply or frequently reflexed from them, through the Aer, to the Eye: so is it the property of *Sounds* to represent the different Conditions and Qualities of bodies, by the mediation of the Aer percussed

[1]Beeckman 1939–1953, vol.1, pp. 92 (1616), 211 (1618); vol. 2, p. 240 (1623, atoms of light); also vol. 1, p. 28 (light the agent of vision), and vol. 3, p. 49 (Lucretius's effigies refuted).

[2]Gassendi to Peiresc [late 1620s], in Tannizey de Larroque 1688–1698, vol. 4, pp. 178–81; Gassendi [1649], vol. 1, pp. 422–32 (*De luce*), 441–9 (*De simulacris*), citation on p. 422; vol. 2, pp. 369–82 (*De visu et visione*), esp. pp. 380–1 (Kepler's theory); 1642, pp. 16–18 (redressed retinal image), 59 (light corporeal). Cf. Brett 1908, pp. 73–8; Fischer 2005a, 2005b, pp. 33–7; Lodoro 2007, pp. 69–72.

> and broken by their violent superficial impaction, or collision, and configurate into swarms of small consimilar masses, accomodable to the Ear.

Charleton also hesitated on the nature of colors: in one section of his treatise he made them a contamination of the reflected light by particles of the surface of the illuminated body; in another he adopted the Aristotelian idea of a fine mixture of light and shadow.[3]

Atomism being commonly regarded as a threat to Christianism, Gassendi and Charleton strove to demonstrate the compatibility of their philosophy with the existence of God and the immortality of the soul. So too did the British supporters of Descartes's variety of mechanical philosophy. The Cambridge neo-Platonist Henry More praised Descartes's divide between *res cogitans* and *res extensa*, as he took it to confirm the Platonic notion of the immateriality of the soul. In a treatise of 1659 on this subject he nonetheless rejected Descartes's identification of matter with extension as well as the reduction of every interaction to the contact of rigid particles. More regarded matter as the continuous union of "indescerpible" (indivisible) parts with no definite shape. A space-filling natural spirit accounted for the interaction of these parts.[4]

## 3.2 Newton's early investigations

*Globules and colors*

In philosophical notes written around 1664, Isaac Newton paraphrased Charleton's deduction of the necessity of atoms, praised More's argument for the existence of indescerpible parts, and criticized much of Descartes's *Principia*. Newton agreed with Charleton that matter was necessarily composed of a finite number of indivisible parts with vacuous interstices and not of Descartes's space-filling elements. He rejected the Cartesian explanation of light as pressure between the globules of the second element by arguing that, if it were true, light would be generated when the globules were pressed by gravity, by the motion of the earth, or even by the motion of the observer. In a later manuscript on gravitation and the equilibrium of fluids, he showed that pressure was transmitted uniformly through the whole mass of a fluid in equilibrium. This result implicitly contradicted Descartes's explanation of the rectilinear propagation of light.[5]

When Newton began his researches on colors, he had already excluded Descartes's theory and adopted the atomist view of light as a stream of "globules" moving very quickly in straight lines. Accordingly, he reinterpreted Descartes's proofs of the laws of reflection and refraction in terms of the actual motion of individual corpuscles of light. In this view, refraction should alter the velocity of the corpuscles of light. In the earliest optical experiments described in the philosophical notes of 1664, Newton used a prism as a velocity analyzer of the corpuscles of light. From observations of a paper painted in two different colors through a prism, he concluded that color corresponded to the velocity (or

[3]Charleton 1654, pp. 136 (citation), 145 (colors), 209 (citation), 191 (colors). Cf. Kargon 1964.

[4]More 1659. Cf. Henry 2007.

[5]Newton [c. 1664], pp. 1–3 (atoms), 32 (against Descartes on light); *De gravitatione* [c. 1668?]. On the roots of Newton's atomism, cf. Westfall 1962. On his criticism of Descartes, cf. Shapiro 1974.

momentum) of the particles as they struck the retina while white and black corresponded to heterogeneous velocity. He sketched two theories of the colors of bodies, one in which color was produced by enhancement of a velocity class among particles of equal mass, another in which it resulted from enhancement of a momentum class among particles of different masses and equal initial velocity. At that stage, Newton already had the idea that white light was a heterogeneous mixture of lights of different colors and that a prism could be used to separate the various colored components.[6]

In a later manuscript "Of colours," Newton described a more direct consequence of this idea. He passed a narrow beam of sunlight, selected by a small hole on the shutter of his window, through a prism, and observed the resulting spot of light on a distant wall (see Fig. 3.1). The spot did not have the circular shape it would have had if all rays had been equally refracted (the prism being in the position of minimum deviation for which the angles of incidence and emergence are equal). It had an elongated shape and displayed a series of colors of which Newton estimated the characteristic refractions. In a posterior experiment, which he would later call *experimentum crucis*, he showed that the resulting colored rays had a well-defined refraction by a second prism (see Fig. 3.2), by an amount

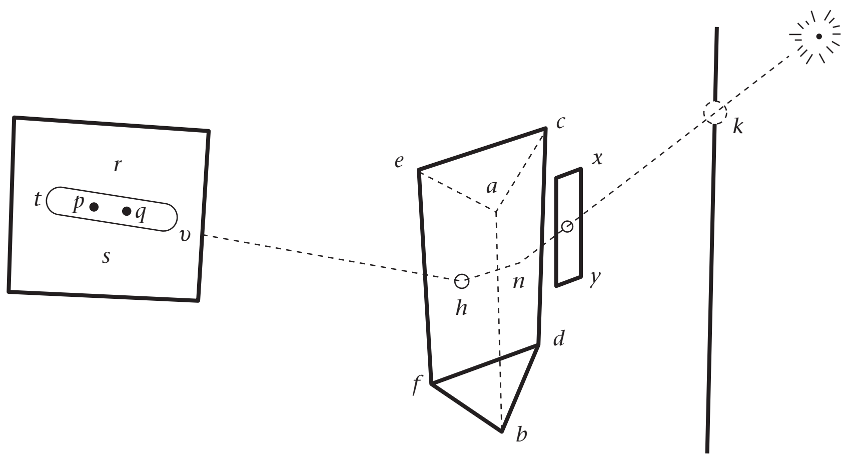


**Fig.** 3.1. Newton's setup for the spectrum of white light. From Newton [c. 1666], 2. Courtesy of *The Newton Project* (http://www.newtonproject.sussex.ac.uk). The light from the sun passes through the hole *k* in the blinds of the window and through the diaphragm *xy*. The resulting beam is deflected by the prism *eacbdf* (in the position of minimal deflection) and produces the oblong spectrum *tv* on the screen.

[6]Newton, "Of colours," in Newton [c. 1664], pp. 63–8. Cf. Westfall 1980, pp. 156–61. A large number of Newton's manuscripts are available through the excellent *Newton Project* directed by Rob Iliffe, http://www.newtonproject.sussex.ac.uk .The mechanisms that Newton then imagined to explain the colors of bodies allowed for a change of velocity of momentum of the globules of the reflected light, and therefore did not comply with the immutability of simple colors.

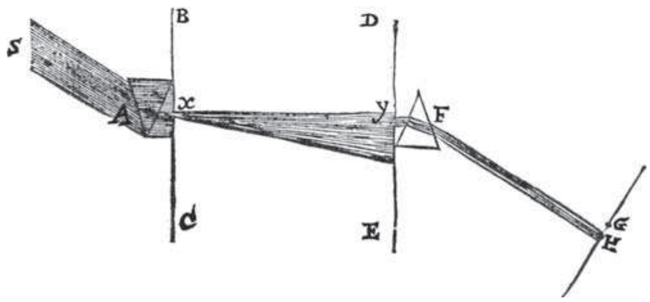


**Fig.** 3.2. Newton's *experimentum crucis*.[8] The light S from a small opening on the window of a dark room passes through the prism A and the hole x in the diaphragm BC. The portion of this beam selected by the second diaphragm DE enters the prism F at well-defined incidence and emerges at a well-defined angle, as verified from the narrowness of the spot on the screen GH. This angle depends on the simple color selected by the hole y. From Newton 1672d, p. 5016.

depending on the color. Also, he obtained white light by superposing the various spectral colors.[7]

In the same manuscript "Of colours," Newton described experiments with two prisms firmly pressed against each other in which he accidentally observed the colored fringes produced by trapped bubbles of airs. In order to control the thickness of the interstitial air, he used a convex lens pressed on a glass plate. He explained the resulting colored rings by "vibrations of the medium" with a well-defined "thickness of pulses" for each simple color. He presumably had in hand the essentials of his later theory of thin plates, according to which the corpuscles of light produce periodic progressive waves in the film of air or ether when entering it. The corpuscles are either reflected or transmitted by the second air/glass interface, depending on the length of the waves. These considerations are probably contemporary to Newton's reading Hooke's *Micrographia* (1665), although Newton does not cite Hooke in this regard.[9]

Newton's idea of waves by impact of bodies (the corpuscles of light) on an interface probably derived from analogy with the waves produced by a stone thrown into water or with the sound produced by hitting a bell. That Newton had an acoustic analogy in mind can be inferred from his contemporary analysis of the way visual information is transferred from the retina to the brain:

> Light seldom striks upon the parts of grosse bodys (as may bee seen in its passing through them), its reflection & refraction is made by the diversity of æthers, & therefore

[7]Newton [c. 1666], pp. 2, 12. Cf. Shapiro 1984, "Introduction"; Westfall 1980, pp. 118, 166–74. According to Newman [2011], Newton's new emphasis on the immutability of simple colors and on the synthesis of white light resulted from his familiarity with Boyle's anti-Aristotelian concept of chemical mixture, in which the corpuscles of the mixed substances survived the mixing.

[8]In the *experimentum crucis* the prisms need not be in the position of minimum deflection because the holes *x* and *y* select a precise ray between the two prisms. The color of this ray is simple to the extent that the direction of the rays of the incoming sunbeam is well defined.

[9]Newton [c. 1666], pp. 9–11, 21. Cf. Shapiro 1993, pp. 8–12, chap. 2.

> its effect on the Retina can only bee to make this vibrate which motion then must bee either carried in the optick nerve to the sensorium or produce other motions that are carried thither … [This motion] can noe way bee conveyed to the sensorium so entirely as by the æther it selfe. Nay granting mee but that ther are pipes filld with a pure transparent liquor passing from the ey to the sensorium & the vibrating motion of the æther will of necessity run along thither. Ffor nothing interrupts that motion but reflecting surfaces, & therefore also that motion cannot stray through the reflecting surfaces of the pipe but must rush along (like a sound in a trunk) intire to the sensorium. And that vision bee thus made is very conformable to the sense of hearing which is made by like vibrations.

This citation shows that Newton believed that both vision and hearing implied the excitation of the vibrations of some part of the relevant organ, and the propagation of this vibration to the brain through a channeled medium. Nothing more can be said on his understanding of ether or air waves, which was probably precarious at this early stage of his natural philosophy.[10]

*To the Royal Society*

Newton integrated these results in the Optical lectures that he delivered in 1670–1672 from the Lucasian chair in which he succeeded Isaac Barrow. As an evident consequence of his theory, optical lenses have different foci for each spectral component of white light, a defect now called chromatic aberration. In late 1671, Barrow brought to the Royal Society a telescope that Newton had built with a spherical mirror instead of the objective lens, in order to avoid this defect (see Fig. 3.3). This instrument caused a sensation, and the

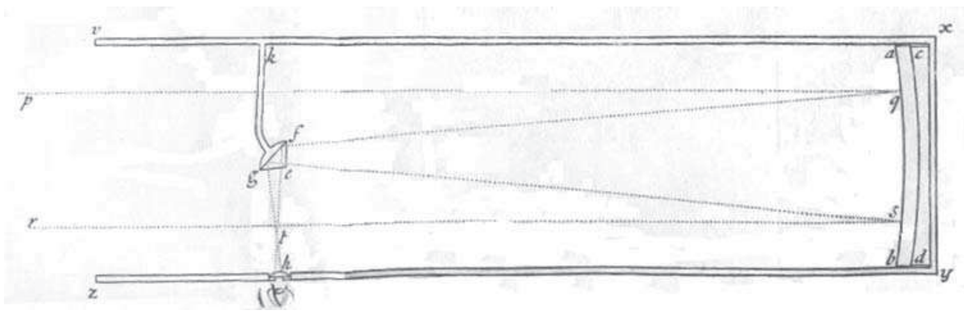


**Fig.** 3.3. Newton's refractor. The light beam pr from a distant object is reflected on the glass mirror acbd (the convex side cd is silvered) to converge on the glass prism fge. After reflection at the bottom fg of this prism the light passes through a semi-convex lens whose focus f coincides with the focus of the mirror-prism system. From Newton 1704, book 1, part 1, fig. 29.

[10]Newton [c. 1666], pp. 19–20. As can be judged from later writings (1675), the first obscure sentence of the citation means that light cannot travel along the curved path of a nerve by repeated scattering by the particles of the liquor contained in the nerves, because such scattering would imply opacity (besides, Newton explains reflection and refraction by a change of ether density, not by collisions between light corpuscles and material corpuscles, because this process would no yield a well-defined direction of reflection or refraction).

Society elected Newton on 11 January 1872. On 18 January, Newton promised to its secretary Henry Oldenburg soon to give the theory that had induced him to construct the telescope: "the oddest, if not the most considerable detection w$^{ch}$ hath hitherto beene made in the operations of Nature." Newton kept his word in the famous letter of 6 February 1672 that Oldenburg printed in the *Transactions* of the Society under the title "New theory about light and colours."[11]

Newton's letter begins with the first spectrum experiment:

> SIR,
> TO perform my late promise to you, I shall without further ceremony acquaint you, that in the beginning of the Year 1666 (at which time I applyed my self to the grinding of Optick glasses of other figures than *Spherical*,) I procured me a Triangular glass-Prisme, to try therewith the celebrated *Phænomena* of *Colours*. And in order thereto having darkened my chamber, and made a small hole in my window-shuts, to let in a convenient quantity of the Suns light, I placed my Prisme at his entrance, that it might be thereby refracted to the opposite wall. It was at first a very pleasing divertisement, to view the vivid and intense colours produced thereby; but after a while applying my self to consider them more circumspectly, I became surprised to see them in an *oblong* form; which, according to the received laws of Refraction, I expected should have been *circular*.

Newton then carefully eliminated "suspicions" that this effect might be caused by irregularities in the glass of the prism, the finite size of the sun, or a curvature of the emerging rays. He went on:

> The gradual removal of these suspitions, at length led me to the *Experimentum Crucis*, which was this: I took two boards, and placed one of them close behind the Prisme at the window, so that the light might pass through a small hole, made in it for the purpose, and fall on the other board, which I placed at about 12 feet distance, having first made a small hole in it also, for some of that Incident light to pass through. Then I placed another Prisme behind this second board, so that the light, trajected through both the boards, might pass through that also, and be again refracted before it arrived at the wall. This done, I took the first Prisme in my hand, and turned it to and fro slowly about its *Axis*, so much as to make the several parts of the Image, cast on the second board, successively pass through the hole in it, that I might observe to what places on the wall the second Prisme would refract them. And I saw by the variation of those places, that the light, tending to that end of the Image, towards which the refraction of the first Prisme was made, did in the second Prisme suffer a Refraction considerably greater than the light tending to the other end. And so the true cause of the length of that Image was detected to be no other, than that *Light* consists of *Rays differently refrangible*, which, without any respect to a difference in their incidence, were, according to their degrees of refrangibility, transmitted towards divers parts of the wall.

[11] Newton to Oldenburg, 18 January 1672, in Turnbull 1959–77, vol. 1, p. 82; Newton 1672a. Cf. Westfall 1980, pp. 232–7. For the optical lectures, cf. Shapiro 1984. Newton did not doubt that the sine law of refraction applied to simple colors, although his experimental proof of this point was untypically floppy: cf. Lohne 1961.

Newton briefly described the chromatic aberration of lenses, and he recalled his success in building a reflecting telescope in which this cause of aberration did not exist. He formulated the heterogeneity of white light independently of the corpuscular interpretation: "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." His only allusion to the corporeality of light was brief and cautious:[12]

> These things being so, it can no longer be disputed, whether there be colours in the dark, nor whether they be the qualities of the objects we see, no nor perhaps, whether Light be a Body. For, since Colours are the *qualities* of Light, having its Rays for their intire and immediate subject, how can we think those Rays *qualities* also, unless one quality may be the subject of and sustain another; which in effect is to call it *Substance*. We should not know Bodies for substances, were it not for their sensible qualities, and the Principal of those being now found due to something else, we have as good reason to believe that to be a Substance also.
>
> Besides, whoever thought any quality to be a *heterogeneous* aggregate, such as Light is discovered to be. But, to determine more absolutely, what Light is, after what manner refracted, and by what modes or actions it produceth in our minds the Phantasms of Colours, is not so easie. And I shall not mingle conjectures with certainties.

## 3.3 Early response

*Pardies and Huygens*

The most successful of the results announced in this letter was the reflecting telescope, which the members of the Royal Society had already tested, and which Newton described in a subsequent letter. No one denied that Newton had produced the first working telescope of this kind, although James Gregory and Laurent Cassegrain had earlier made similar proposals. Newton's considerations on colors soon underwent criticism from three authorities in optics: Pardies, Huygens, and Hooke. Pardies politely suggested that the divergence of the refracted beam in Newton's first prism experiment might result from ordinary refraction. He promptly apologized after Newton told him that his publication already contained the answer: in the selected position of minimum deflection for the prism, the two refractions at the prism preserve the parallelism of the beam.[13]

After some initial praise, Huygens reproached Newton with introducing a continuous spectrum of simple colors as he agreed with Hooke that two base colors (yellow and blue) should be sufficient to generate all other colors. He added that Hooke's assumption would be easier to explain mechanically than Newton's. Newton replied that the simplicity of every component of the spectrum was an incontrovertible fact of experiment, and that the corpuscular hypothesis provided an easy mechanical interpretation of this diversity if the simple colors corresponded to the size or velocity of the corpuscles. The latter argument failed to convince Huygens, who favored a wave theory with none of the periodicity that

[12] Newton 1672a, p. 3081.

[13] Newton 1672b (reflector); Pardies 1672a, 1672b; Newton 1672c, 1672d.

could have represented simple colors. Nevertheless, he soon accepted Newton's experimental results as well as his analysis of chromatic aberration.[14]

*A debate with Hooke*

In a condescending letter, Hooke approved Newton's experiments so much as to suggest that he knew them all in advance. He nonetheless rejected the heterogeneity of white light and the corpuscular hypothesis. A clever acoustic analogy inspired his criticism:[15]

> But why there is a necessity, that all those motions, or whatever else it be that makes colours, should be originally in the simple rays of light, I do not yet understand the necessity of, no more than that all those sounds must be in the air of the bellows, which are afterwards heard to issue from the organ-pipes; or in the string, which are afterwards, by different stoppings and strikings produced; which string (by the way) is a pretty representation of the shape of a refracted ray to the eye; and the manner of it may be somewhat imagined by the similitude thereof: for the ray is like the string, strained between the luminous object and the eye, and the stop or fingers is like the refracting surface, on the one side of which the string hath no motion, on the other a vibrating one. Now we may say indeed and imagine, that the rest or streightness of the string is caused by the cessation of motions, or coalition of all vibrations; and that all the vibrations are dormant in it: but yet it seems more natural to me to imagine it the other way.

In his haughty reply, Newton maintained that the heterogeneity of white light was a direct consequence of his experiments and that it did not depend on any hypothesis on the nature of light. He added that his own preferred hypothesis, that light was made of corpuscles, was not so different from the objector's view:[16]

> For certainly it has a much greater affinity with his own *Hypothesis*, than he seems to be aware of; the Vibrations of the *Æther* being as useful and necessary in *this*, as in *his*. For, assuming the Rays of Light to be small bodies, emitted every way from Shining substances, those, when they impinge on any Refracting or Reflecting superficies, must as necessarily excite Vibrations in the *æther*, as Stones do in water when thrown into it. And supposing these Vibrations to be of several depths or thicknesses, accordingly as they are excited by the said corpuscular rays of various sizes and velocities; of what use they will be for explicating the manner of Reflection and Refraction, the production of Heat by the Sun-beams, the Emission of Light from burning, putrefying, or other substances, whose parts are vehemently agitated, the *Phænomena* of thin transparent Plates and Bubles, and of all Natural bodies, the Manner of Vision, and the Difference of Colors, as also their Harmony and Discord.

For the sake of comparison, Newton characterized Hooke's hypothesis as follows:

> *That the parts of bodies, when briskly agitated, do excite Vibrations in the Æther, which are propagated every way from those bodies in streight lines, and cause a Sensation of Light by beating and dashing against the bottom of the Eye, something after the manner*

[14] Huygens 1673a, 1673b; Newton 1673a, 1673b.

[15] Hooke [1672], p. 11. On this exchange, cf. Westfall 1980, pp. 241–7.

[16] Newton 1672e, p. 5087.

> *that Vibrations in the Air cause a Sensation of Sound by beating against the Organs of Hearing.*

He then proceeded to demonstrate that this hypothesis, if properly developed, justified his conception of white light and all his other considerations on colors:[17]

> Now, the most free and natural Application of this *Hypothesis* to the Solution of *phænomena* I take to be this: *That* the agitated parts of bodies, according to their several sizes, figures, and motions, do excite Vibrations in the *æther* of various depths or bignesses, which being promiscuously propagated through that *Medium* to our Eyes, effect in us a Sensation of Light of a *White* colour; but if by any means those of unequal bignesses be separated from one another, the largest beget a Sensation of a *Red* colour, the least or shortest, of a deep *Violet*, and the intermediat ones, of intermediat colors; much after the manner that bodies, according to their several sizes, shapes, and motions, excite vibrations in the Air of various bignesses, which, according to those bignesses, make several Tones in Sound: *That* the largest Vibrations are best able to overcome the resistance of a Refracting superficies, and so break through it with least Refraction; whence the Vibrations of several bignesses, that is, the Rays of several Colors, which are blended together in Light, must be parted from one another by Refraction, and so cause the *Phænomena* of *Prismes* and other refracting substances: And *that* it depends on the thickness of a thin transparent Plate or Buble, whether a Vibration shall be *reflected* at its further superficies, or *transmitted*; so that, according to the number of vibrations, interceding the two superficies, they may be reflected or transmitted for many successive thicknesses. And since the Vibrations which make *Blew* and *Violet*, are supposed shorter than those which make *Red* and *Yellow*, they must be reflected at a less thickness of the Plate: Which is sufficient to explicate all the ordinary *phænomena* of those Plates or Bubles, and also of all natural bodies, whose parts are like so many fragments of such Plates.

This remarkable sketch of the wave theory of light contains the first known suggestion that frequency is the parameter of color, based on analogy with the pitch of sounds. More exactly, Newton speaks of the "bigness" of the vibrations. Under this word, he certainly meant to include the wavelength, as the analogy with sound and the interpretation of the colors of thin plates in terms of this bigness clearly indicate. He also meant the amplitude of the vibration, as indicated by the proposed interpretation of dispersion. The reason for this seeming contradiction (which has puzzled many commentators) is to be found in the analogy with water waves. The waves created by throwing a stone into water have lengths and amplitudes both growing with the size of the stone, so that early wave theorists commonly assumed a correlation between length and amplitude.[18]

After arguing the compatibility of the wave hypothesis with his theory of colors, Newton proceeded to refute this hypothesis:

> For, to me, the Fundamental Supposition 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

[17]Ibid., p. 5088. [18]Cf. Sabra 1963; Blay 1980.

> way into the quiescent Medium, where they are terminated by it … What I have said of this, may easily be applied to all other *Mechanical Hypotheses*, in which Light is supposed to be caused by any Pression or Motion whatsoever, excited in the *æther* by the agitated parts of Luminous bodies. For, it seems impossible, that any of those Motions or Pressions can be propagated in *Streight* lines without the like spreading every way into the shadow'd Medium, on which they border.

Newton here expressed for the first time what he believed to be the definitive objection against any medium theory. As we saw, he probably reached this conclusion in a critical analysis of the concept of pressure in Descartes's *Principia*.[19]

In his next paragraph, Newton insisted that his theory of colors did not require any specific hypothesis on the nature of light. Somewhat surprisingly, he went on with an acoustic analogy for the colors of bodies:

> For if *Light* be consider'd abstractly without respect to any *Hypothesis*, I can *as* easily conceive, that the several parts of a shining body may emit rays of differing colours and other qualities, of all which Light is constituted, *as* that the several parts of a false or uneven string, or of uneavenly agitated water in a Brook or Cataract, or the several Pipes of an Organ inspired all at once, or all the variety of Sounding bodies in the world together, should produce sounds of several Tones, and propagate them through the Air confusedly intermixt. And, if there were any natural bodies that could *reflect* sounds of one tone, and stifle or *transmit* those of another; then, as the *Echo* of a confused Aggregat of all Tones would be that particular Tone, which the Echoing body is disposed to reflect; so, since (even by the *Animadversor's* concessions) there are bodies apt to *reflect* rays of one colour, and stifle or *transmit* those of another; I can as easily conceive, that those bodies, when illuminated by a mixture of all colours, must appear of that colour only which they reflect.

The reason why Newton here develops an analogy that would seem to favor the wave hypothesis becomes clear in the next few lines, in which he condemns Hooke's use of the acoustic analogy to disprove the heterogeneity of white light:[20]

> But when the *Objector* would insinuate a difficulty in these things, by alluding to Sounds in the string of a *M*usical instrument before percussion, or in the Air of an Organ Bellowes before its arrival at the Pipes; I must confess, I understand it as little, as if one had spoken of Light in a piece of Wood before it be set on fire, or in the oyl of a Lamp before it ascend up the match to feed the flame.

While Newton here caught a genuine weakness of Hooke's analogy, he failed to see that Hooke had unveiled a genuine logical error in his deduction of the heterogeneity of light. Newton's three basic facts, the splitting of a ray of white light by a prism, the stability of the resulting colored rays, and the possibility of synthesizing white light by superposing these colored rays, by no means imply that white light should be a mixture of these rays. As Hooke's own theory of colors already suggested, the superposition of lights of different colors does not need to preserve the individual properties of these lights. Hooke made

[19] Newton 1672c, p. 5089. [20] Ibid., p. 5091.

these points in an attempted reply to Newton. He also rehearsed the string and organ analogies, without answering Newton's objection (that the air from the bellow, not being a sound, could not be compared to white light), but adding a clever comparison between the refraction of simple colors and the resonance of pure tones:[21]

> 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 than there is sound in the air of the bellows before it passt through the pipes of ye organ—for A ray of light may receive such an impression from the Refraction 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 powere of moving an harmonious body, and not of moving bodys of Differing tones.

In the modern wave optics based on Fourier analysis, the superposition of periodic signals may well be a signal that does not exhibit any periodicity whatsoever, and yet spectroscopes are able to separate the abstractly superposed components of this signal. Hooke's reasoning anticipated this point. Newton's and others' failure to appreciate it presumably derived from their unconscious integration of a minimal consequence of every corpuscular theory of light: any stable property of light should be represented as a stable individual property of the corpuscles. They implicitly reasoned as follows: since simple colors are stable (the color cannot be altered by any optical device), they must correspond to a stable, preexisting property of the individual corpuscles of light; therefore, white light is heterogeneous.[22]

## 3.4 An hypothesis

*Corpuscles and ethers*

Newton resumed his investigation of the colors of thin films in 1671–72 and communicated the improved results and the accompanying theory in 1675 to the Royal Society. On this occasion, he no longer refrained from hypotheses and developed a theory in which light corpuscles and ether waves both played a role. On the corpuscular or ray side, he assumed that light consisted of "swift corpuscles" or "any impulse or motion of any other medium" that propagated in rays. At any rate, light could not be ethereal vibrations, because these would fail to explain rectilinear propagation, the existence of opaque bodies, and the periodicity of the colors of thin films. The acoustic analogy illustrated the two first impossibilities: "Were [light] these vibrations, it ought always to verge copiously in

[21] Hooke to Lord Brouncker, June 1672, in Turnbull 1959–77, vol. 1, pp. 198–203, on pp. 202–3.

[22] This minimal consequence of the corpuscular view is what Buchwald 1989 (pp. xviii, 50–1) (following Thomas Young) called "selectionism" in the context of early nineteenth-century optics.

crooked lines into the dark or quiescent medium, destroying all shadows; and to comply readily with any crooked pores or passages, as sounds do."[23]

Newton nevertheless gave many reasons to assume a pervasive, multi-component ether in the explanation of thermal, gravitational, electric, magnetic, chemical, physiological, and optical phenomena. In the optical context, he explained the refraction of light by a different density of the ether contained in different substances. As in Descartes's reasoning (to which Newton referred), this difference implies a perpendicular force curving the rays in the vicinity of the "aethereal superficies" between two media. Newton then associated the refrangibility of a simple color with the "bigness or strength" of the corresponding rays. The violet rays, which are the most refracted, must be the weakest; the red ones the strongest. As refraction does not change the bigness, color cannot be altered by any further refraction.[24]

*Ether waves*

Newton then introduced ether waves as a means of explaining partial reflection:

> And for explaining this, I suppose, that the rays, when they impinge on the rigid resisting æthereal superficies, as they are acted upon by it, so they react upon it and cause vibrations in it, as stones thrown into water do in its surface; and that these vibrations are propagated every way into both the rarer and the denser mediums; as the vibrations of air, which cause sound, are from a stroke, but yet continue strongest where they began, and alternately contract and dilate the æther in that physical superficies ... And so supposing that light, impinging on a refracting or reflecting æthereal superficies, puts it into a vibrating motion, that physical superficies being by the perpetual appulse of rays always kept in a vibrating motion, and the æther therein continually expanded and compressed by turns; if a ray of light impinge upon it, while it is much compressed, I suppose it is then too dense and stiff to let the ray pass through, and so reflects it; but the rays, that impinge on it at other times, when it is either expanded by the interval of two vibrations, or not too much compressed and condensed, go through and are refracted.

Newton here assumed more analogy between air and the ether than anyone had done before. Earlier in the same text he wrote: "There is an æthereal medium much of the same constitution with air, but far rarer, subtler, and more strongly elastic." Moreover, he clearly related sound and its propagation to the compressibility and elasticity of the air, a rare insight at that time.[25]

Newton next elaborated his earlier idea that light excited vibrations of the retina transmitted to the brain through the substance of the optical nerve:

[23] Newton [1675], pp. 254–5.

[24] Ibid., pp. 255–8. On p. 263, Newton writes: "And, because refraction only severs them, and changes not the bigness or strength of the rays, thence it is, that after they are once well severed, refraction cannot make any further changes in their colour." Thus, he implicitly identifies the "bigness" with the mass of the corpuscles. On Newton's ether, see also Newton to Boyle, 28 February 1679, in Birch 1756–7, vol. 1, pp. 70–3. The variety of spirits included in Newton's aether and its tensional quality may have reflected his alchemical concerns, although his optical ether was mostly mechanical: cf. Westfall 1980, pp. 269–71.

[25] Newton [1675], pp. 258, 253. See also Newton to Oldenburg, 10 January 1676, in Turnbull 1959–77, vol. 2: "That aether is a finer degree of air and air a vibrating Medium are old notions and ye principles I go upon."

> I suppose, that as bodies of various sizes, densities, or sensations, do by percussion or other action excite sounds of various tones, and consequently vibrations in the air of various bigness; so when the rays of light, by impinging on the stiff refracting superficies, excite vibrations in the æther, those rays, whatever they be, as they happen to differ in magnitude, strength or vigour, excite vibrations of various bigness … And therefore the ends of the capillamenta of the optic nerve, which pave or face the retina, being such refracting superficies, when the rays impinge upon them, they must there excite these vibrations, which vibrations (like those of sound in a trunk or trumpet) will run along the aqueous pores or crystalline pith of the capillamenta through the optic nerves into the sensorium (which light itself cannot do) and there, I suppose, affect the sense with various colours, according to their bigness and mixture; the biggest with the strongest colours, reds and yellows; the least with the weakest, blues and violets; the middle with green, and a confusion of all with white, much after the manner, that in the sense of hearing, nature makes use of aereal vibrations of several bignesses to generate sounds of divers tones; for the analogy of nature is to be observed.

Newton here emphasized the acoustic analogy and related it to a general principle, "the analogy of nature," which he would often evoke in his philosophy. As a reflection of God's perfection, nature had to be conformable to itself, to present all sorts of analogies between different phenomena and different scales.[26]

### *The music of colors*

In this frame of mind, Newton did not hesitate to revive the Pythagorean analogy between the harmonies of colors and sounds:

> And further, as the harmony and discord of sounds proceed from the proportions of the aereal vibrations, so may the harmony of some colours, as of golden and blue, and the discord of others, as of red and blue, proceed from the proportions of the æthereal. And possibly colour may be distinguished into its principal degrees, red, orange, yellow, green, blue, indigo, and deep violet, on the same ground, that sound within an eighth is graduated into tones.

Newton believed his observations of the spectrum of white light to confirm this musical pattern. He drew the diagram of Fig. 3.4, in which the lines separating two different colors are placed as the frets of a monochord that would yield the notes DEFGABC of the modern English scale. He had earlier reflected on the best means to divide the octave, although his interest in this problem was more mathematical than musical.[27]

[26]Newton [1675], p. 262. See also Newton to Briggs, 25 April 1685, in Turnbull 1959–77, vol. 2, pp. 417–19: "Nature is after all simple, and is normally self-consistent throughout an immense variety of effects, by maintaining the same mode of operation. But how much more so in the causes of the related senses?" On Newton's "analogy of nature," cf., e.g., Shapiro 1993, pp. 43–4.

[27]Newton [1675], 262–3; Newton [c. 1665], ff. 137r–143v; Musical calculations, Cambridge University Library, Add. 4000, ff. 104r–113v and Add. 3958 (B), f. 31r. Cf. Wardhaugh 2006, pp. 103–7, 253–9; McGuire and Rattansi 1966; N. Hutchison 2004; Gouk 1986, 1988, 1999 (chap. 7). Hooke had compared musical and chromatic harmony a few weeks earlier at the Royal Society: see above, chap. 2, p. 55. Newton also used a musical division for the colors of thin plates: cf. Shapiro 1993, pp. 89–92, 174.

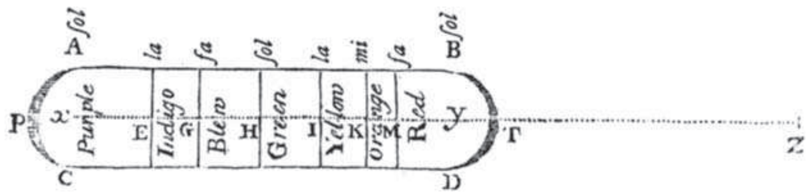


**Fig.** 3.4. Newton's analogy between spectrum and musical scale. From Newton [1675], p. 262. The points x, E, G, H, I, K, M mark the ends of a vibrating string beginning at z. The corresponding sounds (marked in a contemporary notation that has nothing to do with the present naming of notes in Latin languages; DEFGABC in the modern English scale) yield the limits between two successive colors of the spectrum ABCD. For instance, y is an octave higher than x and I is a fifth higher than x because yz/xz = 1/2 and Iz/xz = 2/3.

Newton then described his investigation of the colors of thin plates, and the ensuing theory of the colors of bodies. He did so to greater length and precision in another paper of the same year. As in his manuscripts of the mid-1660s, he imagined the impact of the rays on the first surface of the plate to produce ether waves. Transmission or reflection of the rays at the second surface depended on whether the waves, having reached this surface faster than the rays, produced a condensation or a rarefaction of the ether in its neighborhood. For the colors of bodies, Newton recycled Hooke's analogy with the colors of thin plates. He imagined the bodies to be made of transparent particles immersed in a medium of smaller optical index. This picture provided a link between the size of the particles of bodies and their color, in the spirit of Boyle's *Touching colours* of 1664. It implied that colors by transmission should be complementary to colors by reflection and was therefore compatible with Newton's more phenomenological theory of 1666, according to which the colors resulted from selective reflection or transmission of the simple components of white light.[28]

*Diffraction*

Newton briefly discussed diffraction, about which he knew from Honoré Fabri's account of Grimaldi's discovery and from Hooke's more recent experiments on this matter. Despite Grimaldi's evidence to the contrary and despite Hooke's comparison with the "straying of sound," Newton argued that diffraction was only a special case of refraction, caused by ethereal atmospheres near the surface of bodies, and perhaps involving thin-film effects. Whereas Hooke took diffraction to confirm the analogy between light and sound, Newton took it to confirm the essential role of the ether in refraction. In his opinion, the

[28]Newton [1675], pp. 263–7 (rings), 268 (colors of bodies); Newton [1676]; Boyle 1664. Cf. Shapiro, 1993, chaps. 2–4. As Newton understood, the color generated by the particles does not depend much on the angle of observation if their size is of the order of the optical wavelength.

diffraction implied by the wave theory of light was so large that it completely excluded shadows.[29]

## 3.5 The *Opticks*

The papers that Newton read in 1675 to the Royal Society did not appear in print until 1757. Although he began to work on a systematic treatise, the controversy around his first publications so irked him that he withheld his manuscript until 1704: "To avoid being engage in disputes over this matters, I have hitherto delayed the printing, and I should still have delayed it, had not the importunity of friends prevailed upon me." This gave him time to consolidate his main results and to include new materials on thick plates, the colors of bodies, diffraction, and extraordinary refraction. In the main text of the *Opticks*, Newton refrained as much as possible from hypotheses on the nature of light, as he had done in the short communication of 1672. He favored a neutral language of rays, defined as "the least parts [of light], and those as well successive in the same lines as contemporary in several lines." He left most of his speculations on light corpuscles and ether waves to a series of appended queries whose number increased at each new edition of his treatise.[30]

### *Geometrical optics*

Newton devoted an unusually small amount of space to what we would now call geometrical optics: eight definitions for rays, reflection, refraction, and homogeneous light, and nine "axioms" giving the laws of reflection and refraction, the condition of approximate stigmatism, and the locus of images for homogeneous light. The most remarkable features of his presentation are the restriction of the usual laws to homogeneous light (simple colors), and a definition of virtual images (axiom VIII) borrowed from Barrow: "An object seen by reflection or refraction, appears in that place from whence the rays after their last reflexion or refraction diverge in falling on the spectator's eye." Newton gave a terse justification: "For these rays do make the same picture in the bottom of the eyes as if they had come from the object really placed at [that place] … ; and all vision is made according to the place and shape of that picture."

In his optics lectures of 1670–72, Newton had integrated and even improved some of Barrow's more refined results. In his treatise, he ignored stigmatic surfaces and caustics, as these concepts became secondary in an optics dominated by chromatic dispersion and aberration. He confined himself to the basic principles: "This may suffice for an introduction to readers of quick wit and good understanding not yet versed in optics."[31]

In conformity with the phenomenological tone of his treatise, Newton gave only a brief and fragmentary derivation of the law of refraction. He assumed the refraction to be caused by a force perpendicular to the interface and depending only on the distance from

[29]Newton [1675], pp. 268–9 (diffraction, Hooke's opinion); Fabri 1669, first dialogue. Hooke announced his own discovery of diffraction (which he called "inflection") on 18 March 1675 at the Royal Society: cf. Birch, 1756–7, vol. 3, pp. 194–5, and the more detailed MS in Hooke 1705, pp. 186–90. Fabri anticipated the idea of a refracting atmosphere. Cf. Hall 1990.

[30]Newton 1704, p. 1: "Advertisement." Cf. Blay 1983; Hall, 1993.

[31]Newton 1704, pp. 1–13.

the interface. In this case, he asserted, the parallel component of "the motion or moving thing whatsoever" is conserved, and the square of the normal component changes by a constant amount. The sine law of refraction evidently follows from these two mechanical results. Newton left their derivation to his sagacious reader. They correspond to the conservation of the parallel component of the momentum, and to a simple generalization of Galileo's law of fall. Newton had already given a more geometrical proof of the sine law in his *Principia* of 1687, based on the parabolic shape of the trajectory in bands of constant force. Newton thus justified Descartes's result through a precise mechanical reasoning in which the velocities of the deflected "bodies" became identical to the velocity of light. He accepted Rømer's measurement of this velocity, and noted that it was larger in (optically) denser media.[32]

Newton's derivation of the sine law of refraction does not require any assumption about the way color is related to force, mass, and velocity, besides the implicit requirement that, for a given color, these three parameters must have a definite value. In modern terms, energy conservation yields

$$m(\upsilon'^2 - \upsilon^2) = 2\Delta$$

where $\upsilon$ is the initial velocity, $\upsilon'$ the final velocity, $m$ the mass, and $\Delta$ the integral of the force over its range. The conservation of the parallel component of momentum yields

$$\upsilon \sin i = \upsilon' \sin r.$$

Consequently, the sine law of refraction $\sin i = n \sin r$ holds with

$$n^2 - 1 = 2\Delta/m\upsilon^2.$$

The index varies with $m$, $\upsilon$, and $\Delta$. In his derivation, Newton did not decide to which of these variations a change of (simple) color should be traced. The probable reason for this silence is his hesitation about the dispersion law, as we will see in a moment.

*Chromatic dispersion*

Newton devoted the first book of his optics to the demonstration of the heterogeneity of white light, to its consequences on the design of optical instruments, to the theory of the rainbow, and to the perception of colors. Having learned how easily he could be misunderstood, he gave detailed descriptions of numerous experiments meant to prove the heterogeneity of white light and to refute the theories that made colored light a modification of white light. These were refinements of the early experiments of 1666, as shown for instance in Figs. 3.5 and 3.6.

In applications of the dispersion of light to the theory of optical instruments, it is important to know how the index of refraction varies with the simple color and with the nature of the refracting interface. Newton addressed these questions through his musical division of the spectrum and through the following "experiment":

[32]Ibid., book 2, part 3, props. 10–11. Newton 1687, pp. 227–30 (props. 94–96), 231 (scholium).

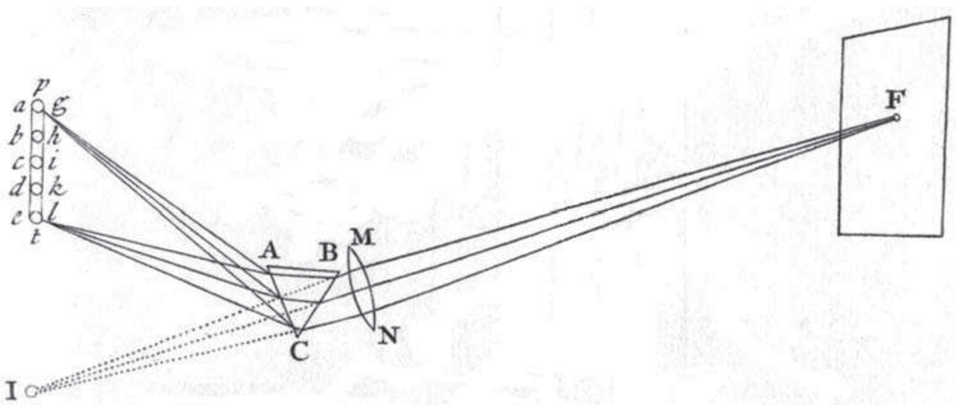


**Fig.** 3.5. Newton's improved contrivance for the analysis of white light. Without the prism, the lens MN would focus the light from the tiny hole F to the intersection of the dotted lines. With the prism, it would focus homogeneous light on a point of the segment pt. The tiny circles g, h, i, k, l represent the foci for five simple colors. From Newton 1704, book 1, part 1, fig. 24.

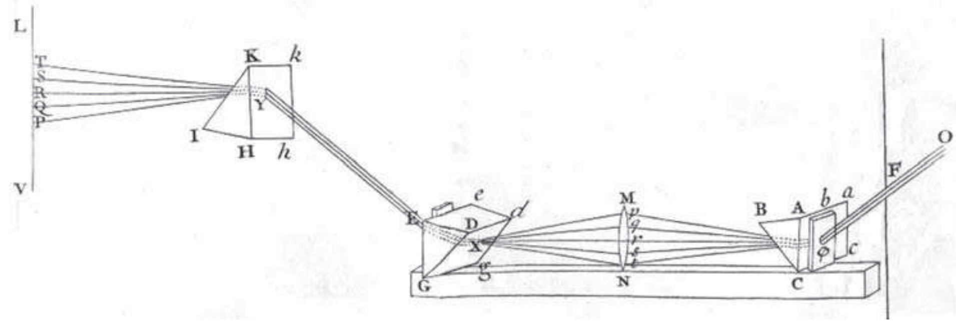


**Fig.** 3.6. Newton's synthesis of white light from simple colors. The prism FDG recombines the colors separated by the first prism ABC, so that the beam FY has all the properties of white light. The blocking of one simple color at the points p, q, r, s, t of the lens MN implies a missing color P, Q, R, S, T in the spectrum produced by the prism KIH. From Newton 1704, book 1, part 2, fig. 16.

> I found … that when light goes out of air through several contiguous refracting mediums as through water and glass, and thence goes out again into air, whether the refracting superficies be parallel or inclin'd to one another, that light as often as by contrary refractions 'tis so corrected, that it emergeth in lines parallel to those in which it was incident, continues ever after to be white. But if the emergent rays be inclined to the incident, the whiteness of the emerging light will by degrees in passing on from the place of emergence, become tinged in the edges with colours. This I try'd by refracting light with prisms of glass placed within a prismatic vessel of water.

This means that a ray of white light cannot be deviated without loosing its whiteness. Hence achromatic lenses or prisms cannot be built. Newton "gathered" two "theorems" from this experiment. Calling $n$ the modern index of refraction, the first theorem states that for any two colors $a$ and $b$ the ratio $(n_a-1)/(n_b-1)$ is the same for any refraction occurring at the interface between a given medium (say air) and another medium (water, glass, etc.). The second theorem gives the relation $n_{13} = n_{12}n_{23}$ between the indexes for the various interfaces of three media labeled 1, 2, 3.[33]

The second theorem is an immediate consequence of the Newton–Descartes derivation of the sine law of refraction, which makes the index a ratio of velocities. The first theorem is more mysterious. As Samuel Klingenstierna showed some fifty years later, it is only compatible with the "experiment" to the extent that all angles of incidence are small. It is compatible with the musical division of the spectrum; but we will now see that it does not square well with the Newton–Descartes derivation of the law of refraction, on the basis of which Newton had earlier favored another dispersion law.

As we saw, the mechanics of corpuscular refraction yields the relation

$$n^2 - 1 = 2\Delta/m\upsilon^2,$$

where $m$ is the mass of the deflected body, $\upsilon$ its initial velocity, and $\Delta$ what we would now call the total variation of the potential of the deflecting force. This relation implies the universality of $(n_a^2 - 1)/(n_b^2 - 1)$ for refraction from a given medium to any other medium, granted that the force parameter $\Delta$ does not depend on the selected color.[34] Newton gave this dispersion law in his optical lectures of 1670–72. Although he did not provide the derivation, his statement of this law clearly reflects a construction in which the parallel component of velocity is conserved and the acquired perpendicular component is the same for every color at grazing incidence. The latter condition is only met if the ratio $\Delta/m$ is the same for all colors while the initial velocity $\upsilon$ is the parameter of color. At that time Newton favored this assumption in analogy with gravitation, for which the acceleration of a body does not depend on its mass.[35]

At some point, Newton nonetheless opted for the universality of $(n_a-1)/(n_b-1)$, presumably because he had stakes in the impossibility of achromatic lenses. It is not clear whether he ever performed the prism-in-prism experiment. He described this experiment in a draft letter to Hooke of 1672, with a result opposite to that given in the *Opticks*! His settling for the linear dispersion law may perhaps be related to its approximate validity for water and the kind of glass that Newton was using. The incompatibility with his earlier mechanical analysis did not necessarily bother him. He may have tolerated a variable $\Delta/m$,

[33]Newton 1704, book 1, part 2, exp. 7 (musical division), exp. 8 (prism in prism). Cf. Bechler 1973, 1975; Shapiro 1979, 2005.

[34]As this parameter depends on the choice of the initial medium, the universality cannot be extended to any pair of medium. This is the probable reason why Newton keeps one of the two media constant in his first theorem.

[35]Newton (optical lectures), in Shapiro 1984, pp. 198–201, 335–7. The construction of Newton's derivation is confirmed in the MS "Of refraction," in Turnbull 1959–1977, vol. 1, p. 103. Cf. Shapiro 1984, pp. 199n–200n.

as he was aware of forces (for instance magnetic forces) for which different masses undergo different accelerations.[36]

*The circle of colors*

The *Opticks* goes on with a rule for determining the sensible color produced by the mixture of simple colors. In his seminal letter of 1672, Newton had already explained that the superposition of two (or more) simple colors could produce a color perceptively equivalent to another simple color but nevertheless analyzable through a prism. Hooke's and Huygens's claims that two base colors could generate all other colors prompted him to elaborate the distinction between compound colors and simple colors. The celebrated circle of colors gave a precise empirical rule for determining the colors produced by any given mixture of simple colors (Fig. 3.7).[37]

Newton divided a circle into arcs proportional to the intervals of the successive notes of his musical division of the spectrum. For each component of the mixture, he drew small disks of size proportional to the amount of the component. He then marked the gravity

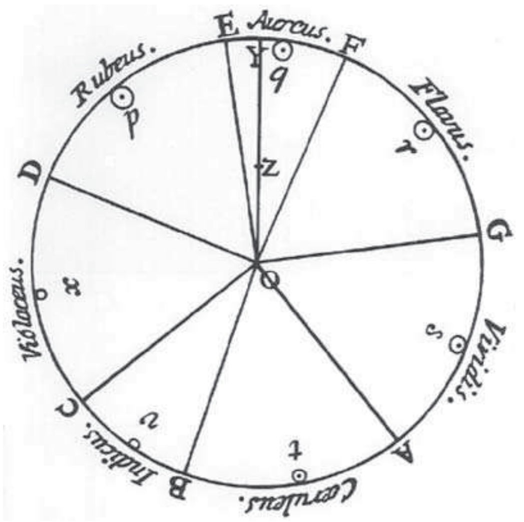


**Fig.** 3.7. Newton's circle of colors. From Newton 1704, book 1, part 2, fig. 11.

[36]Draft of Newton to Hooke (1672), MS Add. 3970, f. $529^{r}$, discussed in Shapiro 1979; Newton 1687, p. 411 (magnetic forces). On the approximate validity of the linear dispersion law, cf. Boegehold 1928. To assume an invariant $\upsilon$ and to make $m$ the parameter of color (as Newton did in Query 21 of the *Opticks*) leads to the same dispersion law as the velocity model. The only possible way out is to assume that the refractive force depends on color. This option is compatible with the indefiniteness of the force law assumed in Newton's derivations of the sine law of refraction. It may be justified by making color depend on the inner structure of the light particles, as for instance Bošković later did (see chapter 4, p. 128, note 46). For a different view, see Bechler 1974.

[37]Newton 1704, book 1, part 2, props. 3 (musical division of the spectrum), 6 (circle of colors). The color circle does not appear in Newton's earlier writings. One important issue, on which Newton's had to change his mind, is the number of simple colors necessary to produce whiteness (from an infinite number to two or three): cf. Shapiro 1980b.

center, z, of these disks and the radius OY passing through it. The point Y on the circle gives the resulting color. The ratio Oz/OY gives the “fullness or intenseness” of the color. The idea of mapping the spectrum on a circle may seem artificial, since it implies the contiguity of the most extreme colors of the spectrum (red and violet). Newton possibly drew this idea from contemporary representations of the division of the octave through points on a circle. The division is natural in the musical case because of the optimal consonance of octaves.[38]

*Thin plates*

In the second book of his treatise, Newton gave a detailed account of his experiments on thin plates, with accurate determinations of the effects of thickness and inclination (see Figs. 3.8 and 3.9). He carefully separated the observations from the theory, and he kept the

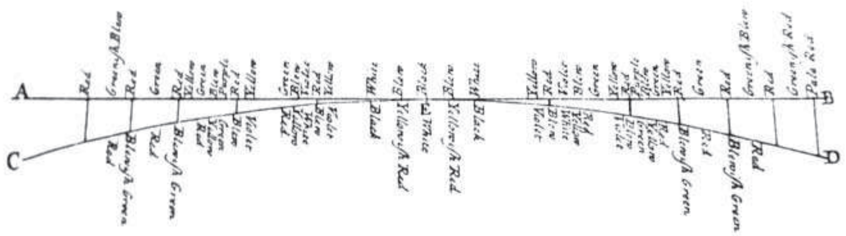


Fig. 3.8. The colors of Newton’s rings. AB represents the inferior surface of a large plane-convex lens, and CD the superior surface of a biconvex glass lens. The colors of reflected (above) and transmitted (below) light depend on the thickness of the interstitial air. From Newton 1704, book 2, part 1, fig. 3.

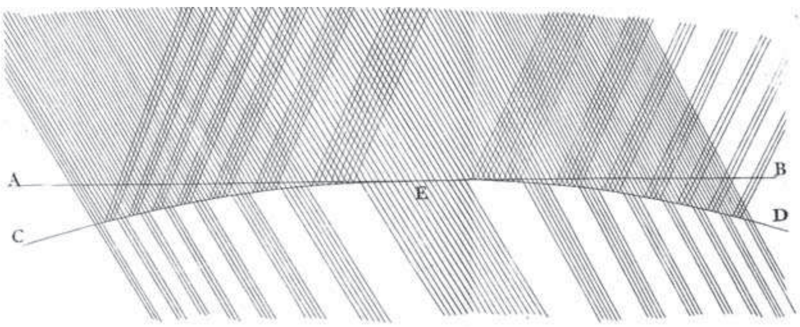


**Fig.** 3.9. Newton’ s drawing of the reflection and transmission of (inclined) rays of monochromatic light by the thin layer of air trapped between a spherical and a plane glass surface. The light from above is either transmitted or reflected by the second surface it encounters, periodically depending on the thickness of the layer. From Newton 1704, book 2, part 1, fig. 4.

[38]Cf. Wardhaugh 2006, pp. 253–6.

theory as close as possible to the phenomena. He rephrased his older, ether-based explanation of colored rings and partial reflection in terms of the more economical notion of "fits of easy reflection or transmission" for the rays themselves:

> Prop. XII. Every ray of Light in its passage through any refracting surface is put into a certain transient constitution or state, which in the progress of the ray returns at equal intervals, and disposes the ray at every return to be easily transmitted through the next refracting surface, and between the returns to be easily reflected by it.
> Prop. XIII. The reason why the surfaces of all thick transparent bodies reflect part of the Light incident on them, and refract the rest, is, that some rays at their Incidence are in fits of easy reflexion, and others fits of easy transmission.

In the case of light entering a thin layer of transparent material normally, transmission occurs at the second surface whenever the thickness of the layer is equal to a whole number of intervals of the fits. In the case of Newton's rings, the thickness varies as the square of the distance from the contact point of the two glasses. Therefore, the radii of the successive rings of monochromatic light (as seen through a prism) are to each other as the square roots of successive integers.[39]

Newton briefly indicated a wave-based explanation of the fits:

> What kind of disposition this is? Whether it consist in a circulating or vibrating motion of the ray or a vibrating motion of the ray, or of the medium, or something else? I do not here enquire. Those that are averse from attending to any new discoveries, but such as they can explain by an Hypothesis, may for the present suppose, that as Stones by falling upon Water put the Water into an undulating motion, and all Bodies by percussion excite vibrations in the Air: so the rays of Light, by impinging on any refracting surface, excite vibrations in the refracting or reflecting medium or substance, and by exciting them agitate the solid parts of the refracting or reflecting Body, and by agitating them cause the Body to grow warm or hot; that the vibrations thus excited are propagated in the refracting medium or substance, much after the manner that vibrations are propagated in the Air for causing sound, and move faster than the rays so as to overtake them; and that when any ray is in that part of the vibration which conspires with its motion, it easily breaks through a refracting surface, but when it is in the contrary part of the vibration which impeded its motion, it is easily reflected; and, by consequence, that every ray is successively disposed to be easily reflected, or easily transmitted, by every vibration which overtakes it. But whether this Hypothesis be true or false I do not here consider. I content my self with the bare discovery, that the rays of Light are by some cause or other alternately disposed to be reflected or refracted for many vicissitudes.

This is a variant of the hypothesis of 1675, with the same acoustic analogy, and with a new insistence that the related fits of easy reflection or transmission are experimental facts that do not depend on this hypothesis.[40]

[39]According to Shapiro (1993, pp. 171–2), Newton designed the theory of fits in the early 1890s after studying thick plates and while rewriting Part 4 of his treatise. He borrowed the term "fit" from contemporary medical language, in which it meant a recurrent attack of a periodic ailment such as malaria: cf. Shapiro 1993, p. 180.

[40]Newton 1704, pp. 78, 80. In this variant, the vibrating entity is the matter of the body, not the ether; although the explanation of partial reflection in Prop. 13 would rather require ethereal vibrations.

As he had done in 1675, Newton related the colors of bodies to those of thin plates. He placed the relevant considerations after the observations on thin plates and before the theory of fits: he valued the resulting insights into the corpuscular structure of matter so much that he did not want their reception to depend on any specific theory of the colors of thin plates. This was a wise decision, as we will see in the next chapter.[41]

*Thick plates*

The mirrors of Newton's reflecting telescopes were made of spherical shells of glass silvered on the convex side. Newton accidentally discovered that the diffuse light outside the geometrical image of a distant source of light presented colors analogous to the colors of thin plates. The precise setup (Fig. 3.10) with which he studied these colors involves a white screen perpendicular to the axis of the mirror and containing the center of its spherical shell. The light from the distance source passes through a small hole on this screen around the center. It is then reflected on the mirror. A small portion of the returned light is diffusely reflected and casts colored rings on the screen. Newton gave much importance to this little phenomenon, for he regarded it as a confirmation of his theory of fits. In his explanation, a ray from the source enters the glass shell of the mirror in a fit of easy transmission and returns to the concave surface after diffuse reflection on imperfections of the silvered surface, in a fit that depends on the thickness of the shell and on the inclination of the reflected ray. From his earlier determination of the effect of inclination in thin plates, he could quantitatively determine the rings produced on the screen. The result matched his observations:[42]

> And thus I satisfy'd my self, that these rings were of the same kind and original with those of thin plates, and by consequence that the fits or alternate dispositions of the rays to be reflected or transmitted are propagated to great distances from every reflecting and refracting surface.

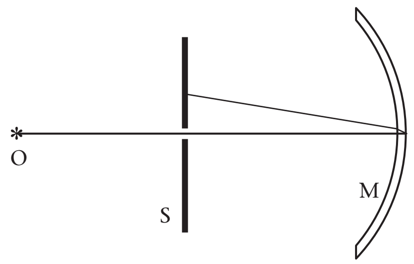


**Fig.** 3.10. Newton's setup for observing the rings of thick plates. The light from the source O, passing through the hole in the screen S, is diffusely reflected on the spherical glass mirror M. The rings appear on the (white) face of the screen facing on the mirror.

[41]Newton 1704, book 2, part 3, props. 1–7.

[42]Newton 1704, book 2, obs. 8. Thomas Young's later explanation of this phenomenon involves two-ray interference and scattering by dust particles on the external surface of the mirror. See below, p. 176.

*Inflexion*

Newton devoted the third and last book of his treatise to a short account of a few quantitative observations regarding diffraction, which he called "inflexion" in conformity with his view that this phenomenon corresponded to a bending of rays in the vicinity of a material body. In contrast with the other books of his treatise, Newton here offered no theoretical analysis beyond the broad assertion of inflected rays. The probable reason for this reticence is the difficulties he encountered in imagining the possible paths of inflected rays.[43]

Newton's first observations were made with the "hair of a man's head," placed in a beam of sunlight from a tiny hole in a shutter. The observed shadow was larger than the geometrical shadow, and it presented three colored fringes on each side. Newton did not see the internal fringes included in Grimaldi's account. There is manuscript evidence that he first assumed that the fringes were made of thin, flat bundles or rays (*fasciae*) and therefore propagated rectilinearly from the inflexion zone to the screen. This assumption, together with his later observation that the relative distances of the fringes are the same at any distance, leads to the implausible consequence that the inflexion of the rays increases with their distance from the hair. In his published account, Newton emphasized that the shadow became broader in proportion to the distance of the screen from the hair when this distance decreased. He explained this fact by a rapid decrease of the rays' inflection with their distance from the hair (see Fig. 3.11).[44]

Newton also described diffraction by the edge of a blade, by two parallel blades, and by two intersecting blades. For a sufficient narrowness of the space between the two blades,

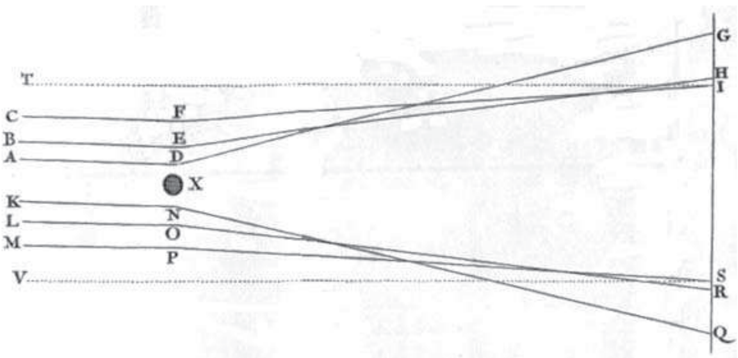


**Fig.** 3.11. The inflexion of light by a hair (X) according to Newton. From Newton 1904, book 3, plate 1. The ray CFG is less inflected than the ray ADG, which is closer to the hair. Consequently, the ratio of the shadow's breadth IS over the distance of the screen from the hair increases when the screen is closer to the hair.

[43] Newton 1704, book 3. [44] Ibid., obs. 1–4. Cf. Stuewer 1970; Shapiro 2001.

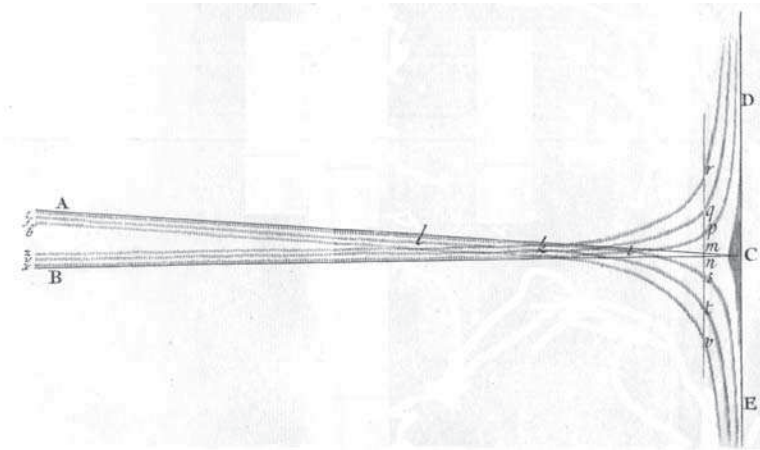


**Fig.** 3.12. Newton's drawing of the diffraction fringes from two intersecting knives. From Newton 1704, book 3, plate 1, fig. 3. The straight lines AC and BC represent the limits of the geometrical shadow of the knives. For a large spacing of these edges (on the left side of the figure), the fringes (x, y, z; e, f, g) are outside the shadow, close to each edge. For a small spacing (on the right side of the figure), the fringes (p, q, r; s, t, u) are in the shadow.

he found that the light bent into the shadow. He used the two intersecting blades (Fig. 3.12) in an attempt to determine the distance from the hair at which the rays responsible for a given fringe were inflected (assuming that the intersection of two symmetrical fringes corresponded to undeflected rays). The result again contradicted his earlier assumption that the fringes propagated rectilinearly from the source:

> I gather, that the light which makes the fringes upon the paper is not the same light at all distances of the paper from the knives, but when the paper is held near the knives, the fringes are made by light which passes by the edges of the knives at a less distance, and is more bent than when the paper is held at a greater distance from the knives.

This circumstance, the very existence of the fringes, and the fact that bending occurred sometimes into, sometimes from the geometrical shadow were formidable theoretical challenges. Newton left them to posterity.[45]

*Queries*

At the end of his treatise, Newton proposed a series of queries, "in order to a further search to be made by others." In the first edition of 1704, he refrained from any assumption on the nature of light. He assumed only that a universal action at a distance between rays of light and material bodies explained reflection, refraction, inflexion, the heating of bodies

[45]Newton 1704, book 3, obs. 5–10, citation from obs. 9. Newton's observations are compatible with the predictions of Fresnel's theory of diffraction, with a precision of about 2%: cf. Nauenberg 2000. In queries 3, Newton suggested that the fringes might result from an eel-like motion of the rays.

by light, the emission of light by heated bodies, and vision. He repeated his old idea that the rays of light excited vibrations of the retina transmitted to the brain through the optic nerve, and compared color and pitch:[46]

> *Qu.* 13. Do not several sorts of rays make vibrations of several bignesses, which according to their bignesses excite sensations of several Colours, much after the manner that the vibrations of the Air, according to their several bignesses excite sensations of several sounds? …
>
> *Qu.* 14. May not the harmony and discord of Colours arise from the proportions of the vibrations propagated through the fibres of the optick Nerves into the Brain, as the harmony and discord of sounds arises from the proportions of the vibrations of the Air? For some Colours are agreeable, as those of Gold and Indico, and others disagree.

In the Latin translation of his treatise, published in 1706, Newton added seven new queries in which he at last came out as a supporter of the corpuscular concept of light: "Are not the rays of Light very small bodies emitted by shining substances?" He asked this question after rejecting any medium theory for a variety of reasons: colors would need to be explained by modifications of the rays, the rays would bend in the shadow, the asymmetry (polarization) of the rays from a doubly refracting crystal would remain unexplained, the colors of thin plates would require two ethers (one for the rays, one for the fits), and the ether would slow down the motion of celestial bodies. In favor of the corpuscular view, he cited the easy mechanical explanations of rectilinear propagation, reflection, and refraction; the interpretation of colors as referring to the size of the corpuscles of light; the interpretation of the fits in terms of vibrations excited by the impact of the corpuscles; the interpretation of double refraction and polarization by "some attractive virtue lodged in certain sides both of the rays, and of the particles of the crystal."[47]

Lastly, in the second English edition of his treatise (1718), Newton inserted eight queries in which he introduced the ether as a medium that was useful to explain the fits, heat transfer through a vacuum, refraction, inflexion, gravitation (by the tendency of bodies to go from the denser parts to the rarer parts of the ether), vision, propagation along nerves; and he now judged that the ether could be so rare as to allow the unimpeded motion of celestial bodies. The chronological order of writing of the queries clearly depended on their explanatory level: queries concerning the distance action between rays and matter came first, those concerning the corpuscular representation of rays came second, and those concerning the ether-based explanation of all action at a distance came last.[48]

[46]Newton 1704, pp. 132, 136.

[47]Newton 1706, queries 17–23 (citations from query 21), renumbered 25–31 in Newton 1718. After much hesitation, Newton chose the "size" (mass) of the corpuscles as the parameter of color, and not the velocity, because in 1692 the Astronomer Royal John Flamsteed had failed to observe a consequence of the velocity model: Jupiter's satellites should turn blue at the instants preceding their occultation (since a larger velocity implies a lesser refraction in the Descartes–Newton model): cf. Shapiro 1993: 145–6. As was mentioned above, p. 97, note 36, both choices are compatible with Newton's derivation of the law of refraction, and neither is compatible with his linear law of dispersion.

[48]Newton 1718, queries 17–24.

The analogy with sound played an important role in justifying ether waves produced by light, as it already did in the early optical papers:[49]

> If a stone be thrown into stagnating Water, the Waves excited thereby continue some time to arise in the place where the Stone fell into the Water, and are propagated from thence in concentrick Circles upon the Surface of the Water to great distances. And the Vibrations or Tremors excited in the Air by percussion continue a little time to move from the place of percussion in concentrick Spheres to great distances. And in like manner, when a Ray of light falls upon the Surface of any pellucid Body, and is there refracted or reflected, may not Waves of Vibrations, or Tremors, be thereby excited in the refracting or reflecting Medium at the point of Incidence, and continue to arise there, and to be propagated from thence as long as they continue to arise … , and are not these Vibrations propagated from the point of Incidence to great distances?
>
> Is not Vision perform'd chiefly by the Vibrations of this Medium, excited in the bottom of the Eye by the Rays of Light, and propagated through the solid, pellucid, and uniform Capillamenta of the optick Nerves into the place of Sensation? And is not Hearing perform'd by the Vibrations either of this or some other Medium, excited in the auditory Nerves by the Tremors of the Air, and propagated through the solid, pellucid, and uniform Capillamenta of those Nerves into the place of Sensation? And so of the other Senses.

Newton also used the acoustic analogy to exclude medium-based theories of light. In Query 19 of 1706, he wrote:

> If [light] consisted in Pression or Motion, propagated either in an instant or in time, it would bend into the Shadow … The Waves on the Surface of stagnating Water, passing by the sides of a broad Obstacle which stops part of them, bend afterward and dilate themselves gradually into the quiet Water behind the Obstacle. The Waves, Pulses or Vibrations of the Air, wherein Sounds consist, bend manifestly, though not so much as the Waves of Water. For a Bell or a Cannon may be heard beyond a Hill which intercepts the sight of the sounding Body, and Sounds are propagated as readily through crooked Pipes as through straight ones. But Light is never known to follow crooked Passages nor to bend into the Shadow.

As we saw earlier, the apparent impossibility of explaining the rectilinear propagation of light in a medium theory probably determined Newton's original preference for the corpuscular view.[50]

The second book of the *Principia mathematica* (1687) contained several arguments of this kind. In Proposition 41, Newton reproduced his old anti-Descartes remark that the rectilinear transmission of pressure along contiguous balls required an improbable alignment of the balls (see Fig. 3.13). He also argued that the isotropy of pressure in a fluid implied that the pressure transmitted beyond a diaphragm necessarily acted on the sides of the cone delimited by the diaphragm (see Fig. 3.14).[51]

[49]Ibid., queries 17, 23. [50]Newton 1706, query 19. [51]Newton 1687, pp. 354–6.

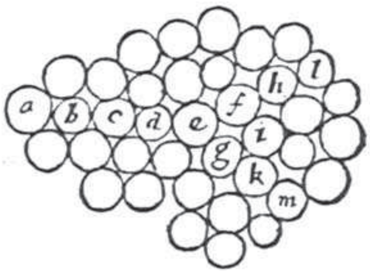


**Fig.** 3.13. Newton's diagram for excluding rectilinear propagation of endeavor in a hard-ball model. From Newton 1687, 354. A pressure applied on the ball *a*, is transmitted rectilinearly along *abcde*, then obliquely along *efhl* and *egkm*.

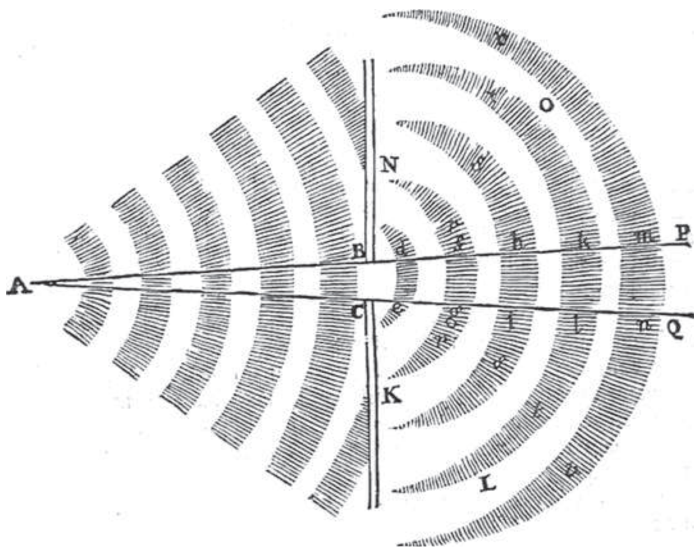


**Fig.** 3.14. Newton's drawing for the straying of pressure (or water waves, or air waves, or continuous flow) beyond a diaphragm. From Newton 1687, pp. 355, 357. The isotropy of hydrostatic pressure implies that the pressure transmitted in the truncated cone BPCQ across the surfaces *de*, *fg*, etc. must also act across the surfaces BP and CQ. In the case of water waves, the water heaps *de*, *fg*, etc. imply a flow toward the intermediate valleys and beyond the lines BP and CQ as well.

In Proposition 42, Newton gave a proof that "*All motion propagated through a fluid diverges from a rectilinear progress into the unmoved space*." In the case of water waves, he argued that water had to descend from the heaps that passed the diaphragm at equal speed in the forward and sideways directions. In the case of pulses in an elastic fluid, he similarly argued that truncated zones of compressed fluid beyond the diaphragm had to expand with equal speed in the forward and sideways directions. In the case of any flow through a diaphragm, he argued that the isotropy of pressure implied divergence. In the elastic-fluid case, Newton commented:

> We find the same by experience in sounds which are heard through a house interpose; and if they come in to a chamber through the window, dilate themselves into all parts of the room, and are heard in every corner; and not as reflected from the walls, but directly propagated from the window.

Newton then gave his theory of wave propagation in an elastic medium, the first mathematical theory of plane elastic waves that yielded the propagation velocity as a function of the elasticity and the density of the medium. An optical scholium followed:[52]

> The last propositions respect the motions of light and sounds; for since light is propagated in right lines, it is certain that it cannot consist in action alone (by Props. 41 and 42). As to sounds, since they arise from tremulous bodies, they can be nothing else but pulses of the air propagated through it.

In a discourse on the cause of gravity appended to his *Traité de la lumiere*, Huygens addressed the incompatibility of his theory of light with Newton's Proposition 42:

> I answer that what I have brought up to prove that light (excepting reflection and refraction) spreads directly does not impair the validity of the said Proposition [42 of Book 2]. For I do not deny that when the Sun shines through a window, there is motion strayed beyond the lit space; but I say that these detoured waves are too weak to produce light. And even though [Newton] wants to believe that the emanation of sound proves that these sideways effusions are sensible, I take it for certain that this emanation rather proves the contrary. Indeed if sound, after passing an opening, would spread sideways, as Mr. Newton wants it to be, it would not so exactly respect the equality of the angles of incidence and refraction in echo … As for his argument that wherever one stands in a room whose window is open, one can hear the sound from outside not by reflection on the walls but coming directly from the window; it is easily seen to be misleading, because of the multitude of repeated reflection occurring as in one instant … I admit that in the case of the undulations or circles formed on the surface of water, things are roughly as Mr. Newton asserts … But for sound, I say that the sideways emanations are nearly insensible to the ear, and that in the case of light they have no effect whatsoever on the eyes.

Huygens here suggested that sideways propagation occurred for any kind of waves, but to a different degree depending on the kind of waves. He did not give any reason for this difference. As we saw, in the *Optice* of 1706 Newton admitted Huygens's contention that the straying of sound was inferior to that of water waves; yet he remained convinced that this straying made rectilinear propagation impossible.[53]

[52]Ibid., pp. 356–9, 363–72, citations from pp. 358, 369. More will be said on Newton's theory of sound propagation in chapter 4, pp. 153–4.

[53]Huygens, *Discours de la cause de la pesanteur*, in Huygens 1690, p. 164.

### 3.6 Conclusions

To summarize, Newton's optics involves three levels of description, which we may call the heuristic, phenomenological, and observational levels. At the heuristic level, Newton has light corpuscles interact with matter and ether, and also produce waves by impact on the interface between two different media. The mass (or velocity) of the corpuscles corresponds to the simple colors and determines the length of the waves. As we just saw, this heuristic level has three sublevels corresponding to the successive queries of 1704, 1706, and 1718. Even though this level undoubtedly permeated Newton's investigations from the earliest trials to the latest refinements, it did not appear in print before these queries were published. The phenomenological level is the level of rays endowed with selective refrangibility and fits of easy reflection or transmission. The observational level corresponds to theory-neutral accounts of experiments, which Newton calls "Observations" in his *Opticks*. Newton was very careful in separating these three levels, to make sure that future controversy at the heuristic level would not contaminate the other levels.

The main investigative tools through which Newton reached this elaborate conceptual system were the laws of mechanics as Newton understood them, precise and quantitative experiments, some mathematics, and the creative use of various analogies. His understanding of mechanics determined his rejection of Cartesian optics and his emissionist reinterpretation of Descartes's derivation of the law of refraction. With Huygens, Newton was the only optician of the seventeenth century to perform precise quantitative experiments in support of his theories. He was well ahead of his time in his control of the imaginative, material, and interpretive dimensions of experimentation. His definition of color through measurable parameters of refraction or selective transmission (through thin plates) contributed to make physical optics a quantitative science.

However, Newton's use of mathematics in optics was essentially limited to the derivation of the law of refraction and to some geometrical optics. He rather relied on "the analogy of nature," according to which nature should be conformable to itself at different scales or for different kinds of phenomena. For instance, he applied the laws of macroscopic mechanics to the motion of the light corpuscles; or he explained the colors of bodies by analogy between their parts and thin plates. Most frequently and most systematically, he relied on acoustic analogies or disanalogies. The reason for this characteristic of Newton's optics is not to be found in his predilection for music, for he reportedly declared music to be an "ingenious nonsense" and "when hearing Haendel play on the harpsichord, could find nothing worthy of remark but the elasticity of his fingers." Rather, the colors of thin plates and Hooke's challenges called for the consideration of ether waves; and sound waves, as they began to be understood in Newton's times, were the best illustration of such waves.[54]

Newton used the acoustic analogy in four different manners. First, he used it *ab absurdo*: if light were similar to sound, it would bend in the shadow. Secondly, in his reply to Hooke he used this analogy to conciliate the wave theory with his concept of the heterogeneity of white light. He thus pioneered the correspondence between color and frequency, as well as the idea that white light was a mixture of components with various frequencies. Thirdly,

[54]On Newton and music, cf. Gouk 1986, p. 101.

Newton used the acoustic analogy to explain aspects of light that the corpuscular or ray theory could not capture. He explained the fits of easy reflection and the propagation of visual signals along the optical nerves by analogy with the aerial vibrations produced by the impact of two bodies. Fourthly, he assumed that colors and tones obeyed the same rules of harmony: he compared the rainbow to a musical scale, and the harmony of two colors to consonance. This fourth mode of analogy was not unrelated to the third mode, for Newton associated both (simple) color and tone with frequency, the perception of colors being conditioned by the traveling of periodic waves through the optical nerve.

When Newton developed these analogies, the concept of sound as a compression wave was gaining ground, as a consequence of Boyle's pneumatic experiments and of the general progress of experimental acoustics. In his *Principia* of 1687, Newton gave the first mathematical theory of a plane periodic progressive wave of compression. He thus obtained the relation between velocity, density, and compressibility by balancing the pressure gradient on a slice of the fluid with its inertial force. In this concept of wave propagation, there is a spatial periodicity of the compression and of the velocity of the fluid, in contrast with the earlier concepts of sound in which the only periodicity was temporal. This aspect is essential in Newton's wave interpretation of the fits of easy transmission.[55]

Beyond plane-wave propagation, Newton could only guess the behavior of waves from analogy with the observed properties of sound or water waves. Thus, he inferred the straying of light in the wave theory of light from the straying of sound behind obstacles. He drew the relation between the mass of the light corpuscles and the length of the waves produced by their impact from analogy with water waves. Had he known the relation between wavelength and diffraction, he would have lost the main argument in favor of the corpuscular interpretation of light. Had he better understood the acoustic vibrations caused by impact, he would have lost his wave interpretation of the fits of easy transmission.

In sum, a large amount of Newton's heuristics crucially depended on the contemporary state of the theory of vibrations, and also on his related preference for the emissionist concept of light. At the same time, his phenomenology of rays, colors, and fits was solidly anchored on numerous experiments of unprecedented quality. In conformity with his famous *Hypotheses non fingo*, Newton believed he could cleanly separate this phenomenological level from the heuristic level. In reality, some of his phenomenology bore unconscious traces of the emissionist viewpoint, such as the preexistence of rays of simple color in white light or the idea that the second interface of a thin plate controlled the selection of colors. Thus, the various levels of Newton's optics were not as cleanly separated as he wished them to be. The distinction is nevertheless useful in understanding the structure and the reception of his work.

[55]In earlier concepts of sound, the analogy between sound and water waves did not imply spatial periodicity. The analogy was mostly used to illustrate circular perturbation from a center.