In part one of this series, we looked at the very early history of refraction but could not disentangle it from the history of light and vision and even from the political history of the era. We saw how the ancient Greeks had developed optics to a high level, and how this was absorbed and advanced by the Romans and finally by the Arab and Ottoman Empires. All of this is based on what we know, or think we know, because evidence is scarce and largely dependent on much later writings, some of the most significant being copies of earlier copies that have passed through several different languages. It should not be thought that as research was being pursued in, say, Byzantium, that the rest of the world was static, but the story is simplified if we focus on certain aspects. Now our attention moves back to Western Europe and the 13th century and in particular Oxford in the south of England. There was still nothing that we would recognize as specialization at this stage of philosophical development. Life, religion, science, and technology were all tied together and politics was not excluded from the mix. The universities were essentially controlled by the Roman Catholic Church. We attempt to distinguish an optical thread in all of it but our attempt is purely artificial.

Optics in the 13th Century

At the stage of learning in the 13th century in Western Europe there still existed, particularly in ecclesiastical circles, a belief in an ultimate truth emanating from a divine source and revealed by internal inspiration. Such knowledge was of a different, higher quality from that resulting from observations[1]. This approach can be traced back to Plato and competes with the idea that it is observations that are of primary importance. Added to this was that Nature always prefers the simplest and most regular rules.

Our account begins with Roger Grosseteste (1175–1253) who held many posts, some simultaneously, but was for much of his career Bishop of Lincoln and taught at Oxford where he may have been Chancellor for a time. Grosseteste lectured on theology, although he may also have lectured on optics[2], and like many scholars he was interested in all natural phenomena. He wrote, amongst other works, an important text on the rainbow, another on astronomy, and one on the nature of light. Grosseteste is credited with the beginnings of the modern scientific method. There is a problem in science that has been called the Riddle of Induction[3,4]. A syllogism in Aristotelian logic argues from the general to the particular. The major premise expresses what is given as an attribute of all the members of a given class. The minor premise affirms the membership of its particular subject in that class. The conclusion, therefore, is that the subject possesses the given attribute. Science argues in the opposite direction. The density of this silver sample is Z. Therefore Z is the density of silver. Our modern scientific approach is that this argument is valid as long as the experimental measurement is sufficiently well controlled and, usually, we will add extra verification by additional confirming experiments. Science constantly checks and revises its ideas based on the acquisition of additional knowledge and understanding. There is support for this interpretation from Aristotle himself, but the sponsor who introduced these ideas into modern science was Grosseteste, and he greatly motivated the scientists who followed. However, Grosseteste himself was still much influenced by the idea of an ultimate truth[1] and this shows clearly in his treatment of refraction.

To Grosseteste, the well known law of reflection that the angle of reflection and the angle of incidence were exactly equal was a demonstration of an ultimate truth. Not only was the surface responsible for this reflected behavior of a light ray, but it was also responsible for the inseparable refraction on transmission. Since the behaviors were completely linked, there was an inescapable conclusion that equal angles in
reflection should be accompanied by equal angles in transmission. Which angles might these be? In reflection there are three directions, the direction of the incident ray, of the surface normal, and of the reflected ray. In transmission we have the continuation of the incident ray, the normal to the surface, and the redirected transmitted or refracted ray. These must be the directions that define the equal angles that in a denser medium must in turn be the angle between the normal and the refracted ray and between the refracted ray and the continued incident ray. This view of the equality of these two angles is of fundamental importance[1]. It leads directly to the statement that the angle of refraction is half the angle of incidence, but that is a secondary observation.

This model is completely Grosseteste’s own, devised by him without any supporting authorities nor supporting measurements. Eastwood[1] explains it as a statement of the quality of light rather than that of a particular behavior. Alhacen’s Book of Optics was apparently not known to Grosseteste. The best known version was a translation from Arabic into Latin around 1270 as Opticae The-saurus Alhazen, although it had also been translated a little earlier. Thus it was known to Roger Bacon (c. 1210–1292). Bacon was a Franciscan friar and very interested in natural philosophy. He studied at Oxford and although it is not completely certain that it was during Grosseteste’s tenure, he was clearly much influenced by Grosseteste’s ideas. Bacon lectured at Oxford and at the University of Paris. He was outspoken, particularly in respect of church reform, and not at all popular with the Franciscan authorities. His career was interrupted by periods of house arrest—he was even imprisoned for some years—when he was certainly banned from involvement in any scientific pursuit. In spite of this, he was one of the great pioneers of the scientific method, recognizing the importance of observation over supposition and the basing of theories on known facts. Optics was one of his fields of study. He wrote extensively, some fragments of which remain. His greatest work is his Opus Majus, which includes a Part V on optics that was later extracted and presented as a separate treatise entitled “Perspectiva.” There is some convincing evidence[2] that Bacon suggested the use of lenses in spectacles or as magnifying glasses to improve vision and also in telescopes, although it is possible he may have been repeating some of what was already known, possibly by Grosseteste. Our records, unfortunately, are sparse and incomplete.

Also at Oxford was another Franciscan, John Peckham (c. 1230–1292) a contemporary of Bacon who eventually became Archbishop of Canterbury. His book on optics, Perspectiva Communis, became a text that was used all over the European continent for three centuries. Its treatment of vision was based very much on Alhacen and it emphasized the involvement of the brain in visual perception. Doesschate[2], however, judges Bacon’s work as more original.

Vitellio (c. 1230–1290), or Witelo, of mixed Polish and Thuringian parentage, studied at Padua and later, as a friar, moved to Viterbo. At that time, papal relations with Rome were perturbed and Viterbo, in central Italy, was the seat of the Curia. In the 1270s, almost in parallel with Bacon’s treatise, but a few years later, Vitellio produced an enormous book on optics, Perspectiva, based largely on Alhacen but, as we now know, including material from Ptolemy via Alhacen, and in particular his results on refraction. It is suggested by Doesschate[2] that the receipt of Bacon’s Opus Majus at the Papal Court may have prompted the Curia to invite Vitellio, who was not out of favor, to write the book as an independent confirmation, or otherwise, of Bacon’s optical work. Vitellio’s book was eventually printed and reprinted and greatly influenced later workers, especially Kepler.

14th to 16th Centuries

In the centuries immediately after the 13th, optical developments continued, advancing on a broad front throughout Europe, along with the general advances in scientific and medical knowledge that received contributions from giants like Leonardo da Vinci (1452–1519). The production of mirrors of exceptionally high quality became possible through improvements in glass making. Spectacles became an important industry. Astronomy continued to flourish. Books were now printable, and Peckham’s Perspectiva Communis, Vitellio’s Perspectiva, and the translation Opticae Thesaurus Alhazen circulated widely.
In medieval universities, the seven liberal arts were divided into two groups, the Trivium, containing rhetoric, grammar, and dialectic, and the Quadrivium, containing the mathematical sciences, which were arithmetic, geometry, harmonics, and astronomy. At Oxford, Bacon had been successful in introducing optics as part of the Quadrivium and the greater availability of books allowed much wider teaching of optics. However, much of practical optics was empirical. The properties of a manufactured lens, for example, would be found once it was made and spectacles would be fitted completely by trial and error. This empirical nature began to change towards the close of the period.

The astronomer Tycho Brahe (1546–1601) was born in what is now Sweden to a noble Danish family, and spent the earlier two decades of his career at an observatory he had built, supported by the King of Denmark, where he performed measurements of unprecedented accuracy using instruments designed and built by himself, but without the advantage of the telescope. That had to wait until the next generation of astronomers. In 1597, he moved to Prague where he was appointed Imperial Astronomer. In 1600, he hired Johannes Kepler as his assistant. Kepler (1571–1630), born in Baden-Württemberg, was educated at the University of Tübingen in theology (not unusual at a university of that time) but with mathematics and astronomy included in his curriculum. His initial employment was as a teacher of mathematics in Austria where he continued his astronomical studies and wrote a book, Mysterium Cosmographicum, supporting the Copernican system, which attracted Tycho Brahe’s attention. He had little time as his assistant because Brahe died in 1601, but it was long enough for Kepler to learn much, and more importantly, it gave him access to Brahe’s tightly held data. He was appointed to the position of Imperial Mathematician, essentially succeeding Brahe, which he held for 12 years. We are now at the start of the 17th century, when events began to move much more quickly.

Kepler is perhaps best known for his laws of planetary motion that confirmed the heliocentric model of our solar system, but he made enormous progress in optics in general and can be considered as introducing modern ideas to optics. He was much influenced by Alhacen through Vitello’s Perspectiva and in 1604 published Ad Vitellionem Paralipomena, nominally a commentary on the Perspectiva and Alhacen, but actually much more, and revolutionary in its ideas. In his book, Kepler, admittedly inspired by Alhacen, used Ptolemy’s values for refraction, as repeated by Vitello. However, rather than following Alhacen, who did not get it quite right, he performed his own ray tracing and succeeded amongst other things, in explaining the imaging qualities of a water-filled glass sphere that mimicked the eye, agreeing with experiment and with more modern calculations. Smith[5] gives an excellent and detailed account including a comparison of the two sources, and concludes, “Kepler’s account ... marks the birth of modern lens-theory ...” Kepler thus gave the first correct account of the imaging process in the human eye, pointing out that the image was spread out over the retina and was inverted[6]. Model experiments confirmed his analysis.

Clearly, Kepler was well aware of the refractive properties of media boundaries. How is it that he missed the enunciation of the Law of Refraction? He did instinctively feel that there should be some geometrical rule connecting the angles with the ratio of the densities of the media and he did investigate the possibility, but failed to find it. Part of the problem is that he used Ptolemy’s results that include very slight errors, possibly because of rounding to half degrees, possibly because of some smoothing carried out by Ptolemy himself, or his translators. However, optics was now ready for the Law of Refraction and the community responded.
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It is not at all clear who should be accorded the priority. Rather like most scientific advances, the Law of Refraction seems to have occurred to many different people at around the same time. By 1602, the underrated English mathematician and astronomer Thomas Harriot (1560–1621) knew the correct relationship, but whether he learned or devised it is not known. Like many of his contemporaries, much of his work went unpublished, existing only in manuscripts many of which have since been lost. Although he had knowledge of the relationship, he kept it to himself and when Kepler asked him for it, he received a table of results with no analytical expression[7].

Snell is the Anglicized name we usually associate with the Law of Refraction although, by Stigler's Law of Eponymy[8], that should immediately disqualify Snell from being the true originator. Snell was actually Willebrord Snel van Royen (1580–1626), or Latinized, Willebrord Snellius. He was born in the Netherlands and educated at the University of Leiden where he was appointed professor of mathematics. It seems that Snell never actually published his formula although it was written in one of his manuscripts.

The first person actually to publish the Law of Refraction or the Law of Sines in a reasonably modern form, was René Descartes (1596–1650). Descartes is well known for advances in philosophy, mathematics and science. He is considered to have launched modern western philosophy. The Cartesian coordinate system is named after him and he was an important pioneer of analytical geometry. A good deal of his most productive periods were spent in the Netherlands.

Descartes used a type of corpuscular argument. The component parallel to the surface of movement in an incident ray would not be affected in its contact with a surface and this led immediately to the equal angles in the Law of Reflection. Also, when combined with the assertion that somehow due to an extra impulse delivered at the interface, light traveled faster, with increased strength, in a denser medium, the Law of Refraction was obtained. In France, this is usually known as the Law of Descartes. He wrote this up in his 1637 work, Dioptrics. Newton's arguments at the end of the century followed a somewhat similar path. Of course we know now that the reasoning was actually incorrect, because we are dealing with waves that travel more slowly in a denser medium, but the faulty reasoning actually led to the correct result. It is difficult to escape the conclusion that the result was already known and the argument was designed to yield it.

Now Fermat enters the story. Pierre de Fermat (c. 1601–1665) was born to a rich family involved in the leather trade. His initial years at the University of Toulouse were spent in the study of law but he later moved to Bordeaux where he began his work in mathematics. Still later he resumed his legal studies in Orléans and from 1631 occupied the post of counsel at the Parliament of Toulouse. At the same time, he continued his interest in mathematics and became known in a much wider circle, and notably to Marin Mersenne (1588–1648) with whom he corresponded and who became aware that Fermat was solving problems that were beyond the reach of the conventional mathematical methods of the time. Mersenne, founder of the Académie Parisienne, the forerunner of the Académie des Sciences and a close friend of Descartes, was very well connected with the scientific community and brought Fermat much attention. Fermat, however, was first and foremost a lawyer, not particularly interested in publication, and much of his work was contained in letters that he wrote. Like Descartes, he was a pioneer in analytical geometry. He developed a kind of calculus predating Leibnitz and Newton and he essentially created number theory. He also had some differences of opinion with Descartes that were eventually agreeably resolved. It is his insight into the problem of refraction that interests us most.

Hero of Alexandria is reputed to have proposed the principle that light follows the shortest path between two points, and this is absolutely correct in a single homogeneous medium. In 1657, Marin Cureau de la Chambre (1594–1669) wrote a book entitled *Light*, a copy of which he sent to Fermat. His argument was based on Hero's principle rather than the corpuscular treatment of Descartes and he assumed that light propagation was instantaneous, that is of infinite velocity. This allowed the immediate derivation of the equal angles in reflection but appeared to predict no deviation in a ray that penetrates a surface at oblique incidence since a straight line would obviously be the shortest distance between source and destination. His refraction argument was therefore complicated and confused. Fermat wrote to him in 1657 pointing out that light would have a finite velocity and that distance should be replaced by time[9]. He postulated that the resistance to light would be greater in a denser medium and so the velocity would be less. The ray would follow the path of least time, not least distance. This leads directly to the Law of Sines, as he showed in his later 1662 letter to de la Chambre, and is the first correct theoretical analysis that does so[9]. Perhaps we should be calling it Fermat's Law but that might in turn violate Stigler's Law of Eponymy.
A slightly different but equally valid explanation was given by Christiaan Huygens (1629–1695), in his 1690 book on optics[10]. His idea of the propagation of light involved the transmission of movement from one ether particle to another so that each particle was the source of a spherically propagating disturbance. Light advancing on a plane broad front stimulated a broad array of particles to emit the movement and the combination of all their spherically propagating disturbances yielded a wavefront that continued in the same direction retaining the form of a plane. It sufficed to draw the incoming oblique plane wave and the spherical disturbances radiating from the particles of the surface to arrive at the changed propagation of the plane wave into the second medium at a different speed and obeying the Law of Sines. This is virtually indistinguishable from the explanation one finds in most modern introductory textbooks on optics. However, the Law of Refraction, or of Sines, was still stated as a constancy of the ratio of the sines, the constant being usually itself in the form of a ratio, such as $3/4$ for water and $3/2$ for glass. Because the incident material was air, this can be translated into refractive indices for water and glass of 1.33 and 1.50 respectively.

Newton, too, used a model quite similar to that of Descartes in his 1704 Opticks[11]. While Fermat and Huygens had a good physical model from which they deduced the law, Newton approached it a little differently. He first verified experimentally the constancy of the ratio of sines and then devised a geometrical construction. The constant was still expressed as a ratio. So far this was correct. When, however, he attempted an explanation, he asserted the equality on both sides of the surface of the motion parallel to it, thus falling into the same trap as Descartes, because it inevitably requires a greater velocity in a denser medium. The incorrect reasoning led once again to the correct result.

The tendency at that time was still to consider refraction as a property, refrangibility, of the light ray rather than the material. There is a fleeting allusion to a term refractive power by Robert Hooke (1635–1703) on page 50 of his great book Micrographia[12] where he mentions that the presented interference colors (as we now understand them) were “according to the greater or less refractive power of the pellucid body.” Then Isaac Newton (1642–1727) too, used a similar term in a letter to the Royal Society[13] in which he described his experiments into the nature of color using a prism. “Having made these observations, I first computed from them the refractive power of that glass, and found it measured by the ratio of the sines, 20 to 31.” It becomes clear, however, that he was not thinking of a material property, but a property of the light rays “some of which are more refrangible than others... not by any virtue of the glass, or other external cause, but from a predisposition, which every particular Ray hath to suffer a particular degree of Refraction.”

Thus by the close of the 17th century the constancy of the ratio of sines was well established and well known. However, the concept of refractive index as a parameter of a single material was still missing. Refraction was a property of a light ray meeting a surface rather than a characteristic of a particular material.

18th Century

The 18th century was a period of great development in technology of all kinds including optics. Remarkable progress was made in microscopes, telescopes, spectacles, and navigational instruments like the sextant. The availability of improved astronomical telescopes contributed to astronomical advances of great significance. The technological advances did not demand any revolutionary understanding of the fundamental nature of light itself, but optics did benefit enormously from the improvements in manufacturing techniques in general, as illustrated vividly by Greivenkamp and Steed[14] who describe the enormous improvement brought about in telescope construction by the new availability of precision drawn tubes of brass. The Law of Refraction was well understood, but the ratio of the sines was still expressed as a fraction. Refrangibility was still considered to be more a property of a light ray than of a material. In the middle of the century, John Dolland (1706–1761) showed[15] that different transparent materials could present different dispersions (in our modern terminology). He was inspired by a report of a confidential method of combining a positive and negative lens of different materials to yield an achromatic doublet, inspiration for him to carry out experiments and arrive at the design of such a doublet lens that he patented in 1757. His son Peter used the patent to pursue competitors in the courts and won a significant judgment against challengers because the true originator had merely kept the invention secret, so that any benefit to the public was wholly derived from the exercise of the published patent. The achromat revolutionized optical instrumentation and inspired new developments in lenses. By the end of the century, optics was ready for the next leap forward.
Early 19th Century

We have already encountered Thomas Young (1773–1829) in our travel through the history of calculation techniques for optical coatings[16]. Young was by profession a physician but he was skilled in every branch of philosophy in its broadest sense. It was Young who introduced the first convincing argument of the wave nature of light[17]. In 1801, he was appointed Professor of Natural Philosophy at the Royal Institution, charged with delivering lectures on this subject. In 1803, he resigned the position to devote more attention to his medical practice, but this did in no way mean that he dropped his other interests. His lectures on natural philosophy had been accompanied by copious notes on every division of the natural sciences and he now converted them into a two-volume treatise that was published in 1807[18]. On page 413 of Volume I of this impressive work we have, in his introduction to optics: “The refractive powers of different substances, are usually estimated by a comparison of the refractions produced at their surfaces in contact with the air, which, in all common experiments, has the same sensible effect as a vacuum or an empty space; the ratio of the angles of refraction and incidence, when small, and that of their sines, in all cases, being expressed by the ratio of 1 to a certain number, which is called the index of the refractive density of the medium.” He rapidly shortened this term to index of refraction, although sometimes also used refractive density, and it is clear that he considered it as a property of the material rather than of the light ray. He retained the term refrangibility when discussing the ray itself. This is the first time we see the modern name of the refractive index parameter in print, but the strong sense we get from the wording is that it was an already accepted term, perhaps dating back to Young’s lectures that began in 1801 or still earlier.

Conclusion

At the start of the 19th century, we find the concept of refractive index in its modern form and well understood. We are still some way from the complex index that also contains the extinction coefficient and that will be included in the third part of this series.

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