

Experiment and mathematics in Newton's theory of color

Newton's decade-long struggle to devise a mathematical theory of color—abandoned in his landmark *Opticks*—gives unusual insight into his concept of a scientific theory.

Alan E. Shapiro

On 18 January 1672 Isaac Newton wrote Henry Oldenburg, Secretary of the Royal Society, that he would send him a paper that he modestly described¹ as "being in my Judgment the oddest if not the most considerable detection wch hath hitherto beene made in the operations of Nature." Newton was

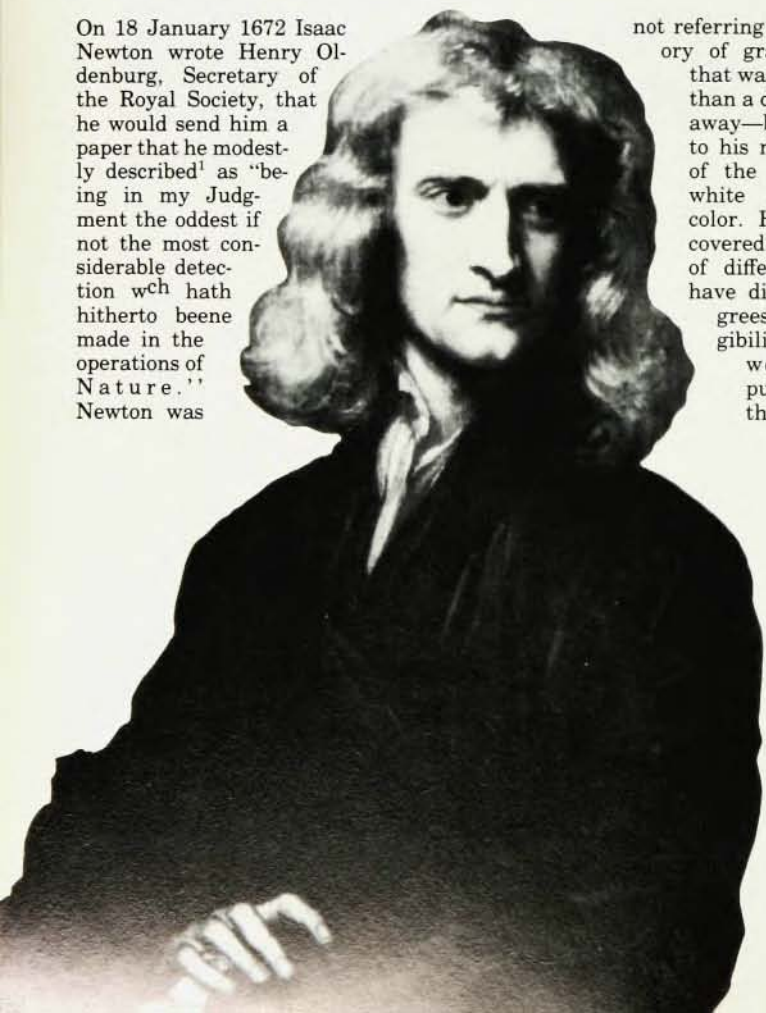
not referring to his theory of gravitation—that was still more than a dozen years away—but rather to his new theory of the nature of white light and color. He had discovered that rays of different color have different degrees of refrangibility—or, as we would put it, that the index of

refraction varies with wavelength—and that white light and, in particular, sunlight consist of a mixture of innumerable colors. Less than three weeks later, as Newton promised, he sent to the Royal Society his famous paper, "A New theory about light and colors," which was published at once in the *Philosophical Transactions*. In the "New theory" he boldly proclaims:²

A naturalist would scarce expect to see y^e science of [colours] become mathematicall, & yet I dare affirm that there is as much certainty in it as in any other part of Opticks. For what I shall tell concerning them is not an Hypothesis but most rigid consequence, not conjectured by barely inferring 'tis thus because not otherwise or because it satisfies all phaenomena (the Philosophers universall Topick), but evinced by y^e mediation of experiments concluding directly & wthout any suspicion of doubt.

These are pretty strong claims, and my first aim in this article is to consider Newton's quest for certainty, his attempt in his *Optical Lectures* to create a mathematical science of color, and the role of experiment in this endeavor.

Isaac Newton in 1689, at age 46. This painting by Sir Godfrey Kneller is the earliest surviving portrait of Newton. (Courtesy of the trustees of the Portsmouth Estates.)

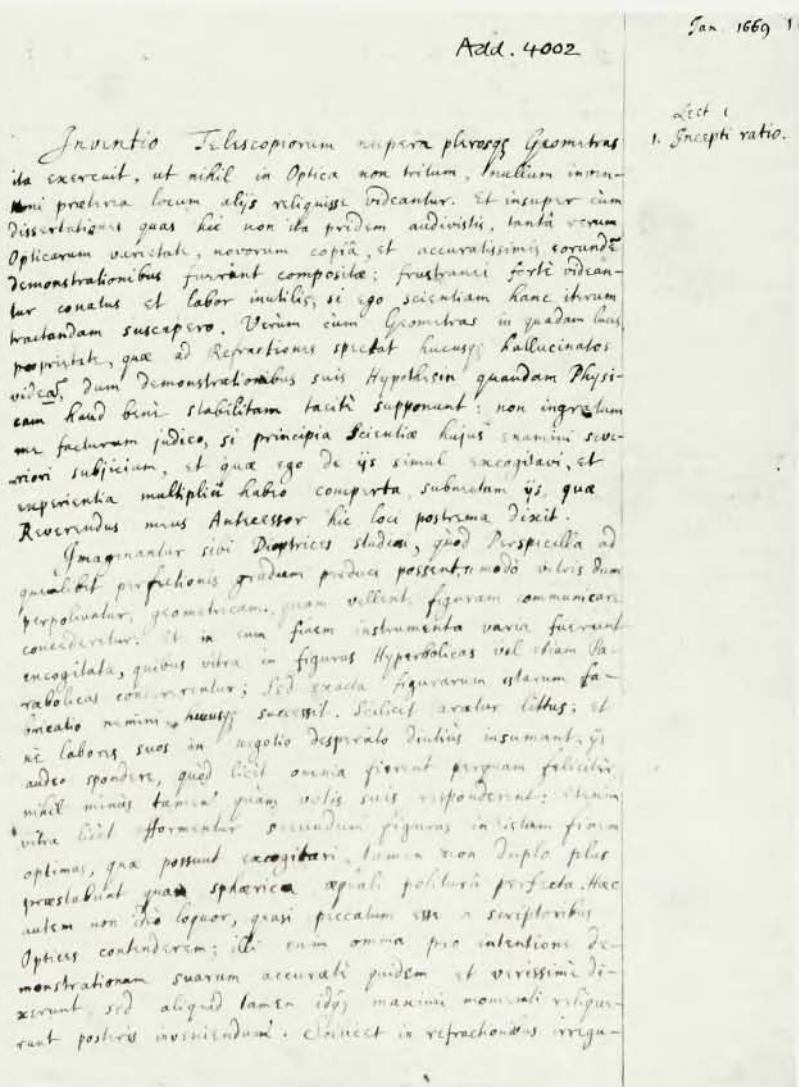


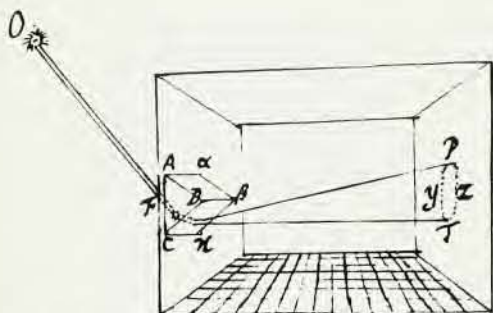
Then I will describe how he came to abandon his new mathematical science and acknowledge the contingency of an experimental theory. To caricature my own argument, I will show how Newton initially intended his *Optical Lectures* to be, as it were, his *Principia*, or a mathematical treatise, and then how it became his *Opticks*, an experimental treatise. In fact, I will show that the mathematical theory of his *Lectures* is of a very different sort from that of the *Principia*.

Lectiones opticae

Most physicists know Newton's theory of color from his *Opticks*, which he composed in the early 1690s and published in 1704, about thirty to forty years after he had made his optical discoveries. Some also know the "New theory," but that is just a brief outline of his theory of color. Newton's principal early work on the subject is his little-known (even by historians of science) *Lectiones opticae* or *Optical Lectures*. When Newton, who was not yet 27 years old, was appointed Lucasian Professor of Mathematics at the University of Cambridge in the fall of 1669, he chose to deliver his inaugural

Optical Lectures. This is the first page of the earlier version of the *Optical Lectures*, in Newton's hand. (Cambridge University Library, Add. MS 4002. Courtesy of the Syndics of Cambridge University Library.)





Experiment. This is Newton's own rendering of his basic prismatic experiment. After passing through the small circular hole *F*, a beam of sunlight *OF* is refracted by the prism *AαBβCκ*, set at minimum deviation, and casts the spectrum *PYTZ* on the opposite wall. (Add. MS 4002, page 3. Courtesy of the Syndics of Cambridge University Library.)

series of lectures from 1670 to 1672 on the theory of color and refraction that he had developed in the preceding half decade. This was Newton's first physical treatise and the most comprehensive account of his theory of color that he would ever present, serving as the immediate source for his "New theory" and, twenty years later, the foundation for Book I of his *Opticks*.

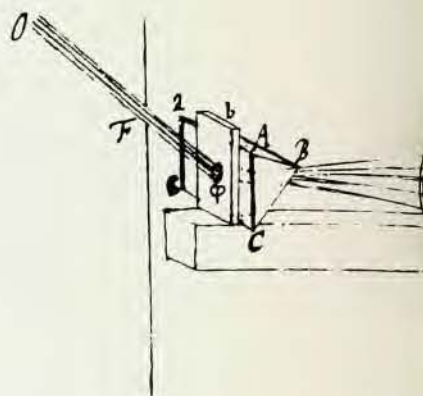
There are two versions of his *Optical Lectures*, with the second one being a substantially enlarged and reorganized version of the first. Both are in Latin. In early 1672 Newton had intended to publish the revised version, but he soon decided against it. However, in accordance with university statutes, in October 1674 he deposited a copy in the university library, from which a number of copies were made.

Newton begins the *Optical Lectures*, as he does the "New theory," with a demonstration of the central idea of his theory, that sunlight consists of rays of unequal refrangibility. The fundamental experiment in demonstrating that discovery is that of passing light through a prism and projecting its image or spectrum onto a screen. Experiments with prismatic spectra were quite common in the seventeenth century, but Newton's arrangement of passing a narrow circular beam of light through a prism at minimum deviation was an original, and by no means obvious, one. (See the figure above.) He deduced that in this situation if all rays were equally refrangible, as was then universally held, then the image should be nearly circular. He then

measured the spectrum and found that it was greatly elongated, about five times longer than broad. This was the key—measurement and calculation. He had to eliminate other possible causes for the elongation, of course, but once he had established that there could be no other cause than that the Sun's direct light consists of rays of unequal refrangibility, he had, or so it seemed, a mathematical measure for color: the degree of refrangibility. On the one hand, this allowed the possibility of developing a mathematical theory of color. On the other hand, this experiment provided Newton with the fundamental experimental and conceptual tool of his theory of color. It gave him his method of analysis or decomposition: separating rays of different colors from one another by their unequal refrangibility.

Argument for mathematics. At this point in the enlarged and reorganized *Optical Lectures*, after Newton had demonstrated unequal refrangibility, we encounter the most striking change from the earlier version, for Newton interchanged the mathematical part on color, putting the mathematical part first. However, in both versions, immediately after he introduces the propositions of his experimental theory, he makes a pronouncement on his method for demonstrating them that provides us with an early, revealing insight into his conception of a scientific theory. To justify his mathematical treatment of colors, Newton makes³ the following argument, which characterizes well the outlook that guides him throughout his *Optical Lectures*. (Here we can read Newton's terms "geometry" and "philosophy" as "mathematics" and "physics," respectively):

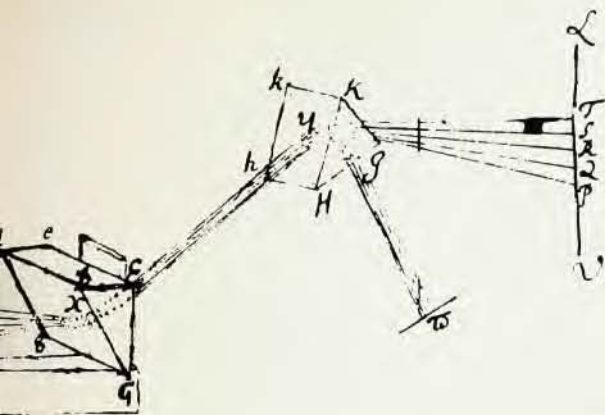
...the generation of colors in-



cludes so much geometry, and the understanding of colors is supported by so much evidence, that for their sake I can thus attempt to extend the bounds of mathematics somewhat, just as astronomy, geography, navigation, optics, and mechanics are truly considered mathematical sciences even if they deal with physical things. . . . Thus although colors may belong to physics, the science of them must nevertheless be considered mathematical, insofar as they are treated by mathematical reasoning. Indeed . . . I hope to show—as it were, by my example—how valuable mathematics is in natural philosophy. I therefore urge geometers to investigate nature more rigorously, and those devoted to natural science to learn geometry first. Hence the former shall not entirely spend their time in speculations of no value to human life, nor shall the latter, while working assiduously with an absurd method, fail to reach their goal. But truly with the help of philosophical geometers and geometrical philosophers, instead of the conjectures and probabilities that are being blazoned about everywhere, we shall finally achieve a natural science supported by the greatest evidence.

Thus, from the beginning of his career, Newton was as concerned with reforming the methods of natural science as with the science itself. While in the heading to this passage Newton avows that "these propositions are to be treated not hypothetically and probably, but by experiments or demonstratively," in the passage itself he speaks only about mathematics and not experiment, except for a vague refer-

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White-light analyzer. Newton designed this instrument with two prisms and a lens mounted on the wooden beam **CG**. Its purpose is to decompose and recombine a beam of sunlight so as to demonstrate that the reconstituted white light **EY** is identical in all its properties to the Sun's direct light **OF**. (Add. MS 4002, page 67. Courtesy of the Syndics of Cambridge University Library.)

ence to "evidence." In his desire to establish a new, more certain science, Newton does not clearly separate two distinct aspects of this reform, the introduction of mathematics and the elimination of the "hypothetical physics" that René Descartes and other mechanical philosophers had introduced earlier in the Scientific Revolution. The mechanical philosophers claimed that we could not truly know the inner workings of nature, as the Aristotelians had believed, and that the best we could do was to construct a likely account—an hypothesis—that could explain the phenomena. The "hypothetical physics" had indeed gotten out of hand with the construction of arbitrary models, based on conjectured invisible mechanisms. Newton's aim was to replace these qualitative, probable explanations, and to establish a new sort of certainty and truth in which the description of nature is mathematical and based directly on the phenomenon, or on experiment and observation.

Experimental theory of color

Besides the intrinsic problem that in Newton's day the study of color was simply not ready for a unified mathematical treatment, perhaps the major weakness of his attempted mathematical theory of color was that it was only loosely related to his experimental theory or, for that matter, to any experiment or observation. The two theories had few principles in common, and to appreciate their relation, I will briefly sketch them, beginning with the experimental theory. Because that theory is rather well known, I will present only Newton's most important conclusions and simply allude to the extensive series of experiments that he uses to justify them. My sketch will

synthesize his three early accounts—the two versions of the *Optical Lectures* and the "New theory"—while noting significant differences between them.⁴

Newton fully accepted the fundamental assumption of the mechanical philosophy that light rays are not colored but rather cause sensations of different colors depending on their physical constitution. For convenience's sake, however, I will speak of red rays, yellow rays, and so on—as Newton himself often did—instead of using his more precise, though cumbersome, terms, red-making rays, yellow-making rays, and so on.

► Sunlight consists of rays of unequal refrangibility. I already indicated the essence of Newton's proof of this principle, which is the foundation of both theories.

► There is a one-to-one correspondence between refrangibility and color. Newton implicitly assumes that this correspondence is independent of the refracting material. This proposition allows the possibility of constructing a mathematical theory of color, for it in principle assigns a metric to color. However, because it is proved and applied only qualitatively, namely, by observing that red rays are always refracted the least, violet the most, and so on, it could not be strictly established or mathematically formulated. Nonetheless, in the "New theory" Newton (erroneously) asserts that the correspondence "is very precise and strict."

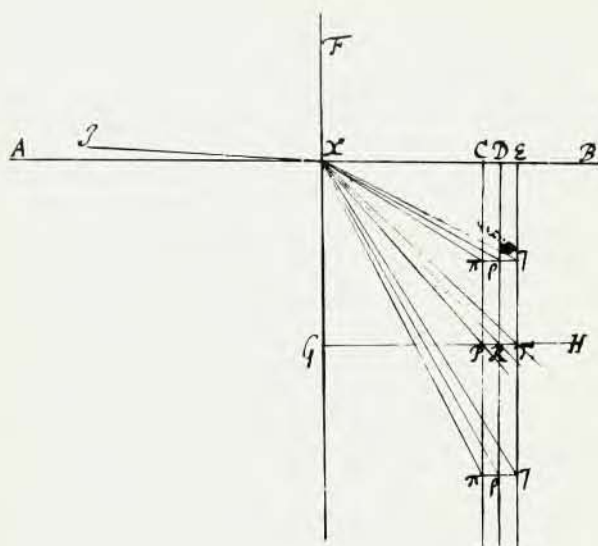
► Color is immutable by refraction, reflection, transmission or any other means. This proposition should be restricted to simple or monochromatic colors, and the fact that it is not reflects Newton's initial problem with properly defining simple and compound colors. He first made this a proposition in the second version of the *Optical Lectures*,

when he recognized that it could be used to prove that colors are innate to white light.

► There are two sorts of color, "simple" and "compound." Orange, for example, can be a simple spectral orange or a compound orange made up of red and yellow rays. These two sorts of color are sensibly identical but physically distinguishable, because compound colors, but not simple ones, are decomposed by a prism. Newton gradually clarified these concepts. In the first version of the *Optical Lectures* they were not even defined, but in a reformulation of his theory for Christian Huygens in 1673, he rigorously defined them in terms of refrangibility and solved this problem.

► Colors similar in sensible appearance to the simple spectral colors can be made by a mixture of the colors on each side of them. Again, this is a proposition that was added in the revision of the *Optical Lectures*, and it shows Newton's growing concern with the composition of colors.

► "But the most surprising and wonderful composition," Newton explained in the "New theory," "was that of Whiteness. . . 'Tis ever compounded. . ." That is, white light, particularly sunlight, is a mixture of rays of every color. Newton recognized that one could not directly prove experimentally that colors are innate to sunlight, and most of his experiments in support of this principle depend on a similarity argument: By various, often ingenious, means he composes white from a mixture of the innumerable spectral colors and shows that in all its properties it is similar to direct sunlight. (See the figure above.) In his *Opticks*, Newton concedes that white could also be composed from a smaller number of colors, perhaps as few as three.



Geometrical model. This is Newton's own geometrical representation of his quadratic dispersion law. The line IX represents a ray of sunlight falling at grazing incidence upon the medium AXB, and XP, XR and XT are its refracted violet, green and red rays. Once the parameters of the model, XC, XD and XE, are fixed, the refractions Xπ, Xρ and Xτ in any other medium are determined by that medium's mean index of refraction. (Add. MS 4002, page 85. Courtesy of the Syndics of Cambridge University Library.)

While there are certainly problems with Newton's experiment-based theory—imprecise and circular definitions and unjustified idealizations and generalizations, for example—there can be no doubt that it is firmly grounded on experiment and observation. It was proved by experiment, and its fundamental concepts, such as unequal refrangibility and simple and compound colors, are operational ones derived from experiment. In contrast, the mathematical theory, as we will now see, makes a virtue of the fact that it has little need for experiment and observation.

Mathematical theory of color

Almost as soon as Newton discovered in 1666 that rays of unequal refrangibility are innate to the Sun's light, he set out to apply mathematics to this new phenomenon: He calculated the chromatic aberration of a plano-convex lens; and he developed a mathematical-physical model of refraction and dispersion to calculate the refractions of various simple colors at the interfaces between various substances, for instance, air and water, or air and glass. I will call the former sort of application of mathematics simply quantitative to distinguish it from a mathematical theory: In the quantitative approach, one determines particular effects by applying traditional geometrical optics with the additional assumption of a varying index of refraction. As a masterful mathematical physicist, Newton was quite successful at this endeavor. The calculation of the table of refractions represents, at least in principle, what I will call a *mathematical theory*, and the sort of theory to which Newton aspired: From a few

fundamental mathematical-physical laws, one may deduce a large variety of phenomena.

Newton's plan to develop a mathematical science of color was never more than a program, and it must be reconstructed from his *Optical Lectures*. Its foundation was to be refrangibility, or index of refraction, which Newton found corresponded to color directly. He assumed in the first place that the sine law of refraction, or Snell's law, was valid for each color apart, and though he proposed an experimental verification, he rejected it as unnecessary. Then, to describe the variation of the degree of refrangibility with color, that is, the dispersion, Newton constructed a refraction model that we now know is based on Descartes's earlier model of corpuscles that receive an impulse as they cross a refractive surface. In his *Optical Lectures*, however, Newton carefully eliminated all traces of its mechanical underpinnings and presented it solely as a mathematical law. The model assumes⁵ that at grazing incidence in any given medium, rays (or corpuscles) of all colors receive the same increment of velocity normal to the refracting surface. (See the figure above.) This model yields what I call Newton's quadratic dispersion law:

$$\frac{\Delta n}{\Delta n'} = \frac{(1/n)(n^2 - 1)}{(1/n')(n'^2 - 1)}$$

In this proportion, Δn is the dispersion or the difference in the indices of refraction for extreme red rays and extreme violet rays in a given medium, n is the mean index of refraction, and the prime indicates a second medium. While the exact form of the law need not concern us, we should note that

implicit in it is the simple but erroneous assumption that dispersion is independent of the nature of the refracting substance and is solely a property of light. For, once the parameters of this model are determined—and only three measurements in one substance are necessary—then knowledge of just a single value of the index of refraction in some substance allows one to determine all refractions in it. Newton was quite proud of this feature and even boasted that with this law one need not "bother anew with experiments."

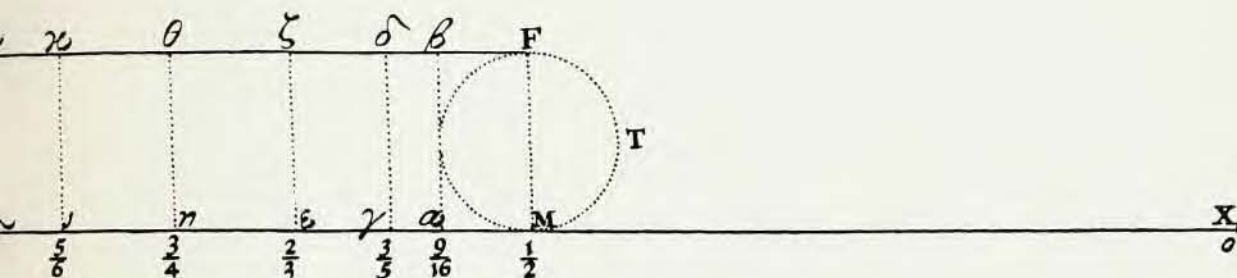
Three principles of refraction. Newton's goal evidently was to develop a rational science of color:

- The sine law defines the refraction of every ray at any angle of incidence in a given medium.
- The dispersion law defines the index of refraction of rays of every color given that of any one color.
- The law of relative indices of refraction, which was already known, but which Newton extended to rays of different refrangibility, gives the index of refraction for any two media with no additional measurements whatever, provided their refraction is known with respect to some common medium, such as air.

Thus, Newton developed a theory in which the barest minimum of measurements are needed to describe the refractions of any color in every medium. When he set forth⁶ his refraction model in his *Optical Lectures*, he freely admitted that

Although I have not yet derived the certainty of this proposition from experiments, nevertheless I do not doubt that it will satisfy all of them which it is possible to do with respect to it . . . meanwhile [I

Musical division of the spectrum. Newton found that the colors of the spectrum **PT** are always divided just as the string **GX** that sounds the notes of an octave. To obtain seven colors required for such a musical division, he added orange $\alpha\gamma$ and indigo $\iota\lambda$ to the five colors—red **Ma**, yellow $\gamma\epsilon$, green $\epsilon\eta$, blue $\eta\iota$ and violet $\lambda\mathbf{G}$ —that he had previously used. (From the first edition of *Opticks*, 1704.)



am] content to assume it gratuitously.

The three principles of refraction given above, as Newton later explained in a draft of a letter for Robert Hooke, were to serve as the foundation for his mathematical science of color. Although Newton considered a different dispersion law in that letter, it is important to note that the actual dispersion law adopted is irrelevant for this program, only the existence of such a law is essential.

We can at this point already discern that the goal of Newton's mathematical science of color was to describe the behavior of colored light, and not to explain its causes. His approach was to be more like that of traditional geometrical optics or kinematics than that of physical optics or dynamics. It is as if Newton had later attempted to derive a celestial mechanics from Kepler's laws rather than Newton's laws and central forces.

Newton devotes most of the remainder of the mathematical part of the *Optical Lectures* to what proved to be a futile attempt to deduce from the three principles of refraction, especially his dispersion law, the propositions that were to form his mathematical science of color. (In the following, I will perforce pass over Newton's most notable optical achievements, which are in traditional geometrical optics with monochromatic radiation.) He first devotes a number of propositions to the relative order and inclination of rays of different colors refracted at a plane surface under different initial conditions, which is as physically uninteresting as it sounds. Then, in two complex pairs of lectures containing some sophisticated mathematics, he turns to

an investigation of the variation of dispersion with respect to variation of the index of refraction. He demonstrates, for instance, that the dispersion increases at a faster rate than the index of refraction. This proposition is wrong, as are all but one in these lectures, because all but one are based on his quadratic dispersion law. Newton, however, could have readily tested this proposition, for example, by comparing common glass and turpentine, where it does not hold. On only one occasion, though, in these two long lectures does he suggest an experimental test, and then only to reject it as insufficiently sensitive.

Likewise, in the brief concluding lecture of the first version, which is on refraction in prisms—the fundamental experimental technique of his entire theory—two of the eight propositions are erroneous. It is particularly notable that one of these establishes incorrectly that the minimum of angular dispersion (that is, the angle contained by the extreme red and violet refracted rays) occurs when the rays pass through the prism symmetrically. Not only is the position of the minimum mistaken, but with the large-angled prisms Newton used there is no minimum at all. Although it is somewhat difficult to distinguish variations of the deviation and those of the angular dispersion, Newton was an acute observer and performed this experiment many times; in an observation in the *Opticks* he did correct this error. Newton seems almost oblivious to relating his mathematical constructions to the real world by experimental tests.

Newton revises optical lectures

When Newton revised his *Optical*

Lectures, he interchanged the two parts so that the mathematical part on refraction would precede that on color. This new order apparently reflected his growing commitment to develop a mathematical theory of color founded upon refraction, but, insofar as I can determine, it had no significant influence on the structure of either the mathematical or experimental theories or on their relation to one another. The dispersion law, by Newton's own admission, was still untested, and while he revised and rearranged his mathematical theory of color a bit, it remained essentially the same. Although he did not—or could not—advance the fundamental mathematical theory, he did add a brilliant section on refraction at spherical surfaces. This section contains two important calculations that treat polychromatic radiation: the chromatic aberration of a lens and the breadth of a rainbow.

For my immediate purpose, Newton's most significant, if not felicitous, addition was his musical division of the spectrum. (See the figure above.) He divided the spectrum into seven "more prominent" colors from red to violet and found⁷ that this division of the spectrum was

... proportional to a string so divided that it would cause the individual degrees of the octave to sound. . . . I could not, however, so precisely observe and define this without being compelled to admit that it could perhaps be constituted somewhat differently.

Nonetheless, he chose the musical division because of his belief in an analogy between the harmonies of sounds and colors. Thus far, Newton was simply adding a new twist to an ancient quest

for harmonies, but he then explained that by an approximation one can find the index of refraction for each color by dividing the indices of refraction between the two extreme colors in the same proportion as the spectrum. This musical division readily yields another (erroneous) dispersion law, which I call Newton's linear dispersion law,

$$\Delta n / \Delta n' = (n - 1) / (n' - 1)$$

As in Newton's earlier quadratic dispersion law, the dispersion here is independent of the nature of the refracting substance, for any two media with the same mean index of refraction will have the same dispersion. Although Newton did not deduce this new law in the *Optical Lectures*, he did briefly adopt it in his draft reply to Hooke just a few months later.

Contradictory laws of dispersion

For the very limited range of substances and indices of refraction examined by Newton, this law does not quantitatively differ much from the earlier quadratic law. However, it has fundamentally different physical implications and is incompatible with that law. Newton based his quadratic law on a dynamical theory of refraction, which he later further developed in the *Principia* using forces. He based his linear law directly on principles of his color theory—the immutability of color and degree of refrangibility—for the linear law implies that the proportion of the spectrum occupied by each color is identical in all spectra. Thus, Newton derived both laws from fundamental theoretical principles whose truth he never doubted. Choosing between them was therefore not in the first place an empirical issue for Newton, and this probably explains, at least in part, why he never subjected them to systematic experimental tests. In the reply that Newton finally sent to Hooke, he suppressed any reference to his dispersion laws, and for the next thirty years he remained publicly silent on this issue. When he finally chose the linear dispersion law in the *Opticks*, he supported it with fabricated experimental evidence, but that is a difficult issue⁸ that I will not treat here.

In this same letter to Hooke, Newton was already backing down from the strong claim of certainty that he had made in the "New theory," as he came to distinguish more clearly between his mathematical and experimental theories and to acknowledge the contingency of his experimental theory. To Hooke's charge that his theory was "not soe certain as mathematical Demonstrations," Newton replied:⁹

I should take notice of a casual expression w^{ch} intimates a greater certainty in these things then I ever promised, viz: The certainty

of *Mathematicall Demonstrations*. I said indeed that the *Science of Colours was Mathematicall & as certain as any other part of Optiques*; but who knows not that Optiques & many other Mathematicall Sciences depend as well on Physicall Principles as on Mathematicall Demonstrations: And the absolute certainty of a Science cannot exceed the certainty of its Principles. Now the evidence by w^{ch} I asserted the Propositions of colours is in the next words expressed to be from *Experments & so but Physicall*: Whence the Propositions themselves can be esteemed no more then *Physicall Principles* of a Science. And if those Principles be such that on them a Mathematician may determine all the Phaenomena of colours that can be caused by refractions... I suppose the *Science of Colours* will be granted *Mathematicall & as certain as any part of Optiques*.

Even this concession, however, is somewhat misleading in its description of Newton's new science, for Newton's mathematical theory was founded upon his three principles of refraction, as he explained in the draft of his reply to Hooke, and not upon the "physicall principles" of his experimental theory. His experimental and mathematical theories in fact had only one and a half principles in common, namely, that sunlight consists of unequally refrangible rays, and that there is a correspondence between refrangibility and color, which, however, is only qualitatively exploited—hence the half.

Why did Newton moderate his claims as to the certainty of his experimental theory and differentiate it from the mathematical theory? The immediate cause, of course, was Hooke's objection, which compelled him to ponder more carefully the nature of scientific theories, and in particular, the methodology and formal structure of his own. But at the same time, I suspect that Newton wanted to sever the two theories, for his goal of developing a mathematical science of color had become stymied. I say this for three reasons:

► First, Newton lacked a dispersion law—or rather he had two—and an exact science must have a certain foundation.

► Second, I find it difficult to believe that after two attempts in his *Optical Lectures* Newton himself did not recognize that he had not actually progressed very far in developing a fundamental theory that modeled reality. His mathematical theory was, rather, nearly a free construction of his intellect. While this approach may have failed Newton here, we should not fail to recognize that his willingness and ability to formulate general mathemat-

ical-physical laws and pursue them in all their ramifications shows the boldness of scientific approach and breadth of intellectual grasp that otherwise served him so well.

► Third, I think that with his growing concern for the composition of colors, Newton had come to recognize that he had fashioned only one part of a theory of color, a theory of unequal refrangibility that could account for the spatial distribution or separation of colors but not for their sensible appearance—that is, their color. I think this would have troubled Newton even if his mathematical theory had been more successful.

Abandons mathematical theory

Whatever the precise reasons, Newton did abandon his mathematical theory and suppress the mathematical part of the *Optical Lectures*. Less than four months after he sent off the "New theory," he decided to suspend publication of his *Optical Lectures* because the appearance of the "New theory" and the ensuing controversies had so disturbed his tranquility. By the time he recovered his equanimity in late 1675 and once again judged the world receptive to his optical theories, much of the *Optical Lectures* was already outdated. Newton was now planning a new work that was very much like the later *Opticks*. For this projected work, he intended to redo the experimental part of the *Optical Lectures* on color as a "discourse about y^e colours of y^e Prism," to omit altogether the mathematical part of the *Lectures*, and to add his recent papers on the colors of thin films. When Newton finally published the *Opticks* in 1704, he included only some specific quantitative results from the *Optical Lectures*, and he even considered it necessary to disavow his *Lectures* in its preface.

In 1672 Newton's experimental theory had also encountered a serious snag that threatened its certainty. In revising his *Optical Lectures*, he had discovered a new, logically rigorous proof that colors are innate to sunlight. The proof depends on the principle of color immutability, and in essence runs as follows: Because colors are absolutely immutable, and sunlight exhibits colors after it is refracted, then it necessarily follows that those colors are innate to sunlight prior to refraction, even though they are not yet apparent.

Newton soon perceived a difficulty in experimentally establishing this proof as formulated, and in 1673 he developed an alternative version. He continued to try to establish the certainty of this proof, returning to it in the early 1690s and again in 1703, but he eventually came to accept that no matter how he formulated it, it was impossible experimentally to prove color immutability for the Sun's immediate light,

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The first Book of Opticks.

I 13.3.

~~It is not~~ ^{My} designe in this Book ^{is not} to explain the properties of Light by Hypotheses but to propose & prove them by reason & experiments. In order to wch I shall premise the following Definitions & Axioms.

DEFINITIONS.

Defin. I

By the Rays of light I understand its least parts & those as well successive in the same lines as contemporary in several lines. For it is manifest that light consists of parts both successive & contemporary, because in the same places you may stop that wch comes one moment & let pass that wch comes presently after, & in the same time you may stop it in any one place & let it pass in any other. For that part of light wch is stoppt cannot be the same wth that wch is let pass. The least light or part of light wch may be stoppt alone without the rest of the light or propagated alone or do or suffer any thing alone wth the rest of it. light both not or suffer not, I call a ray of light.

Defin. II

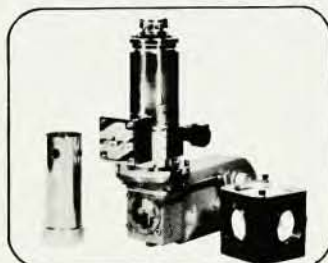
Refrangibility of the rays of light is their disposition to be refracted or turned out of their way

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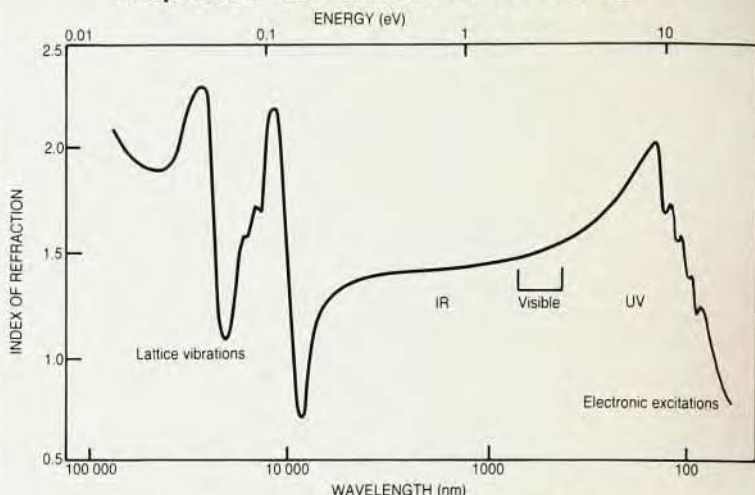
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Dispersion—our current understanding



Index of refraction as a function of wavelength, for a colorless glass.
(From K. Nassau, *The Physics and Chemistry of Color*, Wiley, New York, 1983.)

Transparent glass absorbs some infrared radiation through excitation of lattice vibrations, which involve the bonds between atoms. Glass also absorbs some ultraviolet radiation through the excitation of electrons in atoms and molecules. Each of these absorptions results in large local changes in the refractive index (see figure above) and a more gradual change in the visible, where the variation of the refractive index n with wavelength λ is usually fitted by a two- or three-term Sellmeier equation

$$n^2 = 1 + \sum_i \frac{A_i \lambda_i^2}{\lambda^2 - \lambda_i^2}$$

Here λ_i is the wavelength of an absorption and A_i is the absorption strength. This behavior can be understood as a system of classical damped oscillators. Only a vacuum has no dispersion because it has no absorptions.

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and thus that the colors are innate to it. The problem is that before refraction sunlight appears white, and afterwards it displays all the spectral colors; and if the two are compared, the colors do appear to have changed. The careful reader of the *Opticks* will note that Newton has all but given up his attempt to prove that sunlight is composed of all colors; he devotes just nine rather weak lines of text to it, whereas he spends sixteen pages showing that white light, similar to the Sun's light, may be compounded of all colors. This is indeed a long way from the "most rigid consequence" of the "New theory."

We can now view the *Opticks* from Newton's perspective and his early hopes for a certain and mathematical science of color, and appreciate what must have been his disappointment when he penned the modest opening lines (see the figure on page 41) of the *Opticks* that are just a faint echo of his earlier confident assertions: "My Design in this Book is not to explain the properties of Light by Hypotheses, but to propose and prove them by reason and experiments." To be sure, because we do not put such severe restrictions

on the certainty of a scientific theory, we rightly judge the *Opticks* to be one of the great experimental works of the Scientific Revolution. However, if we are properly to appreciate Newton's *Opticks*, then we must understand it within its own historical context and especially in its relation to his brilliant, but flawed, *Optical Lectures*.

References

1. H. W. Turnbull, ed., *The Correspondence of Isaac Newton*, Cambridge U. P., Cambridge (1959), volume 1, page 82.
2. Reference 1, page 96. Oldenburg deleted this passage in the paper published in Phil. Trans.
3. A. E. Shapiro, ed., *The Optical Papers of Isaac Newton*, Cambridge University Press (1984), volume 1, page 439.
4. See A. E. Shapiro, *Isis* 71, 211 (1980).
5. See Z. Bechler, *Arch. Hist. Exact Sci.* 11, 1 (1973).
6. Reference 3, page 201.
7. Reference 3, page 542.
8. See Z. Bechler, *Brit. J. Hist. Sci.* 8, 101 (1975); A. E. Shapiro, *Arch. Hist. Exact Sci.* 21, 91 (1979).
9. Reference 1, page 187. This passage too was deleted by Oldenburg in the reply published in Phil. Trans. □