OPTICS and the NATURE of LIGHT

For most of human history, the facts of light and optical phenomena have been seen as central to the understanding of Nature. A historical review of ideas about light could certainly fill many books- no such attempt will be made here. Some of the central facts about light that have been understood long before physics include:

(i) Sources of Light: Light is emitted by hot bodies; moreover, intense light also feels hot (we would now say that it carries energy, which heats any object absorbing this energy). Light rays vary enormously in their intensity.

(ii) Propagation: Light travels in lines, or 'rays', that are straight, in any homogeneous medium through which it does travel - it does not apparently 'fall' in the earth's gravity, unlike 'material' bodies. When it does curve or change direction, this is invariably because the medium through which it travels is inhomogeneous. It can travel through gases, and many liquids and solids - which are classified as transparent, translucent, or opaque, depending on the facility with which light passes through them. And crucially - light travels through a complete vacuum, apparently over limitless distances, requiring no material medium for its propagation.

(iii) Interaction with matter: Light is partially refracted upon passing through the interface between 2 transparent media, thereby abruptly changing in direction; and it is also partially reflected. The reflection is specular off a smooth surface. Thus in general we have simultaneous reflection and refraction at the smooth boundary between 2 transparent media. If light meets an opaque medium it is either absorbed or scattered (ie., reflected in many different directions). A smooth opaque medium can reflect it specularly.

(iv) Self-Interaction: Light apparently does not interact with itself - if 2 light beams pass through each other, they do not appear to influence each other at all. This result is of great significance, and yet it is usually thought to be so obvious that it is totally ignored (we take for granted that when we look at some object, this in no way affects what somebody else sees when they look at another object, even though the light rays involved can clearly cross each other).

(v) Speed of Propagation: Light travels incredibly fast (until the measurements of Rømer in 1660, it was not clear that it traveled at all - the fact of light emission led most to suppose this, but it does not force this conclusion). By the Renaissance it was generally considered that light traveled from an object emitting, or reflecting/refracting the light, to the eye. But this was not obvious, and indeed the view until the work of the Islamic astronomer/mathematician philosopher Alhazen was that it traveled from the eye to the object.

All these results, except for the velocity of light, were clear to anyone living in the late 17th century, if they had cared to think about the world around them a little. There were also a number of other results that were less well-known and less obvious, and which were only starting to be explored at this time. The most important of these effects were

(a) Diffraction: Diffraction was discovered by the Jesuit mathematician and astronomer Grimaldi , in work done roughly between 1655 and 1663, when he died, and published posthumously in 1665. It was further investigated by, amongst others, Hooke, Newton, and Huyghens, as a phenomenon in which light passing near a solid surface appeared to bend around corners - it was particularly obvious when light was passed through very thin slits or pinholes.

(b) Nature of colour: The nature of colour had been an object of inquiry since ancient times, but it was Newton who first showed that white light could be split into rays of different colours, and these then reunited into white light. Despite his extensive investigations, many other properties of colour (notably, what governed the apparent colour of different objects) were not clear at this time.

(c) Birefringence: This phenomenon was discovered in 1169 by the Danish scientist Rasmus Bartholin, who gave it the name 'double refraction' (the term 'birefringence' came later). He found it in crystals of calcite (then known as 'Iceland Spar'). It consists in the refraction of light into 2 distinct rays by the crystal, traveling in different directions. It is completely obvious upon inspection, since an object viewed through a birefringent crystal will appear double.

(d) Interference 'fringe' effects: A number of different interference phenomena were known at the time of interest here, in which line-like patterns were seen in light that was multiply reflected between very close surfaces. In particular, Newton was aware of what later became known as 'Newton's rings', used them in his characterization of lenses and mirrors, and studied them in some detail (notably in the *Opticks*); and Hooke also discussed them in his *Micrographia*, published in 1665. Related phenomena that were also studied included the iridescent banded colours of thin films of oil, of peacock feathers, and so on. Hooke considered that these were evidence for a wave-like nature for light (as had Descrates), whereas Newton tried to give a corpuscular explanation.

One can add to this list the physiological facts of light perception, many of which were again understood to some extent long before physics- the role of the eye and the lens in it, and the perception of colour and its subjective qualities. Visual perception is of course by far the most sensitive of the human perceptual capacities, and most people even now assume the common sense view, that visual perception gives us direct access to the world as it is. Even sophisticated philosophers have been led to similar ideas - the whole idea of the primacy of 'sense-data', particularly as discussed by British empiricist philosophers, can best be understood as an attachment to the extraordinary detailed content of our visual apparatus.

Only with the fundamental discoveries made in the 17th century, mostly in the Netherlands and in England, did it become possible to pose sensible questions about the real nature of light. From this crucible there emerged 2 opposing views- the 'corpuscular' of light, championed by Newton, and the wave theory of light, which was given in its most comprehensive form by Huyghens. In what follows we first, in section (1), look at some of the people and the early discoveries that began this process of investigation (notably the invention and use of the telescope and microscope, and the discovery of the laws describing reflection and refraction). We then look in section (2) at Huyghens's work, and his wave theory, and finally in section (3) at Newton's optical work and his corpuscular ideas, and also at some of his philosophical and religious beliefs, insofar as they influenced his ideas.

Note that four major figures in all these optical developments were Galileo, Descartes, Newton, and Huyghens - biographical notes on all these scientists appear elsewhere in these notes.

(1) PIONEERING WORK in the DUTCH REPUBLIC

As discussed elsewhere, the extraordinary explosion of ideas and creativity in the Dutch 'Golden Age' was of very major importance in the development of science (as well as in philosophy as a whole, in art, and in the development of new political ideals). There is no space to give any comprehensive description of the development of Dutch science at this time. Many important characters were involved, the best known being Descartes and Huyghens; others included van Leeuwenhoek, van Schootens, and the philosopher Spinoza. Their work was well known in England, even in the case of Leeuwenhoek, who only wrote in Dutch.

In what follows I simply describe the life and work of a few of the important early figures in this story. The work of Galileo and Descartes is described elsewhere, in the biographical notes devoted to these two. The views of Newton and Huygens are described in sections (2) and (3) below, as well as in the biographical notes devoted to these two.

Hans Lippershey (1570-1619)

Hans Lippershey was a Dutch eyeglass maker who many believe was the inventor of the first telescope- he certainly was the first to apply to patent it. He was born in Wesel, Germany and settled in the Netherlands, opening an eyeglass shop in Middleburg.

According to one story, Lippershey noticed 2 children playing with lenses in his shop. The children found that when they looked through two lenses, a weather vane on a nearby church appeared to be larger. Lippershey then tried it himself, and added a tube placed between the lenses, to make the first telescope. Lippershey's name for his invention was a "kijker" (from the Dutch verb 'kijken, meaning to look or watch). In 1608 Lippershey applied for a patent with the Belgian government. Even though he was paid very well for his invention, a patent was not granted because it was argued that the device was too simple, and so its construction could not be kept a secret- this turned out to be true.

There still much debate about who actually first invented the telescope. Some believe that Giambattista della Porta of Napoli discovered the telescopic properties of lenses in 1589, and it is also possible that it had already been made in Germany before Lippershey. Certainly Galileo was aware of Lippershey's invention before he developed his own telescope, and moreover acknowledged the Dutch priority. It also is fairly certain that Lippershey was the first person to describe a telescope in writing.

Lippershey has also sometimes been credited with the invention of the compound microscope. This is less clear. At least 2 other Dutch spectacle makers, Hans and Zacharias Janssen, made similar devices at about the same time as Lippershey. The Dutch diplomat William Boreel, Who claimed to know all 3 of them in Middleburg during Lippershey's youth, claimed that Lippershey stole his ideas from the Janssens. There is no real resolution of this controversy to date.

As far as is known, Lippershey never did anything with the telescopes he made - this was left to others.

Willebrord Snell (1580-1626)

Willebrord Snell was a Dutch mathematician, best known for determining that transparent materials have different indices of refraction depending upon their composition. Snell was born in Leiden in 1580, and started studying mathematics at a very young age. His father was professor of mathematics at the University of Leiden, and the family was well off.

Snell entered the University of Leiden at a relatively young age- like many others at that time, he studied law. His attention soon focussed on mathematics and he was teaching at the university by the time he was 20 years old. After finishing his degree, he travelled to eastern Europe and visited most of the major astronomers of the day.

In 1613, Snell succeeded his father as professor of mathematics at Leiden. His work seems to have been directed towards practical problems. In 1617, he published his "*Eratosthenes Batavus*", explaining his method for measuring the Earth by triangulation. Snell had difficulty completing this work, but then the Sterrenberg brothers joined in and finished it with his assistance. This work helped develop the foundations of modern geodesy. Snell also published work on comets and in 1624, he published his "*Tiphys Batavus*", a work on navigational theories. His work in pure mathematics involved series expansions, including an improved method of calculating approximate values of π using 96-sided polygons (producing a value correct to 7 decimal places).

By far the best known contribution made by Snell at the present time was his laws of light refraction, although at the time they had no influence- they were not published until almost 70 years after his death! The study of refraction was very old- Ptolemy had proposed a law relating angles of refraction, which unfortunately was not correct, and the Islamic scientist Alhazen made a similar attempt (which was also unsuccessful).

Snell discovered that the angle of bending of a beam of light crossing between 2 media was dependent upon the incident angle of the light beam. Light travelling into the glass perpendicular to the boundary (ie., 'normal' to the boundary) does not change its direction, but at an angle, the light is bent to a degree depending on this angle of inclination. In 1621, Snell found the correct relation between the angle of incidence and the angle of refraction. Snell's law demonstrates that every interface has a specific bending ratiothe "refractive index". The greater the angle of refraction, the higher the refractive index for a substance.

Snell's Law can be described as follows (NB: one should also refer to the slides here). Suppose Where n_1 and n_2 represent the refractive indices of material 1 and material 2, and θ_1 and θ_2 are the angles with respect to the normal of the light beam travelling through these materials. Then Snell's law says that

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{0.1}$$

Notice that if n_1 is greater than n_2 (which will typically happen if the first medium is denser), then the angle of refraction is always smaller than the angle of incidence, ie., the light in the denser medium is bent towards the normal when it comes from the less dense medium . When the two refractive indices are equal, then the light is passed through without refraction (this sometimes happens- it is then very difficult to tell by visual inspection that there is any boundary at all!).

Snell died at the relatively young age of 46, on October 30, 1626 in Leiden. He would never know how his discovery of the laws of refraction would figure in later textbooks on physics and optics.

Antonie van Leeuwenhoek (1632-1723)

Antonie van Leeuwenhoek was born in Delft, Holland, on October 24, 1632. He came from a family of tradesmen, had no fortune, received no higher education, and knew no languages other than Dutch. His father was a basket-maker, and his mother's family were brewers. He was educated as a child in a school in the town of Warmond, then lived with his uncle at Benthuizen; in 1648 he was apprenticed in a linen-draper's shop. Around 1654 he returned to Delft, where he set himself up as a draper. In later years in Delft he also worked as a surveyor, a wine assayer, and as a minor city official. All of this makes him a really unlikely scientist, and would usually have excluded him completely from the scientific community of his time. Yet Leeuwenhoek made some of the most important discoveries in the history of biology- he is often called the father of microbiology and bacteriology. In the course of a long career he discovered bacteria, sperm cells, blood cells, microscopic nematodes and rotifers, and countless other forms of microscopic life, revealing a world which had not been suspected even in the wildest dreams of previous thinkers, at any time in history.

Leeuwenhoek's career began slowly. After setting up his fine wool shop in 1654, he began making microscopes as a hobby. Compound microscopes (ie., microscopes using multiple lenses) had been invented around 1595. Several of Leeuwenhoek's contemporaries, including Robert Hooke in England and Jan Swammerdam in the Netherlands, had built compound microscopes and were using them to make important discoveries. However early compound microscopes were not able to magnify more than 30× and still give good images. Leeuwenhoek's superiority was in being able to make superior microscopes, which were not compound but used only a single lens, and yet which could give good images up to 180× magnification. He made over 500 microscopes (although only 7 survive to this day). The lens was mounted in a tiny hole in a brass plate, and the specimen was mounted on a sharp point opposite the lens- its position and focus could be adjusted by turning screws (see slides). The entire instrument was only 10 cm in size, and had to be used close to the eye; it required good lighting and great patience to use.

During all of this time microscopy was only a hobby for him. In 1669 he succeeded in qualifying to work as a surveyor, and later in 1679 he also obtained a job as a wine-taster. At the same time he was also raising a family- In 16655 he married Barbara de Mey, the daughter of an English silk-merchant, and the couple had five daugthers. Barbara died in 1666; in 1671 he was remarried to Cornelia Swalmius, daughter of Margaretha Uytenbroeck and Cornelius Swalmius, who was a tradesman and governor of Valkenburg,a small city near Leiden.

Until 1673, Leeuwenhoek was hardly known outside his own immediate circle of friends. This circle included Jan Vermeer, the extraordinary painter, also native of Delft, and also born in 1632. How well these two knew each other has long been a matter of debate- some argue that Vermeer must have used more than just a *camera obscura* to get some of the effects in his paintings, and that he would have used lenses made by Leeuwenhoek. Certainly they knew each other well enough that Leeuwenhoek was the executor of Vermeer's will on his death in 1676. During their acquaintance neither was really known outside Delft.

The outside world began to know of Leeuwenhoek in 1673, when he began writing letters to the Royal Society of London, describing what he had seen with his microscopes. This correspondence was initiated by the good offices of Reinier de Graaf, then a fellow of the Society; it continued for the next 50 years. His letters were written in Dutch, and then translated into English or Latin and printed in the Philosophical Transactions of the Royal Society. They included extremely meticulous drawings of his observations- it is believed that many of these were prepared by a draughtsman, although it is not known who this was.

His first communication concerned his observation of bee stings. The next year, in a letter of September 7, 1674, he described observations on lake water. A typical passage is in his description of the green alga Spirogyra, a single-celled protozoa:

"*Passing just lately over this lake, . . . and examining this water next day, I found floating therein divers earthy particles, and some green streaks, spirally wound serpent-wise, and orderly arranged, after the manner of the copper or tin worms, which distillers use to cool their liquors as they distil over. The whole circumference of each of these streaks was about the thickness of a hair of one's head. . . all consisted of very small green globules joined together: and there were very many small green globules as well.*"

This was one of his first observations of what he called 'animalcules', ie., microscopic life forms, although it was not until 1676 that he was discussing things in these terms. He was not believed at first- indeed the reply of Oldenberg to Leeuwenhoek on the 20th of October, 1676, declining the publication of his letter, was quite discouraging:

Dear Mr. Anthony van Leeuwenhoek,

Your letter of October 10th has been received here with amusement. Your account of myriad "little animals" seen swimming in rainwater, with the aid of your so-called "microscope," caused the members of the society considerable merriment when read at our most recent meeting. Your novel descriptions of the sundry anatomies and occupations of these invisible creatures led one member to imagine that your "rainwater" might have contained an ample portion of distilled spirits–imbibed by the investigator. Another member raised a glass of clear water and exclaimed, "Behold, the Africk of Leeuwenhoek." For myself, I withhold judgment as to the sobriety of your observations and the veracity of your instrument. However, a vote having been taken among the members–accompanied I regret to inform you, by considerable giggling–it has been decided not to publish your communication in the Proceedings of this esteemed society. However, all here wish your "little animals" health, prodigality and good husbandry by their ingenious "discoverer."

All working scientists have had to absorb letters of rejection, but rarely written in such terms! Unlike many other scientists of his day, however, Leeuwenhoek seemed able to take such criticism fairly equably. Nevertheless, he enlisted the help of a large number of witnesses, including a pastor, to verify what he had seen. As more and more people were able to repeat his discoveries, including workers in England like Hooke, his reputation spread and his conclusions were gradually accepted. Leeuwenhoek looked at animal and plant tissues, at mineral crystals and at fossils. He was the first to see microscopic foraminifera, which he described as "little cockles. . . no bigger than a coarse sand-grain." He discovered blood cells, and was the first to see living sperm cells of animals. In 1668, he visited England, at the invitation of Hooke- this was the only time he visited abroad.

Probably the most momentous discovery of Leeuwenhoek was that of bacteria. On September 17, 1683, he wrote to the Royal Society about his observations on the plaque between his own teeth, "a little white matter, which is as thick as if 'twere batter." He repeated these observations on 2 women (probably his wife and daughter), and on 2 old men who had never cleaned their teeth in their lives. Looking at these samples, Leeuwenhoek reported:

"*I then most always saw, with great wonder, that in the said matter there were many very little living animalcules, very prettily a-moving. The biggest sort. . . had a very strong and swift motion, and shot through the water (or spittle) like a pike does through the water. The second sort. . . oft-times spun round like a top. . . and these were* *far more in number.... an unbelievably great company of living animalcules, a-swimming more nimbly than any I had ever seen up to this time. The biggest sort. . . bent their body into curves in going forwards. . . Moreover, the other animalcules were in such enormous numbers, that all the water. . . seemed to be alive.*"

Other microscopic life forms discovered by Leeuwenhoek include nematodes and rotifers. It is hardly surprising that these were entertaining to many people. A letter dated December 25, 1702, gives descriptions of many protozoa, including the ciliate Vorticella:

"*In structure these little animals were fashioned like a bell, and at the round opening they made such a stir, that the particles in the water thereabout were set in motion thereby. . . And though I must have seen quite 20 of these little animals on their long tails alongside one another very gently moving, with outstretched bodies and straightened-out tails; yet in an instant, as it were, they pulled their bodies and their tails together, and no sooner had they contracted their bodies and tails, than they began to stick their tails out again very leisurely, and stayed thus some time continuing their gentle motion: which sight I found mightily diverting.*"

With discoveries like these, Leeuwenhoek became famous. In 1680 he was elected a full member of the Royal Society – although he never attended a meeting. Over the years many well known people visited him at his home: amongst these were Christiaan Huyghens and Boerhave, both of whom took a considerable interest in his work, Heinsius, Christopher Wren, Spinoza, and Leibniz during a visit to Spinoza- Leibniz remarked that "*I prefer a Leeuwenhoek who tells me what he sees to a Cartesian who tells me what he thinks.*" The most famous people to visit Leeuwenhoek were Tsar Peter the Great (who sailed on the "Delftse Schie" in company with Leeuwenhoek, and to whom Leeuwenhoek showed the circulation in the capillaries of an eel), Queen Mary Stuart II, wife of William III of Orange, Queen Anne of England, and Frederick the Great. The impression made on these distinguished visitors was apparently of a modest but extraordinary individual who stood out from his scientific contemporaries by his social background, and who stood outside the scientific and political establishment of his day.

Leeuwenhoek lived to the age of 91, outliving both wives, and all but one of his 5 daughters (who looked after him in his old age). He continued his observations until a very late age, and the sheer number of his discoveries is staggering. After his death on August 30, 1723, the pastor of the New Church at Delft wrote to the Royal Society:

"*. . . Antony van Leeuwenhoek considered that what is true in natural philosophy can be most fruitfully investigated by the experimental method, supported by the evidence of the senses; for which reason, by diligence and tireless labour he made with his own hand certain most excellent lenses, with the aid of which he discovered many secrets of Nature, now famous throughout the whole philosophical World.*"

Leeuwenhoek was not the last of the amateur scientists to make a mark on the history of science, without any formal training (another remarkable later figure being Faraday), but he was certainly one of the most remarkable. He was fortunate to live in an intellectual, political, and social climate that made it possible for him to work and be recognized in the way that he was.

(2) HUYGHENS's OPTICS- the WAVE THEORY of LIGHT

Although during his lifetime Huyghens was probably best known for his discovery of Saturn's rings, his mathematical research, and for his invention of the pendulum clock, there is no question now that his most profound work was that which appeared in the '*Traité de la Lumière*' in 1690. This gave his full treatment of the phenomena of optics in terms of his wave theory. A discussion of Huyghens's life and the full range of his scientific work appears elsewhere in these notes.

The first thing that one notices about the *Traité* is the marked difference in style as compared to the works of, eg., Newton or Hooke. Newton is at pains to give a very logical treatment of everything that he is discussing, reminiscent of Euclid, and is also constantly making diversions into what we now think of as more conceptual discussions, very philosophical in their tone. Hooke, in contrast, is very discursive, and very focussed on a description of different phenomena. The writings of Huyghens are something of an interpolation between the two - he focusses on the phenomena at hand and on their explanation, but in a much less formal way than Newton, and with very little in the way of philosophical commentary. His discussions of the ideas and reasoning behind his theoretical work are clear and to the point, but he does not elaborate them into a lengthy exposition of a worldview in the manner that Newton is wont to do. On the other hand it is at times rather obvious that Huyghens has a much clearer understanding than Newton about what we would now think of as the dialogue between theory and experiment. This point was already noted in the notes on Huyghens's life; here let us reprint the entire passage from the Preface to the *Traité*:

"*One finds in this subject a kind of demonstration which does not carry with it so high a degree of certainty as that employed in geometry; and which differs distinctly from the method employed by geometers in that they prove their propositions by well-established and incontrovertible principles, while here principles are tested by the inferences which are derivable from them. The nature of the subject permits no other treatment.*

It is possible, however, in this way to establish a probability which is little short of certainty. This is the case when the consequences of the assumed principles are in perfect accord with the observed phenomena, and especially when these verifications are very numerous; but above all when one employs the hypothesis to predict new phenomena and finds his expectations realized. But then, if all these proofs of probability are satisfied in that which I propose to discuss, as it seems to me they are, this ought to be a very strong confirmation of the success of my inquiry; and it would be very unlucky indeed if the facts are not pretty much as I represent them. I would then believe then that those who love to know the Causes of things, and admire the marvels of Light, will find some satisfaction in these various speculations of mine regarding it, and in the new explanation of its famous refractive properties, which are the main foundation of the construction of our eyes, and of those great inventions which extend so vastly the use of them."

The contrast with Newton, who is constantly exhorting the reader to 'not frame hypotheses', is remarkable - all the more so because Newton's writings are actually full of hypotheses (usually dressed up in some way, for example as 'Queries' in the *Opticks*). This is not to say that Huyghens is not fully concerned with the various experimental facts available - he was just as much of an experimenter and observer as Newton, and the *Traité* has a very careful discussion of these.

In what follows we first look at the main points and arguments on the *Traité*, without discussing any technical details. After this, an exposition is given of the main features of his theoretical construction of waves and wavelets - ie., of his wave theory, and how it explains various phenomena.

2(a) BASIC IDEAS in the *TRAITÉ*

Early on in the *Traité de la Lumière*, Huyghens gives us an idea of where he got his ideas from. The key clues he had were in his observations of the motion of water waves, and his understanding of the necessary to treat sound as a pressure wave in whichever medium it was traveling through.

"*It is inconceivable to doubt that light consists in the motion of some sort of matter. For whether one considers its production, one sees that here upon the Earth it is chiefly engendered by fire and flame which contain without doubt bodies that are in rapid motion, since they dissolve and melt many other bodies, even the most solid; or whether one considers its effects, one sees that when light is collected, as by concave mirrors, it has the property of burning as a fire does, that is to say it disunites the particles of bodies. This is assuredly the mark of motion, at least in the true Philosophy, in which one conceives the causes of all natural effects in terms of mechanical motions. This, in my opinion, we must necessarily do, or else renounce all hopes of ever comprehending anything in Physics.*

And as, according to this Philosophy, one holds as certain that the sensation of sight is excited only by the impression of some movement of a kind of matter which acts on the nerves at the back of our eyes, there is here yet one reason more for believing that light consists in a movement of the matter which exists between us and the luminous body.

Further, when one considers the extreme speed with which light spreads on every side, and how, when it comes from different regions, even from those directly opposite, the rays traverse one another without hindrance, one may well understand that when we see a luminous object, it cannot be by any transport of matter coming to us from this object, in the way in which a shot or an arrow traverses the air; for assuredly that would too greatly impugn these two properties of light, especially the second of them. It is then in some other way that light spreads; and that which can lead us to comprehend it is the knowledge which we have of the spreading of Sound in the air.

We know that by means of the air, which is an invisible and impalpable body, Sound spreads around the spot where it has been produced, by a movement which is passed on successively from one part of the air to another; and that the spreading of this movement, taking place equally rapidly on all sides, ought to form spherical surfaces ever enlarging and which strike our ears. Now there is no doubt at all that light also comes from the luminous body to our eyes by some movement impressed on the matter which is between the two; since, as we have already seen, it cannot be by the transport of a body which passes from one to the other. If, in addition, light takes time for its passage which we are now going to examine it will follow that this movement, impressed on the intervening matter, is successive; and consequently it spreads, as Sound does, by spherical surfaces and waves: for I call them waves from their resemblance to those which are seen to be formed in water when a stone is thrown into it, and which present a successive spreading as circles, though these arise from another cause, and are only in a flat surface. "

Thus, in an informal way and without the cornucopia of Propositions, Theorems, Corollaries, Rules of Reasoning, and Lemmas which which Newton liked to decorate his writings, Huyghens gives us a very clear picture of where he is coming from. Light must be generated by the motion of matter, and only matter; and it acts upon matter. On the other hand it does not interact with itself, and it is not itself material. It travels very fast, but not infinitely fast, and it spreads out uniformly in all directions from its source. And in all this it resembles wave propagation. But wave propagation in what medium? He first pauses to explain that this medium cannot be a material one:

"*Now if one examines what this matter may be in which the movement coming from the luminous body is propagated, which I call Ethereal matter, one will see that it is not the same that serves for the propagation of Sound. For one finds that the latter is really that which we feel and which we breathe, and which being removed from any place still leaves there the other kind of matter that serves to convey Light. This may be proved by shutting up a sounding body in a glass vessel from which the air is withdrawn by the machine which Mr. Boyle has given us, and with which he has performed so many beautiful experiments. But in doing this of which I speak, care must be taken to place the sounding body on cotton or on feathers, in such a way that it cannot communicate its tremors either to the glass vessel which encloses it, or to the machine; a precaution which has hitherto been neglected. For then after having exhausted all the air one hears no Sound from the metal, though it is struck.*

One sees here not only that our air, which does not penetrate through glass, is the matter by which Sound spreads; but also that it is not the same air but another kind of matter in which Light spreads; since if the air is removed from the vessel the Light does not cease to traverse it as before.

And this last point is demonstrated even more clearly by the celebrated experiment of Torricelli, in which the tube of glass from which the quicksilver has withdrawn itself, remaining void of air, transmits Light just the same as when air is in it. For this proves that a matter different from air exists in this tube, and that this matter must have penetrated the glass or the quicksilver, either one or the other, though they are both impenetrable to the air. And when, in the same experiment, one makes the vacuum after putting a little water above the quicksilver, one concludes equally that the said matter passes through glass or water, or through both.

As regards the different modes in which I have said the movements of Sound and of Light are communicated, one may sufficiently comprehend how this occurs in the case of Sound if one considers that the air is of such a nature that it can be compressed and reduced to a much smaller space than that which it ordinarily occupies. And in proportion as it is compressed the more does it exert an effort to regain its volume; for this property along with its penetrability, which remains notwithstanding its compression, seems to prove that it is made up of small bodies which float about and which are agitated very rapidly in the ethereal matter composed of much smaller parts. So that the cause of the spreading of Sound is the effort which these little bodies make in collisions with one another, to regain freedom when they are a little more squeezed together in the circuit of these waves than elsewhere."

The argument that whatever the medium transmitting the light cannot be material is in of course rather obvious - if light travels through a vacuum, then this conclusion follows necessarily. However, since Huyghens is going to plump for a wave theory of light propagation, he definitely needs some medium. This is where the argument becomes more subtle. It was clear to Huyghens that sound waves in air or in a solid or liquid or medium were in fact pressure/density waves. Although a proper theory of this would have to wait for another 200 years, Huyghens already understood that sound waves consisted, either in a regularly ordered solid, or in a liquid or gas of randomly moving particles, in the motion of compressional waves, in which the pressure in regions of compression was higher than that in regions of rarefraction; and that the wave velocity would be higher in proportion to the strength of interactions between the particles. Moreover this interaction strength also determined how *stiff* and/or *hard* the material was - the sound velocity would be proportional to the stiffness.

This immediately leads Huyghens to the conclusion that whatever medium is involved in light propagation, it must be very stiff indeed, far more than any material medium that we can envisage, simply because light travels so fast. This ultra-stiff medium was the invisible aether, which he imagined as having a structure analogous to that of a gas, composed of a set of immaterial particles. In his own words:

"*When one takes a number of spheres of equal size, made of some very hard substance, and arranges them in a straight line, so that they touch one another, one finds, on striking with a similar sphere against the first of these spheres, that the motion passes as in an instant to the last of them, which separates itself from the row, without one's being able to perceive that the others have been stirred. And even that one which was used to strike remains motionless with them. Whence one sees that the movement passes with an extreme velocity which is the greater, the greater the hardness of the substance of the spheres......*

......Now in applying this kind of movement to that which produces Light there is nothing to hinder us from estimating the particles of the ether to be of a substance as nearly approaching to perfect hardness and possessing a springiness as prompt as we choose. It is not necessary to examine here the causes of this hardness, or of that springiness, the consideration of which would lead us too far from our subject. I will say, however, in passing that we may conceive that the particles of the ether, notwithstanding their smallness, are in turn composed of other parts and that

their springiness consists in the very rapid movement of a subtle matter which penetrates them from every side and constrains their structure to assume such a disposition as to give to this fluid matter the most overt and easy passage possible. This accords with the explanation which Mr. Des Cartes gives for the spring, though I do not, like him, suppose the pores to be in the form of round hollow canals. And it must not be thought that in this there is anything absurd or impossible, it being on the contrary quite credible that it is this infinite series of different sizes of corpuscles, having different degrees of velocity, of which Nature makes use to produce so many marvellous effects.

But though we shall ignore the true cause of springiness we still see that there are many bodies which possess this property; and thus there is nothing strange in supposing that it exists also in little invisible bodies like the particles of the Ether. Also if one wishes to seek for any other way in which the movement of Light is successively communicated, one will find none which agrees better, with uniform progression, as seems to be necessary, than the property of springiness; because if this movement should grow slower in proportion as it is shared over a greater quantity of matter, in moving away from the source of the light, it could not conserve this great velocity over great distances. But by supposing springiness in the ethereal matter, its particles will have the property of equally rapid restitution whether they are pushed strongly or feebly; and thus the propagation of Light will always go on with an equal velocity. "

Thus even though the particles of the aether interact very strongly, it is not these particles that we experience, nor do they interact with matter directly. It is rather the waves whose effects we feel.

From a modern point of view his analysis of the way in which the repulsive interactions between a set of particles will lead to sound wave propagation, with a velocity independent of the amplitude of the distortions, is basically correct. Although Huyghens lacked the mathematical tools to come to these conclusions, his physical intuition did not fail him (it would take over a century for mathematical physicists to derive some of these results, starting from Newton's laws of motion, applied to a system of many particles). A key feature of the Huyghens theory is his analogy between, on the one hand, the interactions between the aether particles, and on the other hand, the interactions between ordinary material objects via an elastic restoring force, like a spring. Huyghens was here using the observation that, like a pendulum, a spring can support oscillatory motion whose period is independent of the amplitude of the oscillations, provided this amplitude is small. He also understood that this feature would persist even if the particles were not arranged in a regular lattice structure, but were also in some disordered array, as in a liquid or gas.

2(b) HUYGHENS on REFLECTION and REFRACTION

The first task faced by Huyghens, having established the basic physical picture, was to then show how the standard phenomena of reflection and refraction for light followed naturally from his assumption of wave propagation through the hypothetical aether. He did this by means of what is now know as the 'Huyghens contruction', which is depicted in the notes. Let us see how he developed it in the simple case of light incident upon a slab of glass; and let us begin with his analysis of reflection (see Fig. 1(a) below):

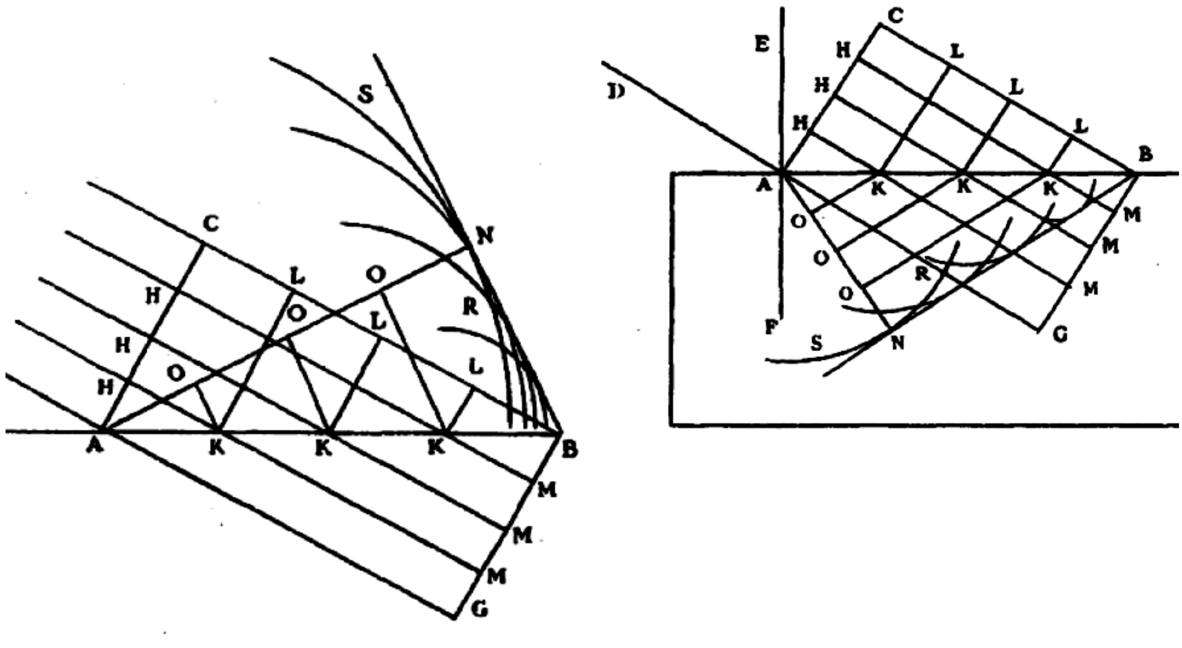
"*Let there be a surface AB; plane and polished, of some metal, glass, or other body, which at first I will consider as perfectly uniform (reserving to myself to deal at the end of this demonstration with the inequalities from which it cannot be exempt), and let a line AC, inclined to AD, represent a portion of a wave of light, the centre of which is so distant that this portion AC may be considered as a straight line; for I consider all this as in one plane, imagining to myself that the plane in which this figure is, cuts the sphere of the wave through its centre and intersects the plane AB at right angles. This explanation will suffice once for all.*

The piece C of the wave AC, will in a certain space of time advance as far as the plane AB at B, following the straight line CB, which may be supposed to come from the luminous centre, and which in consequence is perpendicular to AC. Now in this same space of time the portion A of the same wave, which has been hindered from communicating its movement beyond the plane AB, or at least partly so, ought to have continued its movement in the matter which is above this plane, and this along a distance equal to CB, making its own partial spherical wave, according to what has been said above. Which wave is here represented by the circumference SNR, the centre of which is A, and its semi-diameter AN equal to CB.

If one considers further the other pieces H of the wave AC, it appears that they will not only have reached the surface AB by straight lines HK parallel to CB, but that in addition they will have generated in the transparent air, from the centres K, K, K, particular spherical waves, represented here by circumferences the semi-diameters of which are equal to KM, that is to say to the continuations of HK as far as the line BG parallel to AC. But all these circumferences have as a common tangent the straight line BN, namely the same which is drawn from B as a tangent to the first of the circles, of which A is the centre, and AN the semi-diameter equal to BC, as is easy to see.

It is then the line BN (comprised between B and the point N where the perpendicular from the point A falls) which is as it were formed by all these circumferences, and which terminates the movement which is made by the reflexion *of the wave AC; and it is also the place where the movement occurs in much greater quantity than anywhere else. Wherefore, according to that which has been explained, BN is the propagation of the wave AC at the moment when the piece C of it has arrived at B. For there is no other line which like BN is a common tangent to all the aforesaid circles, except BG below the plane AB; which line BG would be the propagation of the wave if the movement could have spread in a medium homogeneous with that which is above the plane. And if one wishes to see how the wave AC has come successively to BN, one has only to draw in the same figure the straight lines KO parallel to BN, and the straight lines KL parallel to AC. Thus one will see that the straight wave AC has become broken up into all the OKL parts successively, and that it has become straight again at NB.*

Now it is apparent here that the angle of reflexion is made equal to the angle of incidence. For the triangles ACB, BNA being rectangular and having the side AB common, and the side CB equal to NA, it follows that the angles opposite to these sides will be equal, and therefore also the angles CBA, NAB. But as CB, perpendicular to CA, marks the direction of the incident ray, so AN, perpendicular to the wave BN, marks the direction of the reflected ray; hence these rays are equally inclined to the plane AB "



(a) Reflection **(b) Refraction**

FIG. 1: Figure from the *Traité de la Lumière*, in which Huyghens shows the propagation of wave-fronts for a plane wave incident upon a piece of glass with a flat surface. In (a) we see how the wavelets re-emitted outside the glass produce a reflected wavefront; and in (b) how, traveling more slowly inside the glass, the wavelets unite to produce a refracted wavefront. For further description see the text.

In other words, we see that the rays incident onto the interface plane AB from the top left, are re-emitted upwards as circular wavelets from the points on the surface where they strike it; and these wavelets then all add together coherently along the line BN, to give a new wavefront moving away from the surface - this is the reflected ray. In both cases we see that the light rays propagate in the direction perpendicular to the wavefronts. The fact that the angle of incidence equals the angle of reflection is a natural consequence of the assumption that the wavelets are re-emitted upwards at the same velocity as the incoming wavefront (both the downward incoming wavefront and the upward outgoing wavelets are propagating in air).

Now let us consider refraction, where we look at that part of the re-emission of the wavelets which propagates in the downward direction (Fig 1(b)). The key here is that they are propagating at a different velocity, in fact slower than the velocity in air. Thus Huyghens argues:

"*....let AB be the straight line which represents a plane surface bounding the transparent substances which lie towards C and towards N. When I say plane, that does not signify a perfect evenness, but such as has been understood in treating of reflexion, and for the same reason. Let the line AC represent a portion of a wave of light, the centre of which is supposed so distant that this portion may be considered as a straight line. The piece C, then, of the wave AC, will in* *a certain space of time have advanced as far as the plane AB following the straight line CB, which may be imagined as coming from the luminous centre, and which consequently will cut AC at right angles. Now in the same time the piece A would have come to G along the straight line AG, equal and parallel to CB; and all the portion of wave AC would be at GB if the matter of the transparent body transmitted the movement of the wave as quickly as the matter of the Ether. But let us suppose that it transmits this movement less quickly, by one-third, for instance. Movement will then be spread from the point A, in the matter of the transparent body through a distance equal to two-thirds of CB, making its own particular spherical wave according to what has been said before. This wave is then represented by the circumference SNR, the centre of which is A, and its semi-diameter equal to two-thirds of CB. Then if one considers in order the other pieces H of the wave AC, it appears that in the same time that the piece C reaches B they will not only have arrived at the surface AB along the straight lines HK parallel to CB, but that, in addition, they will have generated in the diaphanous substance from the centres K, partial waves, represented here by circumferences the semi-diameters of which are equal to two-thirds of the lines KM, that is to say, to two-thirds of the prolongations of HK down to the straight line BG; for these semi-diameters would have been equal to entire lengths of KM if the two transparent substances had been of the same penetrability.*

Now all these circumferences have for a common tangent the straight line BN; namely the same line which is drawn as a tangent from the point B to the circumference SNR which we considered first. For it is easy to see that all the other circumferences will touch the same BN, from B up to the point of contact N, which is the same point where AN falls perpendicularly on BN.

It is then BN, which is formed by small arcs of these circumferences, which terminates the movement that the wave AC has communicated within the transparent body, and where this movement occurs in much greater amount than anywhere else. And for that reason this line, in accordance with what has been said more than once, is the propagation of the wave AC at the moment when its piece C has reached B. For there is no other line below the plane AB which is, like BN, a common tangent to all these partial waves. And if one would know how the wave AC has come progressively to BN, it is necessary only to draw in the same figure the straight lines KO parallel to BN, and all the lines KL parallel to AC. Thus one will see that the wave CA, from being a straight line, has become broken in all the positions LKO successively, and that it has again become a straight line at BN. This being evident by what has already been demonstrated, there is no need to explain it further.

Now, in the same figure, if one draws EAF, which cuts the plane AB at right angles at the point A, since AD is perpendicular to the wave AC, it will be DA which will mark the ray of incident light, and AN which was perpendicular to BN, the refracted ray: since the rays are nothing else than the straight lines along which the portions of the waves advance.

Whence it is easy to recognize this chief property of refraction, namely that the Sine of the angle DAE has always the same ratio to the Sine of the angle NAF, whatever be the inclination of the ray DA: and that this ratio is the same as that of the velocity of the waves in the transparent substance which is towards AE to their velocity in the transparent substance towards AF. For, considering AB as the radius of a circle, the Sine of the angle BAC is BC, and the Sine of the angle ABN is AN. But the angle BAC is equal to DAE, since each of them added to CAE makes a right angle. And the angle ABN is equal to NAF, since each of them with BAN makes a right angle. Then also the Sine of the angle DAE is to the Sine of NAF as BC is to AN. But the ratio of BC to AN was the same as that of the velocities of light in the substance which is towards AE and in that which is towards AF; therefore also the Sine of the angle DAE will be to the Sine of the angle NAF the same as the said velocities of light."

This explanation appears long-winded because Huyghens is necessarily using the language and style of Euclidean geometry to make his demonstrations - an algebraic proof of all these statements would be extremely short. The gist of the idea is that the wavefront above the interface continues to move horizontally at the same velocity as before, but the downward motion inside the glass is slower, and so this naturally changes the direction of wavefront propagation - the wavefronts above the interface 'get ahead' of the ones below (see Fig 1(b) above).

Suppose we now take it for granted that one can reproduce all the *geometrical* properties of light refraction, reflection, and also diffraction (this latter being less obvious, but see the explanatory diagrams in the course slides). The explicit demonstration of all of this for many different geometries takes up most of the book - and much of it is very ingenious (examples include the optics of transparent systems of spherical, parabolic, and ellipsoidal shape, intended to model objects as diverse as raindrops and glass lenses; and of refraction through inhomogeneous media such as the atmosphere; and of course the remarkable birefringence of 'Iceland Spar', to which we return below). Nevertheless a big question still hangs over all this, viz.; given Huyghens's somewhat sketchy ideas about the aether, how can he explain how it is possible for for light to interact with matter and yet have it so that the aether does not in any way impede the motion of matter through it?

Huyghens is of course very much aware of this question, and the answer he offers to it is quite lengthy. He is first concerned to explain that the aether must permeate everything, including solid and liquid matter. But there is a lot more that needs to be explained - in particular, why it is that light moves more slowly in dense solid or liquid matter than in a gas like air, and that in air it moves faster than in a vacuum. And then one must explain why some material bodies are transparent, and others opaque; and so on. All of these facts make it very clear that even if we do not allow the aether to impede the motion of material objects in any way, nevertheless the properties and behaviour of the aether (and of the light waves through it) are very sensitive to the presence of material objects. His answer proceeds as follows:

" *When light passes across a hollow sphere of glass, closed on all sides, it is certain that it is full of ethereal matter, as much as the spaces outside the sphere. And this ethereal matter, as has been shown above, consists of particles which just touch one another. If then it were enclosed in the sphere in such a way that it could not get out through the pores of the glass, it would be obliged to follow the movement of the sphere when one changes its place: and it would require consequently almost the same force to impress a certain velocity on this sphere, when placed on a horizontal plane, as if it were full of water or perhaps of quicksilver: because every body resists the velocity of the motion which one would give to it, in proportion to the quantity of matter which it contains, and which is obliged to follow this motion. But on the contrary one finds that the sphere resists the impress of movement only in proportion to the quantity of matter of the glass of which it is made. Then it must be that the ethereal matter which is inside is not shut up, but flows through it with very great freedom. We shall demonstrate hereafter that by this process the same penetrability may be inferred also as relating to opaque bodies.*

The second mode then of explaining transparency, and one which appears more probably true, is by saying that the waves of light are carried on in the ethereal matter, which continuously occupies the interstices or pores of transparent bodies. For since it passes through them continuously and freely, it follows that they are always full of it. And one may even show that these interstices occupy much more space than the coherent particles which constitute the bodies. For if what we have just said is true: that force is required to impress a certain horizontal velocity on bodies in proportion as they contain coherent matter; and if the proportion of this force follows the law of weights, as is confirmed by experiment, then the quantity of the constituent matter of bodies also follows the proportion of their weights. Now we see that water weighs only one fourteenth part as much as an equal portion of quicksilver: therefore the matter of the water does not occupy the fourteenth part of the space which its mass obtains. It must even occupy much less of it, since quicksilver is less heavy than gold, and the matter of gold is by no means dense, as follows from the fact that the matter of the vortices of the magnet and of that which is the cause of gravity pass very freely through it.

But it may be objected here that if water is a body of so great rarity, and if its particles occupy so small a portion of the space of its apparent bulk, it is very strange how it yet resists compression so strongly without permitting itself to be condensed by any force which one has hitherto essayed to employ, preserving even its entire liquidity while subjected to this pressure.

This is no small difficulty. It may, however, be resolved by saying that the very violent and rapid motion of the subtle matter which renders water liquid, by agitating the particles of which it is composed, maintains this liquidity in spite of the pressure which hitherto any one has been minded to apply to it.

The rarity of transparent bodies being then such as we have said, one easily conceives that the waves might be carried on in the ethereal matter which fills the interstices of the particles. And, moreover, one may believe that the progression of these waves ought to be a little slower in the interior of bodies, by reason of the small detours which the same particles cause. In which different velocity of light I shall show the cause of refraction to consist.

Before doing so, I will indicate the third and last mode in which transparency may be conceived; which is by supposing that the movement of the waves of light is transmitted indifferently both in the particles of the ethereal matter which occupy the interstices of bodies, and in the particles which compose them, so that the movement passes from one to the other. And it will be seen hereafter that this hypothesis serves excellently to explain the double refraction of certain transparent bodies.

Should it be objected that if the particles of the ether are smaller than those of transparent bodies (since they pass through their intervals), it would follow that they can communicate to them but little of their movement, it may be replied that the particles of these bodies are in turn composed of still smaller particles, and so it will be these secondary particles which will receive the movement from those of the ether.

Furthermore, if the particles of transparent bodies have a recoil a little less prompt than that of the ethereal particles, which nothing hinders us from supposing, it will again follow that the progression of the waves of light will be slower in the interior of such bodies than it is outside in the ethereal matter.

All this I have found as most probable for the mode in which the waves of light pass across transparent bodies. To which it must further be added in what respect these bodies differ from those which are opaque; and the more so since it might seem because of the easy penetration of bodies by the ethereal matter, of which mention has been made, that there would not be any body that was not transparent. For by the same reasoning about the hollow sphere which I have employed to prove the smallness of the density of glass and its easy penetrability by the ethereal matter, one might also prove that the same penetrability obtains for metals and for every other sort of body. For this sphere being for example of silver, it is certain that it contains some of the ethereal matter which serves for light, since this was there as well as *in the air when the opening of the sphere was closed. Yet, being closed and placed upon a horizontal plane, it resists the movement which one wishes to give to it, merely according to the quantity of silver of which it is made; so that one must conclude, as above, that the ethereal matter which is enclosed does not follow the movement of the sphere; and that therefore silver, as well as glass, is very easily penetrated by this matter. Some of it is therefore present continuously and in quantities between the particles of silver and of all other opaque bodies: and since it serves for the propagation of light it would seem that these bodies ought also to be transparent, which however is not the case.*

Whence then, one will say, does their opacity come? Is it because the particles which compose them are soft; that is to say, these particles being composed of others that are smaller, are they capable of changing their figure on receiving the pressure of the ethereal particles, the motion of which they thereby damp, and so hinder the continuance of the waves of light? That cannot be: for if the particles of the metals are soft, how is it that polished silver and mercury reflect light so strongly? What I find to be most probable herein, is to say that metallic bodies, which are almost the only really opaque ones, have mixed amongst their hard particles some soft ones; so that some serve to cause reflexion and the others to hinder transparency; while, on the other hand, transparent bodies contain only hard particles which have the faculty of recoil, and serve together with those of the ethereal matter for the propagation of the waves of light, as has been said."

Again, we see that in the Huyghens theory, the the elastic recoil of aether particles from each other plays a key role in all of the explanations of natural phenomena. His explanation for the slower recoil of aether particles in a dense material body is a little odd, since it implies that the aether particles flow around the solid 'atoms' of the material body; it is hard to reconcile this with the idea that the material bodies do not meet any resistance to motion through the aether, or vice-versa. His hypothesis of the interstices between atoms of water, and his explanation of how it is that water is still very difficult to compress despite these interstices, is both ingenious and partly correct. The fluid properties of water do indeed require that the water molecules easily move around each other, and it is also true that a large part of the internal pressure in water, which keeps it incompressible, is coming from the rapid thermal motion of the water molecules. However a full explanation of the behaviour of water actually requires the notion of chemical bonds, which is a quantum-mechanical feature.

On the other hand his explanation of how some bodies end up being opaque is actually completely wrong - and again, requires quantum mechanics for a full understanding. In the same way his arguments concerning the relative densities of water and quicksilver (ie., what we call mercury), and their implications for the density of the particles making up these two material, are also wide of the mark. What Huyghens did not know, and could not know at that time, was that atoms are composite objects, and that atoms of mercury contain a massive nucleus which itself renders mercury atoms much denser than the atoms of hydrogen and oxygen that make up water. This is the real explanation for the high density of mercury and other heavy elements (although it is also the case that the peculiar structure of water, with the large spaces between the molecules in both the solid and liquid form, is also partly responsible).

No discussion of the theory of Huyghens would be complete without a discussion of the remarkable way in which he applied it to phenomena in Nature (as opposed to the rather limited world of laboratory experiments). In common with Newton, Huyghens paid a great deal of attention to the wonders of the natural world, and did not shrink from attempting to explain these using what tools he than possessed. Attempts like this, to use physical theory to now go back and explain or even predict natural phenomena, were a mark of the new confidence with which science began to address the world - such attempts would have been difficult to imagine in either the Greek or Mediaeval worlds.

We look at two examples of this. First, his discussion of refraction in air:

"*We have shown how the movement which constitutes light spreads by spherical waves in any homogeneous matter. And it is evident that when the matter is not homogeneous, but of such a constitution that the movement is communicated in it more rapidly toward one side than toward another, these waves cannot be spherical: but that they must acquire their figure according to the different distances over which the successive movement passes in equal times.*

It is thus that we shall in the first place explain the refractions which occur in the air, which extends from here to the clouds and beyond. The effects of which refractions are very remarkable; for by them we often see objects which the rotundity of the Earth ought otherwise to hide; such as Islands, and the tops of mountains when one is at sea. Because also of them the Sun and the Moon appear as risen before in fact they have, and appear to set later: so that at times the Moon has been seen eclipsed while the Sun appeared still above the horizon. And so also the heights of the Sun and of the Moon, and those of all the Stars always appear a little greater than they are in reality, because of these same refractions, as Astronomers know. But there is one experiment which renders this refraction very evident; which is that of fixing a telescope on some spot so that it views an object, such as a steeple or a house, at a distance of half a league or more. If then you look through it at different hours of the day, leaving it always fixed in the same way, you will see that the same spots of the object will not always appear at the middle of the aperture of the telescope, but that generally in the morning and in the evening, when there are more vapours near the Earth, these objects seem to rise higher, so that the half or more of them will no longer be visible; and so that they seem lower toward mid-day when these vapours are dissipated.

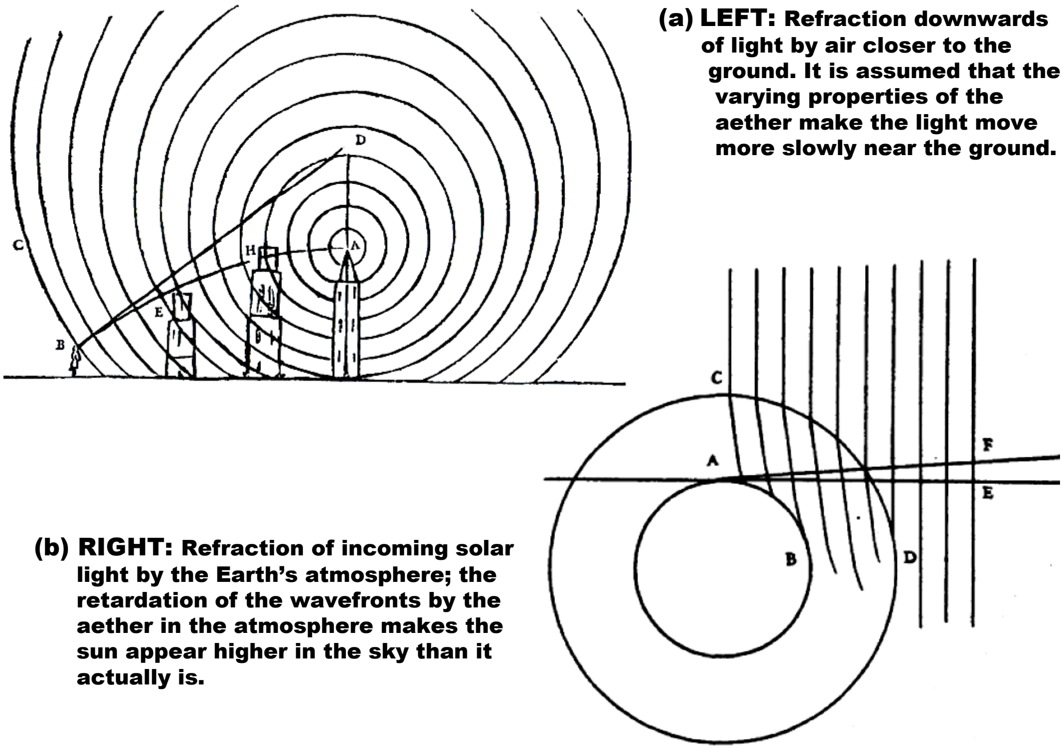


FIG. 2: Figure from the *Traité de la Lumière*, wherein Huyghens shows how light is refracted in air, when the density varies with position. In (a) we see the propagation of light waves through an aether in which the light moves more slowly at lower altitude. In (b) we see how light wavefronts, incident on the earth from the sun, are slowed down by upon reaching the atmosphere (considered to be a spherical layer around the earth, in which the different properties of the aether make it move more slowly), and are hence refracted towards the ground.

Those who consider refraction to occur only in the surfaces which separate transparent bodies of different nature, would find it difficult to give a reason for all that I have just related; but according to our Theory the thing is quite easy. It is known that the air which surrounds us, besides the particles which are proper to it and which float in the ethereal matter as has been explained, is full also of particles of water which are raised by the action of heat; and it has been ascertained further by some very definite experiments that as one mounts up higher the density of air diminishes in proportion. Now whether the particles of water and those of air take part, by means of the particles of ethereal matter, in the movement which constitutes light, but have a less prompt recoil than these, or whether the encounter and hindrance which these particles of air and water offer to the propagation of movement of the ethereal progress, retard the progression, it follows that both kinds of particles flying amidst the ethereal particles, must render the air, from a great height down to the Earth, gradually less easy for the spreading of the waves of light.

Whence the configuration of the waves ought to become nearly such as this figure represents: namely, if A is a light, or the visible point of a steeple, the waves which start from it ought to spread more widely upwards and less widely downwards, but in other directions more or less as they approximate to these two extremes. This being so, it necessarily follows that every line intersecting one of these waves at right angles will pass above the point A, always excepting the one line which is perpendicular to the horizon.

Let BC be the wave which brings the light to the spectator who is at B, and let BD be the straight line which intersects this wave at right angles. Now because the ray or straight line by which we judge the spot where the object appears to us is nothing else than the perpendicular to the wave that reaches our eye, as will be understood by what was said above, it is manifest that the point A will be perceived as being in the line BD, and therefore higher than in fact it is.

Similarly if the Earth be AB, and the top of the Atmosphere CD, which probably is not a well defined spherical surface (since we know that the air becomes rare in proportion as one ascends, for above there is so much less of it to press down upon it), the waves of light from the sun coming, for instance, in such a way that so long as they have not reached the Atmosphere CD the straight line AE intersects them perpendicularly, they ought, when they enter the Atmosphere, to advance more quickly in elevated regions than in regions nearer to the Earth. So that if CA is the wave which brings the light to the spectator at A, its region C will be the furthest advanced; and the straight line AF, which *intersects this wave at right angles, and which determines the apparent place of the Sun, will pass above the real Sun, which will be seen along the line AE. And so it may occur that when it ought not to be visible in the absence of vapours, because the line AE encounters the rotundity of the Earth, it will be perceived in the line AF by refraction. But this angle EAF is scarcely ever more than half a degree because the attenuation of the vapours alters the waves of light but little. Furthermore these refractions are not altogether constant in all weathers, particularly at small elevations of 2 or 3 degrees; which results from the different quantity of aqueous vapours rising above the Earth."*

All of these arguments are basically correct. Again, what is hard to understand in Huyghens's theory is why the speed of light through the aether should vary in a way which so closely corresponds with the density of the material medium in which it travels. It is not until we obtain a proper understanding of what the aether really was (ie., of the electromagnetic field) and of the interactions between this field and matter (which also requires quantum mechanics) that a full explanation of all of this could be found. Nevertheless, given the assumptions he made about the velocity of light wave propagation in air, and how this varies with air density, everything else he then deduced follows naturally from these assumptions - and this is a very convincing demonstration that there is something very important in the wave theory.

2(c) BIREFRINGENCE and ICELAND SPAR

Let us now come to the Huyghens discussion of the refractive properties of Iceland Spar (a soft crystalline material which we now know as calcite). The key interesting feature of this crystalline rock is that it causes 'double refraction (what is now called 'birefringence'); a light ray incident on one of the the crystal faces is split into two rays; the angle between these 2 rays then depends in a very complex way upon the relative orientation of the crystal axes and the crystal face with respect to the direction of the incident light ray. At the time there was no understanding of this phenomenon - not only was the mechanism completely unsuspected, but the laws governing the angles of refraction of the two rays were not understood either.

Huyghens's resolution of the mathematical problem of the laws controlling the refraction angles was at the time considered to be an extraordinary '*tour de force*'. Geometric constructions of great complexity were deployed by him, to explain in detail the complicated behaviour shown in a variety of experiments which he did. Because these constructions are so complex, we do not discuss the details of his explanation. However it is worth recounting the reasoning he used in order to arrive at the way in which the crystal structure influenced the refractive properties of the light traveling through it. The first step is his argument that from the shapes and cleavage properties of crystals, one can discern the underlying arrangement of their constituent material particles (or 'atoms'). There is no point in going through the argument here, since it speaks for itself - what is remarkable is the series of deductions, given that at this time the hypothesis of atoms was entirely without proof, and in content was hardly different from the speculations of the ancient Atomists. We now know that Huyghens's deductions were exactly right, and that his picture of the arrangement of atoms in Iceland Spar was essentially correct. Here is the argument in his own words:

"*There are many bodies, vegetable, mineral, and congealed salts, which are formed with certain regular angles and figures. Thus among flowers there are many which have their leaves disposed in ordered polygons, to the number of 3, 4, 5, or 6 sides, but not more. This well deserves to be investigated, both as to the polygonal figure, and as to why it does not exceed the number 6.*

Rock Crystal grows ordinarily in hexagonal bars, and diamonds are found which occur with a square point and polished surfaces. There is a species of small flat stones, piled up directly upon one another, which are all of pentagonal figure with rounded angles, and the sides a little folded inwards. The grains of gray salt which are formed from sea water affect the figure, or at least the angle, of the cube; and in the congelations of other salts, and in that of sugar, there are found other solid angles with perfectly flat faces. Small snowflakes almost always fall in little stars with 6 points, and sometimes in hexagons with straight sides. And I have often observed, in water which is beginning to freeze, a kind of flat and thin foliage of ice, the middle ray of which throws out branches inclined at an angle of 60 degrees. All these things are worthy of being carefully investigated to ascertain how and by what artifice nature there operates. But it is not now my intention to treat fully of this matter. It seems that in general the regularity which occurs in these productions comes from the arrangement of the small invisible equal particles of which they are composed. And, coming to our Iceland Crystal, I say that if there were a pyramid such as ABCD, composed of small rounded corpuscles, not spherical but flattened spheroids, such as would be made by the rotation of the ellipse GH around its lesser diameter EF (of which the ratio to the greater diameter is very nearly that of 1 to the square root of 8)I say that then the solid angle of the point D would be equal to the obtuse and equilateral angle of this Crystal. I say, further, that if these corpuscles were lightly stuck together, on breaking this pyramid it would break along faces parallel to those that make its point: and by this means, as it is easy to see, it would produce prisms similar to those of the *same crystal as this other figure represents. The reason is that when broken in this fashion a whole layer separates easily from its neighbouring layer since each spheroid has to be detached only from the three spheroids of the next layer; of which three there is but one which touches it on its flattened surface, and the other two at the edges. And the reason why the surfaces separate sharp and polished is that if any spheroid of the neighbouring surface would come out by attaching itself to the surface which is being separated, it would be needful for it to detach itself from six other spheroids which hold it locked, and four of which press it by these flattened surfaces. Since then not only the angles of our crystal but also the manner in which it splits agree precisely with what is observed in the assemblage composed of such spheroids, there is great reason to believe that the particles are shaped and ranged in the same way.*

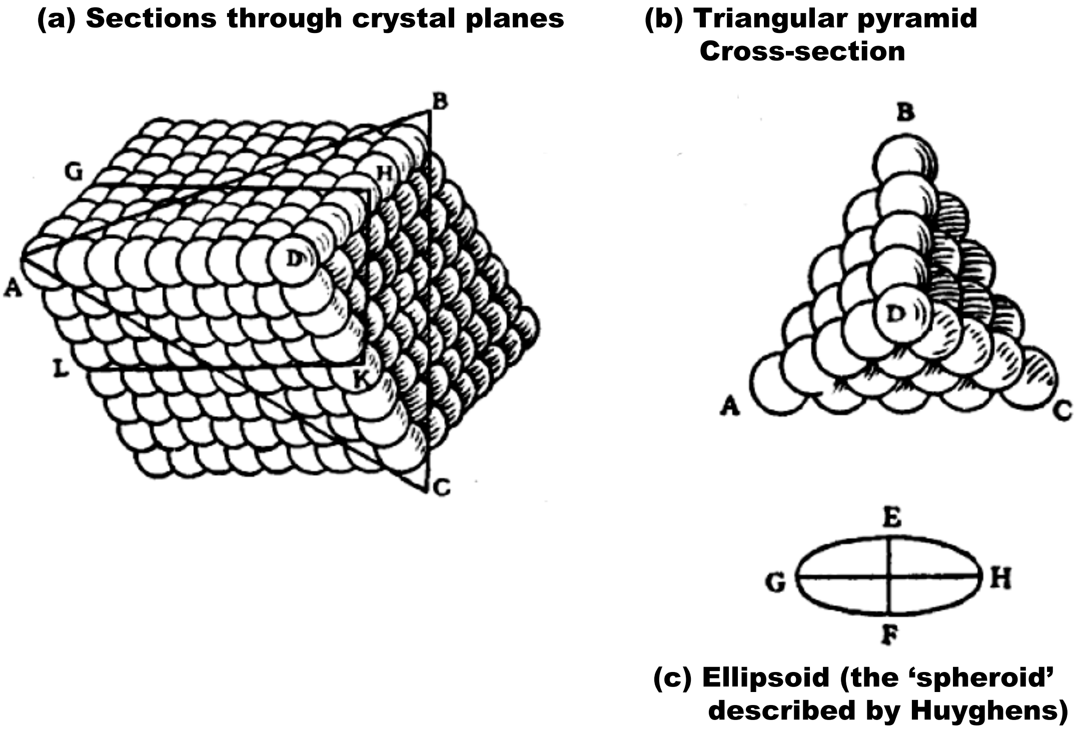


FIG. 3: Figure from the *Traité de la Lumière*, wherein Huyghens depicts his view of crystal structures and how they influence light propagation through the crystals. In (a) we see the hypothetical crystal structure of Iceland Spar, with a triangular pyramid excized from this in (b). In (c) we see the hypothesized 'spheroids' of which the crystal is made.

There is even probability enough that the prisms of this crystal are produced by the breaking up of pyramids, since Mr. Bartholinus relates that he occasionally found some pieces of triangularly pyramidal figure. But when a mass is composed interiorly only of these little spheroids thus piled up, whatever form it may have exteriorly, it is certain, by the same reasoning which I have just explained, that if broken it would produce similar prisms. It remains to be seen whether there are other reasons which confirm our conjecture, and whether there are none which are repugnant to it.

It may be objected that this crystal, being so composed, might be capable of cleavage in yet two more fashions; one of which would be along planes parallel to the base of the pyramid, that is to say to the triangle ABC; the other would be parallel to a plane the trace of which is marked by the lines GH, HK, KL. To which I say that both the one and the other, though practicable, are more difficult than those which were parallel to any one of the three planes of the pyramid; and that therefore, when striking on the crystal in order to break it, it ought always to split rather along these three planes than along the two others. When one has a number of spheroids of the form above described, and ranges them in a pyramid, one sees why the two methods of division are more difficult. For in the case of that division which would be parallel to the base, each spheroid would be obliged to detach itself from three others which it touches upon their flattened surfaces, which hold more strongly than the contacts at the edges. And besides that, this division will not occur along entire layers, because each of the spheroids of a layer is scarcely held at all by the 6 of the same layer that surround it, since they only touch it at the edges; so that it adheres readily to the neighbouring layer, and the others to it, for the same reason; and this causes uneven surfaces. Also one sees by experiment that when grinding down the crystal on a rather rough stone, directly on the equilateral solid angle, one verily finds much facility in reducing it in this direction, but much difficulty afterwards in polishing the surface which has been flattened in this manner.

As for the other method of division along the plane GHKL, it will be seen that each spheroid would have to detach itself from four of the neighbouring layer, two of which touch it on the flattened surfaces, and two at the edges. So that this division is likewise more difficult than that which is made parallel to one of the surfaces of the crystal; where, as we have said, each spheroid is detached from only three of the neighbouring layer: of which three there is one only which touches it on the flattened surface, and the other two at the edges only.

However, that which has made me know that in the crystal there are layers in this last fashion, is that in a piece weighing half a pound which I possess, one sees that it is split along its length, as is the above-mentioned prism by the plane GHKL; as appears by colours of the Iris extending throughout this whole plane although the two pieces still hold together. All this proves then that the composition of the crystal is such as we have stated. To which I again add this experiment; that if one passes a knife scraping along any one of the natural surfaces, and downwards as it were from the equilateral obtuse angle, that is to say from the apex of the pyramid, one finds it quite hard; but by scraping in the opposite sense an incision is easily made. This follows manifestly from the situation of the small spheroids; over which, in the first manner, the knife glides; but in the other manner it seizes them from beneath almost as if they were the scales of a fish.

I will not undertake to say anything touching the way in which so many corpuscles all equal and similar are generated, nor how they are set in such beautiful order; whether they are formed first and then assembled, or whether they arrange themselves thus in coming into being and as fast as they are produced, which seems to me more probable. To develop truths so recondite there would be needed a knowledge of nature much greater than that which we have. I will add only that these little spheroids could well contribute to form the spheroids of the waves of light, here above supposed, these as well as those being similarly situated, and with their axes parallel."

This final passage is an extraordinary mixture of acute empirical observation, theoretical insight, and at times quite rampant speculation. Note worthy are his rather peculiar (at least to modern eyes) ideas about the shape of both the material atoms and the aether particles (an ingredient which gave him some freedom to explain why light propagated through the aether at different velocities along the different crystal axes), and his very perceptive discussion of the anisotropic mechanical properties of the crstal, and how this was related tot he structure of the atomic arrangement.

This passage (notably the final paragraph) also illustrates an important feature of the work and general method of Huyghens, which he shared to some extent with Newton, and which was to show itself to be extremely fruitful in the future of physics. This was his willingness to circumscribe his attempts to explain things - to not try and explain everything, but to confine himself to a sufficiently large and diverse set of facts that he could be confident that he really was capturing some important aspect of Nature, but without imagining that he could explain everything. The open and frank admission that his theory could not be used to explain everything, and that there were limits to what was then known or understood, would in earlier times have destroyed all his credibility in the eyes of his readers. But times had changed - instead of demanding the kind of all-encompassing world-view that Aristotle was supposed to have been giving his Mediaeval followers, the Renaissance scientists were now willing to both speculate beyond what they could establish for certain, and recognize the limits to their understanding. And with a confidence that must have seemed extraordinary to some of their contemporaries, they believed that by a combination of experiment and reasoning they could extend the boundaries of this understanding.

It is in this light that one should read the remarks that Huyghens makes about earlier work on optics and the nature of light, notably that of Descartes. Since Huyghens worked in Paris, it was natural that he should address himself to the ideas of Descartes, who was at that time considered in France to be the pre-eminent authority on matters of science and philosophy (Descartes had died in 1650, some 2 generations earlier). He makes short work of the ideas of his competitor, noting in particular that the ideas of Descartes were incapable of explaining one of the most obvious properties of light waves, viz., that they move through each other without any mutual interaction:

"*Another property of waves of light, and one of the most marvellous, is that when some of them come from different or even from opposing sides, they produce their effect across one another without any hindrance. Whence also it comes about that a number of spectators may view different objects at the same time through the same opening, and that two persons can at the same time see one another's eyes. Now according to the explanation which has been given of the action of light, how the waves do not destroy nor interrupt one another when they cross one another, these effects which I have just mentioned are easily conceived. But in my judgement they are not at all easy to explain according to the views of Mr. Des Cartes, who makes Light to consist in a continuous pressure merely tending to movement. For this pressure not being able to act from two opposite sides at the same time, against bodies which have no inclination to approach one another, it is impossible so to understand what I have been saying about two persons mutually seeing one another's eyes, or how two torches can illuminate one another.*"

Later on, Huyghens calls to mind the work of another quite remarkable man, the French mathematician and lawyer Pierre de Fermat (author of the famous 'last theorem of Fermat', and one of the most creative and profound mathematicians of all time). He points out that Descartes had assumed that light traveled *faster* in dense media, and that this was in conflict with his own theory and with an observation that Fermat had made about the propagation of light rays, viz., that if one supposed that light passed more slowly through dense media, then it seemed that the propagation satisfied the principle of 'least time', viz., that the path taken by light between 2 points was the one which would take the least time for the light. Huyghens immediately then notes that the wave theory give a natural explanation of the result of Fermat. It goes without saying, of course, that the ideas of Descartes are in conflict with experimental facts. Here then is Huyghens's last word on this:

"*I will finish this theory of refraction by demonstrating a remarkable proposition which depends on it; namely, that a ray of light in order to go from one point to another, when these points are in different media, is refracted in such wise at the plane surface which joins these two media that it employs the least possible time: and exactly the same happens in the case of reflexion against a plane surface. Mr. Fermat was the first to propound this property of refraction, holding with us, and directly counter to the opinion of Mr. Des Cartes, that light passes more slowly through glass and water than through air. But he assumed besides this a constant ratio of Sines, which we have just proved by these different degrees of velocity alone: or rather, what is equivalent, he assumed not only that the velocities were different but that the light took the least time possible for its passage, and thence deduced the constant ratio of the Sines.*"

As noted above, the work in the *Traité de la Lumière* was published in 1690, although much of the basic work in it was done earlier (indeed, the first version of it had actually been communicated to the Academy of Sciences in France in 1678). Huyghens felt (and said in the introduction) that the arguments in it were incomplete, and that the exposition was perhaps too informal - but that he did not think he would have time to publish it in a more logical form, in Latin, as had been his original intention. It should perhaps be stressed that he had already been ill for some time, and moreover political changes had made his return to France from the Netherlands unlikely - it seems probable that Huyghens simply no longer had the energy or resources to complete the work. In any case it is clear that he was not aware of the earlier optical work of Newton, and that moreover the *Traité* had been written well before the publication of the *Principia*. Thus we most consider that the published ideas of Huyghens on optics largely predate those of Newton, even though Newton had apparently arrived at some of his ideas on light corpuscles at a similar or even earlier time.

Thus we now turn to Newton's ideas, which were not published in their entirety until 1704, 9 years after the death of Huyghens (and the year after the death of Hooke, who had also earlier published his ideas on optics).

(3) NEWTON's OPTICS- the CORPUSCULAR THEORY of LIGHT

Newton's views on light and its properties developed over a long period. As already discussed in some detail in the section on Newton's life and work, he had arrived at many of his ideas on optical phenomena whilst still young, but they did not become known widely until the publication of his *Opticks* in 1704. This was not his first publication on the topic; in 1671 he published his notes "*On Colour*", and in 1675 he wrote his "*Hypothesis of Light*". He also communicated many papers to the Royal Society over the years on various optical phenomena. One reason for the delay in the publication of the *Opticks* was the one that Newton gave, viz., his desire not to be troubled by criticism, particularly that coming from Hooke (who died in 1703). But another was certainly the feelings of uncertainty Newton himself had about the work - it seemed to demand some sort of non-mechanical explanation (and he brought back the aether to do this), and yet he remained fixed to a particle theory to describe light. The first edition of *Opticks* was published in English. Very soon after, Newton's disciple Samuel Clarke (1675 - 1729) translated it into Latin (in 1706); there were a number of differences between the two texts which caused some later controversy.

In what follows I first discuss his early investigations, on colour and on telescopes. I then turn to a discussion of the corpuscular theory, which he first outlined in detail in a 1675 manuscript. Then we go to the full-blown work which appears in his 1704 book the *Opticks*, wherein a whole compendium of his work is given, inclding excperiments on diffraction and 'Newton's rings', as well as more on the cospuscular theory. Finally, we discuss the philosophical aspects of this work, as sketched by Newton in the *Opticks*.

3(a) EARLY NEWTONIAN WORK ON LIGHT and the TELESCOPE

The earliest optical work by Newton of which we have any kind of comprehensive record was accomplished from 1670-72. Newton investigated the refraction of light by a prism, because of his interest in the way in which white light could be split into light of different colours, ie., into a multi-coloured spectrum. Working with a lens, he showed by various experiments that a lens and a second prism could recompose the spectrum back into white light. The next obvious step was to take one of the colours and refract it with a second prism; he then found that it could no longer be separated any further. Moreover he found that the monocoloured light did not further change its colour in any way, even after shining it on various objects, or further reflecting or transmitting it; moreover, it could still thereafter be recombined with the rest of the spectrum to produce white light.

The style with which Newton summarized these observation in 1672 can be seen in the following extract from his 1972 communication to the Royal Society:

"*I might add more instances of this nature, but I shall conclude with this general one, that the colours of all natural bodies have no other origin than this, that they are variously qualified to reflect one sort of light in greater plenty than another. And this I have experimented in a dark room by illuminating those bodies with uncompounded light of diverse colours. For by that means any body may be made to appear of any colour. They have there no appropriate colour, but ever appear of the colour of the light cast upon them, but yet with this difference, that they are most brisk and vivid in the light of their own daylight colour. Minium* (NB: the modern name here is Cinnabar) *appears there of any colour indifferently, with which it is illustrated, but is yet most luminous in red, and so Bise* (NB: modern name is Azurite) *appears indifferently of any colour with which it is illustrated, but yet most luminous in blue.*

And there place a clear and colourless prism, to refract the entering light towards the further part of the room, which, as I said, will thereby be diffused into an oblong coloured image. Then place a lens of about three foot radius (suppose a broad object-glass of a three foot telescope), at the distance of about four or five foot from thence, through which all those colours may at once be transmitted, and made by its refraction to convene at a further distance of about ten or twelve feet. If at that distance you intercept this light with a sheet of white paper, you will see the colours converted into whiteness again by being mingled. But it is requisite, that the prism and lens be placed steady, and that the paper, on which the colours are cast, be moved to and fro; for, by such motion, you will not only find, at what distance the whiteness is most perfect but also see, how the colours gradually convene, and vanish into whiteness, and afterwards having crossed one another in that place where they compound whiteness, are again dissipated and severed, and in an inverted order retain the same colours, which they had before they entered the composition. You may also see, that, if any of the colours at the lens be intercepted, the whiteness will be changed into the other colours. And therefore, that the composition of whiteness be perfect, care must be taken, that none of the colours fall besides the lens.

Newton's essential deduction from all his experiments was that white light was composed of many different components, each of which we perceive as having different colours; and that these are refracted differently by, eg., a prism. They can be recombined and re-separated at will, using the appropriate combination of refracting material (ie., lenses, prisms etc.). Notice the emphasis Newton placed on the idea that colour is the result of objects interacting with light, itself already possessed of colour, rather than objects generating the colour themselves. One needs to see this emphasis in historical context - at that time, it was generally believed that colour was entirely an attribute or "*quality*" of the object in question; and this belief had acquired some philosophical importance. Here as on many other occasions, Newton felt compelled to combat the philosophical idealism that resulted from ignorance of experimental results, and from disdain for the "experimental philosophy" to which he was attached. However it should be remarked here that Newton's ideas on the nature of colour and how it is generated were by no means the whole story, and in fact objects both reflect and absorb light of different colours, and moreover can emit light (this is obvious in the case of the sun, which is hot - but consider the emission by cold fluorescent materials, or by fireflies). A full understanding of colour would have to wait 220 more years, with the arrival first of the theory of electromagnetic fields, and then with quantum mechanics. However Newton's ideas were a real advance over previous notions.

In the same communication to the Royal Society, Newton also pointed out that this differential refrangibility (ie., the variation of the index of refraction with colour) of glass for different colours was the reason that it was so difficult to get clear images with refracting telescopes made with lenses. However, he noted, this awkward property of refraction did not obtain for reflection - he found that different colors were reflected always by the same angle from a specular (ie., smooth) surface. This led him to the invention of what is now known as the Newtonian or reflecting telescope, used almost universally in observatories today. The idea is to use a large parabolic mirror to reflect parallel light rays from a distant object to a single focus, where they can be picked up by a single small lens, made to show very little colour dispersion. He had some difficulty in making such a mirror, because it had to be really smooth - but eventually he succeeded. In Newton's words:

"*When I understood this, I left off my aforesaid glass works; for I saw, that the perfection of telescopes was hitherto limited, not so much for want of glasses truly figured according to the prescriptions of Optics Authors (which all men have hitherto imagined), as because that light itself is a heterogeneous mixture of differently refrangible rays. So* *that, were a glass so exactly figured as to collect any one sort of rays into one point, it could not collect those also into the same point, which having the same incidence upon the same medium are apt to suffer a different refraction. Nay, I wondered, that seeing the difference of refrangibility was so great, as I found it, telescopes should arrive to that perfection they are now at.......This made me take reflections into consideration, and finding them regular, so that the Angle of Reflection of all sorts of Rays was equal to their Angle of Incidence; I understood, that by their mediation optic instruments might be brought to any degree of perfection imaginable, provided a reflecting substance could be found, which would polish as finely as glass, and reflect as much light, as glass transmits, and the art of communicating to it a parabolic figure be also attained. But these seemed very great difficulties, and I have almost thought them insuperable, when I further considered, that every irregularity in a reflecting superficies makes the rays stray 5 or 6 times more out of their due course, than the like irregularities in a refracting one; so that a much greater curiosity would be here requisite, than in figuring glasses for refraction.*

Amidst these thoughts I was forced from Cambridge by the intervening Plague, and it was more than two years before I proceeded further. But then having thought on a tender way of polishing, proper for metal, whereby, as I imagined, the figure also would be corrected to the last; I began to try, what might be effected in this kind, and by degrees so far perfected an instrument (in the essential parts of it like that I sent to London), by which I could discern Jupiter's 4 Concomitants, and showed them diverse times to two others of my acquaintance. I could also discern the Moon-like phase of Venus, but not very distinctly, nor without some niceness in disposing the instrument.

From that time I was interrupted till this last autumn, when I made the other. And as that was sensibly better than the first (especially for day-objects), so I doubt not, but they will be still brought to a much greater perfection by their endeavours, who, as you inform me, are taking care about it at London."

In the time since Newton, lenses with much reduced chromatic abberation have been made, reducing the problem of differential refraction of light of different colors. However modern large telescopes are entirely based on Newton's mirror design, with a number of different variants. This is for the simple reason that lenses above a certain size cannot support their own weight, and begin to distort in shape. However mirrors can be supported from below by other materials, and the glass itself can be made quite thin as well as having channels and indentations in the back face (designed to reduce the weight without reducing the strength). The largest telescope mirrors nowadays are 10 metres across, whereas the largest telescope lens ever made was the 40 inch (1 metre) main lens of the Yerkes observatory telescope, made in the 19th century.

3(b) HYPOTHESES on LIGHT: CORPUSCLES and the AETHER

After his early publications on optical phenomena Newton, leery of further public controversy, became much more reticent about his ideas. Nevertheless he did continue to send communications to the newly-founded Royal Society about his optical observations, and he worked on various manuscripts, intended more for his own benefit. Upon examination these reveal a very wide-ranging speculative train of thought, which attempted to synthesize his ideas on everything from optical and mechanical phenomena to quasi-religious speculations about the 'prime mover' behind all of the observable phenomena in the universe. It is worth quoting from some of these later communications and manuscripts, because they give not only a good idea of his theoretical picture of optical phenomena, of the aether, and of the relationship between optical and mechanical phenomena, but also because they give us a window on his rather idiosyncratic way of doing things.

The final elaboration of Newton's ideas on light, in his book "*Opticks*", was interesting not only for the very extensive discussion of different optical phenomena in it, and the mathematical discussion of these, but also for the more philosophical remarks he made on how science should be pursued, and on the general methodology of science. Some of these remarks can be regarded as an update on his views, to be compared with earlier thoughts appearing in the *Principia*; others are entirely new. This book was published in 1704, but much of the material was much older. From our present point view the rather exhaustive and methodical account of his experiments is of less interest than the more hesitant attempts he makes to account for them. Newton is uncharacteristically vague in these accounts, and indeed in the *Opticks* he puts most of this discussion at the end, in the form of 'Queries'. The style is curious - it is a mixture of lengthy speculation, punctuated by occasional condemnation of hypothetical reasoning - and Newton was clearly torn between his desire to finally get all of his ideas off his chest, and his self-imposed stricture against the kind of philosophical speculation, unsupported by experimental proof, that he so roundly condemned in others.

In what follows I first discuss the key features of Newton's later work on optics, laying particular emphasis on his speculations concerning the nature of light itself, and his sketchy remarks on his corpuscular hypothesis. Much of this work dates from the period between 1670 and the publication of the *Principia* in 1687. I then go on to discuss some of the ideas he sketched in his *Opticks* on the nature of light, discussing both the specific ideas he had, and also the more general philosophical ideas he sketched in the final stages of the book.

(i) Hypotheses on the Nature of the Aether: It is useful to begin by empahisizing Newton's abjurations against the use of unsupported speculation in scientific work. His reservations refer in what follows refer to the use of unsupported hypotheses in work on optics, but it could equally have referred to work on any topic at all, scientific or otherwise (and the finely-drawn boundaries that we now draw between scientific and non-scientific work hardly existed at the time of Newton). Here is a typical example:

"*Were I to assume an hypothesis, it should be this, if propounded more generally, so as not to determine what light is, farther than that it is something or other capable of exciting vibrations in the ther: for thus it will become so general and comprehensive of other hypotheses, as to leave little room for new ones to be invented. And therefore, because I have observed the heads of some great virtuosos to run much upon hypotheses, as if my discourses wanted an hypothesis to explain them by, and found, that some, when I could not make them take my meaning, when I spake of the nature of light and colours abstractedly, have readily apprehended it, when I illustrated my discourse by an hypothesis; for this reason I have here thought fit to send you a description of the circumstances of this hypothesis as much tending to the illustration of the papers I herewith send you. And though I shall not assume either this or any other hypothesis, not thinking it necessary to concern myself, whether the properties of light, discovered by me, be explained by this, or Mr. HOOKE'S, or any other hypothesis capable of explaining them; yet while I am describing this, I shall sometimes, to avoid circumlocution, and to represent it more conveniently, speak of it, as if I assumed it, and propounded it to be believed. This I though fit to express, that no man may confound this with my other discourses, or measure the certainty of one by the other, or think me obliged to answer objections against this script: for I desire to decline being involved in such troublesome and insignificant disputes.*"

It is important to realize how serious Newton was about the avoidance of speculative hypothesis. His remarks in the above may have been directed at Hooke, with whom he had very significant differences, and against whom he bore a grudge. But the reference to Hooke is in most important ways rather incidental - what motivated Newton more than anything was his distaste for rationalistic philosophy, as exemplified by the work of Descartes, Leibniz, and those that preceeded them. To best appreciate Newton's point of view, it is important to notice what he shared with these thinkers. All of them were agreed that the ultimate explanation of Nature and everyting it was to be found in an appeal to a creator or 'intelligent designer'. This essentally religious point of view is what largely divides us from them - nowawdays the pursuit of scientific understanding has been almost completely divorced from religion. But for Newton and his contemporaries and rivals no such separation existed. What divided Newton from the majority of continental thinkers was more a visceral distate on his part for what he saw as the arrogance of these thinkers, who, he felt, were not prepared to take the trouble to learn from the works of God in formulating their ideas - who instead felt that they could 'second guess' the Creator in trying to deduce what he must have done and how he did it. That their hypotheses were so clearly wrong meant for Newton that were committing something not far from sacrilege, in their attempts to upstage the Prime Mover. Thus we see a remarkable humility on the part of Newton in the face of natural phenomena - the feeling that the only way to proceed was through methodical empirical study, aided by very careful reasoning. And at the same time we see a dismissive arrogance in his rejection of the work of his competitors.

The astonishing then is to see how wide-ranging his own speculations were. Much of this he kept to himself. A very revealing document from these intermediate years is in the form of a paper he delivered verbally to the Royal Society in the year 1675, 15 years after he had first communicated his ideas on colour and the operation of telescopes to the same body. Newton did not at the time want to publish this work - the notes on it were thus kept within the walls of the Royal Society until long after his death, but they were clearly known to his colleagues in Englend, who would have heard them from him at this 1675 meeting. This document is worth quoting from at some length. We begin with his usual abjuration of hypotheses, followed immediately by the elaboration of a whole series of hyptheses of his own:

"*Sir - I had formerly purposed never to write any Hypothesis of light and colours, fearing it might be a means to engage me in vain disputes: but I hope I need not fear that if it proceed no further then to the ears of the Society. Considering therefore that such an Hypothesis will much illustrate the papers I send you; I shall not scruple to describe one so far as it may be done in this cursory letter: not concerning my self whether it shall be thought probable or improbable so it do but render the papers I send you more intelligible.*

But to proceed to the hypothesis: First, it is to be supposed therein, that there is an aethereal medium much of the same constitution with air, but far rarer, subtler, and more strongly elastic. Of the existence of this medium the motion of a pendulum in a glass exhausted of air almost as quickly as in the open air, is no inconsiderable argument. But it is not to be supposed, that this medium is one uniform matter, but compounded, partly of the main phlegmatic body of aether, partly of other various aethereal spirits, much after the manner, that air is compounded of the phlegmatic body of air intermixed with various vapours and exhalations: for the electric and magnetic effluvia, and gravitating principle, seem to argue such variety. Perhaps the whole frame of nature may be nothing but various contextures of some certain aethereal spirits, or vapours, condensed as it were by precipitation, much after the manner, that *vapours are condensed into water, or exhalations into grosser substances, though not so easily condensible; and after condensation wrought into various forms; at first by the immediate hand of the Creator; and ever since by the power of nature; which, by virtue of the command, increase and multiply, become a complete imitator of the copies set her by the protoplast. Thus perhaps may all things be originated from aether.*

At least, the elastic effluvia seem to instruct us, that there is something of an aethereal nature condensed in bodies. I have sometimes laid upon a table a round piece of glass about two inches broad set in a brass ring, so that the glass might be about one eighth or one sixth of an inch from the table, and the air between them inclosed on all sides by the ring, after the manner as if I had whelmed a little sieve upon the table; and then rubbing a pretty while the glass briskly with some rough and raking stuff, till some very little fragments of very thin paper, laid on the table under the glass, began to be attracted and move nimbly to and fro; after I had done rubbing the glass, the papers would continue a pretty while in various motions; sometimes leaping up to the glass and resting there a while; then leaping down and resting there; then leaping up, and perhaps down and up again, and this sometimes in lines seeming perpendicular to the table; sometimes in oblique ones; sometimes also they would leap up in one arch and down in another, divers times together, without sensibly resting between; sometimes skip in a bow from one part of the glass to another without touching the table, and sometimes hang by a corner, and turn often about very nimbly, as if they had been carried about in the midst of a whirlwind, and be otherwise variously moved, every paper with a diverse motion. And upon sliding my finger on the upper side of the glass, though neither the glass, nor inclosed air below, were moved thereby, yet would the papers, as they hung under the glass, receive some new motion, inclining this way or that way, accordingly as I moved my finger. Now, whence all these irregular motions should spring, I cannot imagine, unless from some kind of subtil matter lying condensed in the glass, and rarefied by rubbing, as water is rarefied into vapour by heat, and in that refraction diffused through the space round the glass to a great distance, and made to move and circulate variously, and accordingly to actuate the papers till it return into the glass again, and be recondensed there. And as this condensed matter by rarefaction into an aethereal wind (for by its easy penetrating and circulating through glass I esteem it aethereal) may cause these odd motions, and by condensing again may cause electrical attraction with its returning to the glass to succeed in the place of what is there continually recondensed; so may the gravitating attraction of the earth be caused by the continual condensation of some other such like aethereal spirit, not of the main body of phlegmatic aether, but of something very thinly and subtilly difused through it, perhaps of an unctuous or gummy, tenacious, and springy nature, and bearing much the same relation to aether, which the vital aereal spirit, requisite for the conservation of flame and vital motions, does to air. For, if such an aethereal spirit may be condensed in fermenting or burning bodies, or otherwise coagulated in the pores of the earth and water into some kind of humid active matter, for the continual uses of nature, adhering to the sides of those pores, after the manner that vapours condense on the sides of a vessel; the vast body of the earth, which may be every where to the very center in perpetual working, may continually condense so much of this spirit, as to cause it from above to descend with great celerity for a supply; in which descent it may bear down with it the bodies it pervades with force proportional to the superficies of all their parts it acts upon; nature making a circulation by the slow ascent of as much matter out of the bowels of the earth in an aereal form, which, for a time, constitues the atmosphere; but being continually buoyed up by the new air; exhalations and vapours rising underneath, at length (some parts of the vapours, which return in rain, excepted) vanishes again into the aethereal spaces, and there perhaps in time relents, and is attenuated into its first principle: for nature is a perpetual worker, generating fluids out of solids, and solids out of fluids, fixed things out of volatile, and volatile out of fixed, subtil out of gross and gross out of subtil; some things to ascend, and make the upper terrestrial juices, rivers, and the atmosphere; and by consequence, others to descend for a requital to the former. And, as the earth, so perhaps may the sun imbibe this spirit copiously, to conserve his shining, and keep the planets from receding further from him. And they, that will, may also suppose, that this spirit affords or carries with it thither the solary fewel and material principle of light: and that the vast aethereal spaces between us and the stars are for a sufficient repository for this food of the sun and planets. But this of the constitution of aethereal natures by the by."

from I Newton, "*Hypothesis explaining the properties of light*"
(1675, paper read before the Royal Society)
Published in: Thomas Birch, The History of the Royal Society, vol. 3 (London: 1757), pp. 247-305.

We see that Newton, like most other scientists of his time, felt that one had to call upon the aether to explain the existence of influences acting through the vacuum - it was simply intolerable to suppose that no medium could be involved in their action. But, as we read through his description of the action of the aether, and his speculations on how it is involved in everything from fermentation to magnetic and electrical forces - as well as being involved in gravitation and light propagation - we realize just how far away we are from the late 17th century. At this time there was simply no systematic understanding at all of electrical and magnetic forces - this would have to wait for the painstaking experimental work of Oersted, Coulomb, Ampère, Faraday, and others - and Newton clearly had little clue of how they worked. His idea that the aether was a medium analogous to the atmosphere, and that it could therefore condense and thereby become visible, or lead to fermentation (a phenomenon regarded as very mysterious at that time, because of the way that gas seemed to be created from nothing) seems very naive to us. But we have to realize that scientists of Newton's time felt themselves to be surrounded by a mysterious physical world, in a way which requires an effort for us to imagine. The distinction we make in the early 21st century between electromagnetic phenomena (including light), chemical reactions (like fermentation) and gravitational phenomena was impossible at that time, just because all of the subsequent development of physics was still to unfold.

Newton then goes on to point out what was a central point for the work of Huyghens - that the aether must be able to support vibrations:

"*In the second place, it is to be supposed, that the aether is a vibrating medium like air, only the vibrations far more swift and minute; those of air, made by a man's ordinary voice, succeeding one another at more than half a foot or a foot distance; but those of aether at a less distance than the hundred thousandth part of an inch. And, as in air the vibrations are some larger than others, but yet all equally swift (for in a ring of bells the sound of every tone is heard at two or three miles distance, in the same order that the bells are struck;) so, I suppose, the aethereal vibrations differ in bigness, but not in swiftness. Now, these vibrations, beside their use in reflexion and refraction, may be supposed the chief means, by which the parts of fermenting or putrifying substances, fluid liquors, or melted, burning, or other hot bodies, continue in motion, are shaken asunder like a ship by waves, and dissipated into vapours, exhalations, or smoke, and light loosed or excited in those bodies, and consequently by which a body becomes a burning coal, and smoke, flame; and, I suppose, flame is nothing but the particles of smoke turned by the access of light and heat to burning coals, little and innumerable.*"

from I Newton, "*Hypothesis explaining the properties of light*"
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We see that for Newton, the aether is a medium which can interact with matter in diverse ways. His picture of heat as a violent motion of particles was an old idea - here we see that he imagines that heat is transmitted not just through the interaction of one set of particles with another, but also via vibrations of the aether. But this is only the beginning:

"*Thirdly, as the air can pervade the bores of small glass pipes, but yet not so easily as if they were wider; and therefore stands at a greater degree of rarity than in the free aereal spaces, and at so much a greater degree of rarity as the pipe is smaller, as is known by the rising of water in such pipes to a much greater hight than the surface of the stagnating water, into which they are dipped; so I suppose aether, though it pervades the pores of crystal, glass, water, and other natural bodies, yet it stands at a greater degree of rarity in those pores, than in the free aethereal spaces, and at so much a greater degree of rarity, as the pores of the body are smaller. Whence it may be, that the spirit of wine, for instance, though a lighter body, yet having subtiler parts, and consequently smaller pores, than water, is the more strongly refracting liquor. This also may be the principal cause of the cohesion of the parts of solids and fluids, of the springiness of glass, and bodies, whose parts slide not one upon another in bending, and of the standing of the mercury in the Torricellian experiment, sometimes to the top of the glass, though a much greater hight than twenty-nine inches. For the denser aether, which surrounds these bodies, must croud and press their parts together, much after the manner that air surrounding two marbles presses them together, if there be little or no air between them. Yea, and that puzzling problem; By what means the muscles are contracted and dilated to cause animal motion, may receive greater light from hence than from any means men have hitherto been thinking on. For, if there be any power in man to condense and dilate at will the aether, that pervades the muscle, that condensation or dilation must vary the compression of the muscle, made by the ambient aether, and cause it to swell or shrink accordingly. For though common water will scarce shrink by compression, and swell by relaxation, yet (so far as my observation reaches) spirit of wine and oil will; and Mr. BOYLE'S experiment of a tadpole shrinking very much by hard compressing the water, in which it swam, is an argument, that animal juices do the same. And as for their various pression by the ambient aether, it is plain, that that must be more or less accordingly as there is more or less aether within, to sustain and counterpoise the pressure of that without. If both aethers were equally dense, the muscle would be at liberty, as if pressed by neither: if there were no aether within, the ambient would compress it with the whole force of its spring. If the aether within were twice as much dilated as that without, so as to have but half as much springiness, the ambient would have half the force of its springiness counterpoised thereby, and exercise but the other half upon the muscle; and so in all other cases the ambient compresses the muscle by the excess of the force of its springiness above that of the springiness of the included. To vary the compression of the muscle therefore, and so to swell and shrink it, there needs nothing but to change the consistence of the included aether; and a very little change may suffice, if the spring of aether be supposed very strong, as I take it to be many degrees stronger than that of air.*"

from I Newton, "*Hypothesis explaining the properties of light*"

(1675, paper read before the Royal Society)
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Now we see that Newton wishes to use the aether as a medium capable of transmitting static forces, or forces varying slowly in time. He calls upon what we would now call 'capillary forces' (ie., those forces which are responsible for causing a liquid to 'pull itself' up the side of a solid object) to explain how it is that the aether is supposed to infuse itself into solid bodies, and to mediate forces between them - either pressure forces which push them apart, or suction forces pulling them together. Note that Newton gives no explanation of capillary attraction (which we now know to be due to short-range atttractive forces between atoms, which are electromagnetic in origin).

Once one can have a combination of attractive and repulsive forces amongst bodies, it is possible to discuss a large number of phenomena in Nature. Apart from the physical action of muscles just noted, Newton takes us on a wild ride through everything he can think of:

"*Now for the changing the consistence of the aether; some may be ready to grant, that the soul may have an immediate power over the whole aether in any part of the body, to swell or shrink it at will: but then how depends the muscular motion on the nerves? Others therefore may be more apt to think it done by some certain aethereal spirit included within the dura mater, which the soul may have power to contract or dilate at will in any muscle, and so cause it to flow thither through the nerves. But still there is a difficulty, why this force of the soul upon it does not take off the power of its springiness, whereby it should sustain, more or less, the force of the outward aether. A third supposition may be, that the soul has a power to inspire any muscle with this spirit, by impelling it thither through the nerves. But this too has its difficulties, for it requires a forcible intending the spring of the aether in the muscles, by pressure exerted from the parts of the brain: and it is hard to conceive, how so great force can be exercised amidst so tender matter as the brain is. And besides, why does not this aethereal spirit, being subtil enough, and urged with so great force, go away through the dura mater and skins of the muscle; or at least so much of the other aether to go out to make way for this, which is crouded in? To take away these difficulties is a digression; but seeing the subject is a deserving one, I shall not stick to tell you how I think it may be done.*

First then, I suppose, there is such a spirit; that is, that the animal spirits are neither like the liquor, vapour, or gas of spirit of wine; but of an aethereal nature, subtil enough to pervade the animal juices, as freely as the electric, or perhaps magnetic, effluvia do glass. And to know, how the coats of the brain, nerves, and muscles, may become a convenient vessel to hold so subtil a spirit, you may consider, how liquors and spirits are disposed to pervade or not pervade things on other accounts than their subtilty. Water and oil pervade wood and stone, which quicksilver does not; and quicksilver metals, which water and oil do not: water and acid spirits pervade salts, which oil and spirit of wine do not; and oil and spirit of wine pervade sulphur, which water and acid spirits do not. So some fluids, as oil and water, though their parts are in freedom enough to mix with one another, yet by some secret principle of unsociableness they keep asunder; and some, that are sociable, may become unsociable, by adding a third thing to one of them, as water to spirit of wine, by dissolving salt of tartar in it. The like unsociableness may be in aethereal natures, as perhaps between the aethers in the vortices of the sun and planets; and the reason, why air stands rarer in the boxes of small glass-pipes, and aether in the pores of bodies, than elsewhere, may be, not want of subtilty, but sociableness. And on this ground, if the aethereal vital spirit in a man be very sociable to the marrow and juices, and unsociable to the coats of the brain, nerves, and muscles, or any thing lodged in the pores of those we suppose no great violence done to it to squeeze it out; and that it may not be altogether so subtil as the main body of aether, though subtil enough to pervade readily the animal juices, and that, as any of it is spent, it is continually supplied by new spirit from the heart.

In the next place, for knowing how this spirit may be used for animal motion, you may consider, how some things unsociable are made sociable by the mediation of a third. Water, which will not dissolve copper, will do it, if the copper be melted with sulphur: aqua fortis, which will not pervade gold, will do it by addition of a little sal armoniac, or spirit of salt: lead will not mix in melting with copper, but if a little tin or antimony be added, they mix readily, and part again of their own accord, if the antimony be wasted by throwing saltpeter or otherwise: and so lead melted with silver quickly pervades and liquefies the silver in a much less heat than is requisite to melt the silver alone; but, if they be kept in the test till that little substance, that reconciled them, be wasted or altered, they part again of their own accord. And, in like manner, the aethereal animal spirit in a man may be a mediator between the common aether and the muscular juices, to make them mix more freely; and so, by sending a little of this spirit into any muscle, though so little as to cause no sensible tension of the muscle by its own force; yet, by rendering the juices more sociable to the common external aether, it may cause that aether to pervade the muscle of its own accord in a moment more freely and copiously than it would otherwise do, and to recede again as freely, so soon as this mediator of sociableness is retracted. Whence, according to what I said above, will proceed the swelling or shrinking of the muscle, and consequently the animal motion depending thereon.

Thus may therefore the soul, by determining this aethereal animal spirit or wind into this or that nerve, perhaps *with as much ease as air is moved in open spaces, cause all the motions we see in animals: for the making which motions strong, it is not necessary, that we should suppose the aether within the muscle very much condensed or rarified by this means, but only that its spring is so very great, that a little alteration of its density shall cause a great alteration in the pressure, And what is said of muscular motion, may be applied to the motion of the heart, only with this difference, that the spirit is not sent thither, as into other muscles, but continually generated there by the fermentation of the juices, with which its flesh is replenished, and as it is generated, let out by starts into the brain through some convenient ductus to perform those motions in other muscles by impression, which it did in the heart by its generation. For I see not, why the ferment in the heart may not raise as subtil a spirit out of its juices, to cause these motions, as rubbing does out of a glass, to cause electric attraction, or burning out of fewel, to penetrate glass, as Mr. BOYLE has shewn, and calcine by corrosion metals melted therein....*"

from I Newton, "*Hypothesis explaining the properties of light*"
(1675, paper read before the Royal Society)
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The paper goes on in this vein; Newton is clearly having none of the mind-body dualism of Descartes, and souls are as free to mix it up with the aether as anything else (quite how Newton thought about souls in this context - ie., in what sense they had any mechanical properties - is not quite clear). The preceding discussion is interesting from several points of view. Notice first that Newton is limited by his time, and by his own understanding of forces as coming from contact between material bodies. Thus the aether is, for him, some kind of invisible fluid, in which pressure differences drive motion. Like Huyghens, he realized that the very high pressures that might be necessary for the aether to generate motion implied that the aether must be a very stiff medium, so that even large pressures would not compress it very much. This meant, amongst other things, that influences such as wave excitations would travel very quickly through it.

However what this meant was that somehow, in order for the complex motions of the human body to be possible, an equally complex network of internal forces would be required; and this would not be possible if the aether were allowed to infuse itself equally throughout the body. we recall that Huyghens had confronted the same problem in trying to understand the different velocities of light in different materials - and had solved it by assuming that the aether permeated through material bodies differently, and had different densities and hence different elastic properties in different media. Newton's answer is similar, but more elaborate - he supposes that the aether is unable to penetrate into some parts of the human body (eg., the brain, the nerves, etc.) and easily into others; and moreover that a further variant of aether, which he calls 'animal aether', be a mediator between the universal aether and the 'juices' in animals, allowing the aether to pass into regions of the body from which it would otherwise be excluded. The final picture is what he is looking for - a complex network of tubes, and different regions, rather like an elaborate plumbing system, through which the aether and other material fluids can transmit influences via differences in pressures.

Given that much of the argument here is just argument by analogy (no explanation of the aether or its nature is given, only analogies with known chemical and fluid phenomena) we see that Newton's picture here is both very broad-brush and vague, and speculative in the extreme. We see nevertheless how much he felt compelled to try and give a picture of forces and influences that was capable of explaining the whole of the natural world, not just a small part of it.

(ii) The Corpuscular Hypothesis: Finally, in his 1675 paper, after more lengthy speculations on the properties of the aether, souls, etc., Newton eventually turns back to the discussion of light (which is nominally the subject of the paper). And here we are faced with a surprise - for instead of supposing light to be a vibration of the aether, as had Huyghens, we invokes a quite different explanation:

"*....Hitherto I have been contemplating the nature of aether and aethereal substances by their effects and uses; and now I come to join therewith the consideration of light.*

In the fourth place therefore, I suppose light is neither aether, nor its vibrating motion, but something of a different kind propagated from lucid bodies. They, that will, may suppose it an aggregate of various peripatetic qualities. Others may suppose it multitudes of unimaginable small and swift corpuscles of various sizes, springing from shining bodies at great distances one after another; but yet without any sensible interval of time, and continually urged forward by a principle of motion, which in the beginning accelerates them, till the resistence of the aethereal medium equal the force of that principle, much after the manner that bodies let fall in water are accelerated till the resistance of the water equals the force of gravity. God, who gave animals self-motion beyond our understanding, is, without doubt, able to implant other principles of motion in bodies, which we may understand as little. Some would readily grant this may be a spiritual one; yet a mechanical one might be shewn, did not I think it better to pass it by. But they, that like not this, may suppose light any other corporeal emanation, or any impulse or motion of any other medium *or aethereal spirit diffused through the main body of aether, or what else they can imagine proper for this purpose. To avoid dispute, and make this hypothesis general, let every man here take his fancy: only, whatever light be, I suppose, it consists of rays differing from one another in contingent circumstances, as bigness, form, or vigour; like as the sands on the shore, the waves of the sea, the faces of men, and all other natural things of the same kind differ; it being almost impossible for any sort of things to be found without some contingent variety. And further, I would suppose it diverse, from the vibrations of the aether, because (besides, that were it these vibrations, it ought always to verge copiously in crooked lines into the dark or quiescent medium, destroying all shadows; and to comply readily with any crooked pores or passages, as sounds do,) I see not how any superficies (as the side of a glass prism, on which the rays within are incident at an angle of above forty degrees) can be totally opake. For the vibrations beating against the refracting confine of the rarer and denser aether must needs make that pliant superficies undulate, and those undulations will stir up and propagate vibrations on the other side. And further, how light, incident on very thin skins or plates of any transparent body, should, for many successive thicknesses of the plate in arithmetical progression, be alternately reflected and transmitted, as I find it is, puzzles me as much. For, though the arithmetical progression of those thicknesses, which reflect and transmit the rays alternately, argues, that it depends upon the number of vibrations between the two superficies of the plate, whether the ray shall be reflected or transmitted: yet I cannot see, how the number should vary the case, be it greater or less, whole or broken, unless light be supposed something else than these vibrations. Something indeed I could fancy towards helping the two last difficulties, but nothing which I see not insufficient.*

Fifthly, it is to be supposed, that light and aether mutually act upon one another, aether in refracting light, and light in warming aether; and that the densest aether acts most strongly. When a ray therefore moves through aether of uneven density, I suppose it most pressed, urged, or acted upon by the medium on that side towards the denser aether, and receives a continual impulse or ply from that side to recede towards the rarer, and so is accelerated, if it move that way, or retarded, if the contrary. On this ground, if a ray move obliquely through such an unevenly dense medium (that is, obliquely to those imaginary superficies, which run through the equally dense parts of the medium, and may be called the refracting superficies) it must be incurved, as it is found to be, by observation in water1[4] , whose lower parts were made gradually more salt, and so more dense than the upper. And this may be the ground of all refraction and reflexion: for as the rarer air within a small glass-pipe, and the denser without, are not distinguished by a meer mathematical superficies, but have air between them, at the orifice of the pipe, running through all intermediate degrees of density: so I suppose the refracting superficies of aether, between unequally dense mediums, to be not a mathematical one; but of some breadth, the aether therein, at the orifices of the pores of the solid body, being of all intermediate degrees of density between the rarer and denser aethereal mediums; and the refraction I conceive to proceed from the continual incurvation of the ray all the while it is passing the physical superficies. Now, if the motion of the ray be supposed in this passage to be increased or diminished in a certain proportion, according to the difference of the densities of the aethereal mediums, and the addition or detraction of the motion be reckoned in the perpendicular from the refracting superficies, as it ought to be, the sines of incidence and refraction will be proportional according to what DES CARTES has demonstrated....."

from I Newton, "*Hypothesis explaining the properties of light*"
(1675, paper read before the Royal Society)
Published in: Thomas Birch, The History of the Royal Society, vol. 3 (London: 1757), pp. 247-305.

This discussion is one of the most explicit that Newton ever gives on the nature of light. He supposes it to be a set of corpuscles, ie., very small bodies, which move extremely rapidy through the aether, all the while interacting with it. The light particles are accelerated very rapidly to an extremely high velocity by some constant force acting along the light rays - their final velocity results from the balance between the resistive drag imposed by their interaction with the aether, and the force that is accelerating them. Thus the light corpuscles reach a 'terminal velocity', analogous to the terminal velocity reached by an object falling through the atmosphere, when accelerated by gravity until the resistance from the air is enough to counterbalance the constant gravitational force acting on it.

In a theory like this, everything then depends on the interaction between the light corpuscles and the aether, and on how the aether is distributed in space. Here Newton makes two simple assumptions. First, he assumes that this interaction is such that the light corpuscles are pushed from regions of high aetherial density towards regions of lower density. This means that if the light moves from a region of high aetherial density to lower density, the light corpuscles will end up being accelerated, and this with a higher velocity. He then, in line with his previous discussions, supposes that the aether is densest in a vacumm, where there is nothing else to take up the space occupied by the aether. Conversely in a material body, he supposes that the aether will be less dense,

The net result of these two assumptions is that if light is incident on some material body from a vacuum (or from air) it will either reflect (at the same speed but in a different direction), or it will enter the body and be accelerated. Thus, in this picture, the light corpuscles will move more quickly in the solid or liquid material body. This prediction, which had also been made by Descartes (on the basis of a theory not so different from Newton's) would of course turn out to be quite wrong, although it would be a long time before the key experiment was done.

At one point we also see that Newton addresses the wave theory - here he mentions nobody by name, and indeed he could not have known of the work of Huyghens, which would not be published until 15 years later. In fact it is likely that Newton thought of the wave hypothesis as being associated with Hooke, with whom he had very poor relations. This probably explains the fact that he nowhere makes any attribution of the idea to any specific person. Newton's objections to the wave theory boil down to:

(i) the implication of a wave theory that diffraction phenomena would exist, so that light would be diffracted around corners, in a simlar way to the diffraction of sound waves. Since such diffraction, according to Newton, had not been observed, this was a powerful argument against a wave hypothesis for light;

(ii) the existence of opaque objects was also, according to Newton, a problem for any wave theory; he argued that any wave incident on the surface of some opaque object would excite oscillations in the surfqce profile (ie., excite surface waves, like those on water), and these would then have to propgate into the object;

(iii) Newton's inability to see how a wave theory could explain the phenomenon now known as 'Newton's rings' (which would later be seen as a strong piece of evidence *in favour* of the wave theory). We shall return to Newton's rings below, in the discussion of his "*Opticks*".

After rejecting the wave theory, and arguing that light travels faster in solid bodies that it does in the vacuum, Newton then goes on to give more detail of the ways in which his corpuscular hypothesis can be used to understand the rather diverse properties of light propagation that are observed in Nature:

"*.....This may be the cause and manner of reflection, when light tends from the rarer towards the denser aether: but to know, how it should be reflected, when it stands from the denser towards the rarer, you are further to consider, how fluids near their superficies are less pliant and yielding than in their more inward parts; and, if formed into thin plates, or shells, they become much more stiff and tenacious than otherwise. Thus, things, which readily fall in water, if let fall upon a bubble of water, they do not easily break through it, but are apt to slide down by the sides of it, if they be not too big and heavy. So, if two well polished convex glasses, ground on very large spheres, be laid one upon another, the air between them easily recedes, till they almost touch; but then begins to resist so much, that the weight of the upper glass is too little to bring them together so as to make the black, mentioned in the other papers I send you, appear in the midst of the rings of colours: and, if the glasses be plain, though no broader than a two-pence, a man with his whole strength is not able to press all the air out from between them, so as to make them fully touch. You may observe also, that insects will walk upon water without wetting their feet, and the water bearing them up; also motes falling upon water will often lie long upon it without being wetted: and so, I suppose, aether in the confine of two mediums is less pliant and yielding than in other places, and so much the less pliant by how much the mediums differ in density: so that in passing out of denser aether into rarer, when there remains but a very little of the denser aether to be past through, a ray finds more than ordinary difficulty to get through; and so great difficulty, where the mediums are of very differing density, as to be reflected by incurvation, after the manner described above; the parts of aether on that side, where they are less pliant and yielding, acting upon the ray much after the manner that they would do were they denser there than on the other side: for the resistance of the medium ought to have the same effect on the ray, from what cause soever it arises. And this, I suppose, may be the cause of the reflection of quicksilver, and other metalline bodies. It must also concur to increase the reflective virtue of the superficies, when rays tend out of the rarer medium into the denser: and, in that case therefore, the reflection having a double cause, ought to be stronger than in the aether, as it is apparently. But in refraction, this rigid tenacity or unpliableness of the superficies need not be considered, because so much as the ray is thereby bent in passing to the most tenacious and rigid part of the superficies, so much it is thereby unbent again in passing on from thence through the next parts gradually less tenacious.*

Thus may rays be refracted by some superficies, and reflected by others, be the medium they tend into, denser or rarer. But it remains further to be explained, how rays alike incident on the same superficies (suppose of crystal, glass, or water) may be at the same time some refracted, others reflected. And for explaining this, I suppose, that the rays, when they impinge on the rigid resisting aethereal 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 aether in that physical superficies. For it is plain by the heat, which light produces in bodies, that it is able to put their parts in motion, and much more to heat and put in motion the more tender aether; and it is more probable, that it communicates motion to the gross parts of bodies by the mediation of aether than immediately; as for instance, in the inward parts of quicksilver, tin, silver, and other very opake bodies, by generating vibrations, that run through them, than by striking the outward parts only, without entering the body. The shock of every single ray may generate many thousand vibrations, and by sending them all over the body, move all the parts, and that perhaps with more motion than it could move one single part by an immediate stroke; for the vibrations, by shaking each particle backward and forward, may every time increase *its motion, as a ringer does a bell by often pulling it, and so at length move the particles to a very great degree of agitation, which neither the simple shock of a ray, nor any other motion in the aether, besides a vibrating one could do. Thus in air shut up in a vessel, the motion of its parts caused by heat, how violent soever, is unable to move the bodies hung in it, with either a trembling or progressive motion: but if air be put into a vibrating motion by beating a drum or two, it shakes glass-windows, the whole body of a man, and other massy things, especially those of a congruous tone: yea I have observed it manifestly shake under my feet a cellared free-stone floor of a large hall, so as, I believe, the immediate stroke of five hundred drumsticks could not have done, unless perhaps quickly succeeding one another at equal intervals of time. Aethereal vibrations are therefore the best means by which such a subtile agent as light can shake the gross particles of solid bodies to heat them: and so supposing that light, impinging on a refracting or reflecting aethereal 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 aether 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.*

These may be the causes of refractions and reflections in all cases; but, for understanding how they come to be so regular, it is further to be considered, that in a heap of sand, although the surface be rugged, yet if water be poured on it to fill its pores, the water, so soon as its pores are filled, will evenly overspread the surface, and so much the more evenly, as the sand is finer: so, although the surface of all bodies, even the most polished, be rugged, as I conceive, yet where that ruggedness is not too gross and coarse, the refracting aethereal superficies may evenly overspread it. In polishing glass or metal, it is not to be imagined, that sand, putty, or other fretting powders, should wear the surface so regularly, as to make the front of every particle exactly plain, and all those plains look the same way, as they ought to do in well polished bodies, were reflection performed by their parts: but that those fretting powders should wear the bodies first to a coarse ruggedness, such is sensible, and then to a finer and finer ruggedness, till it be so fine that the aethereal superficies evenly overspreads it, and so makes the body put on the appearance of a polish, is a very natural and intelligible supposition. So in fluids, it is not well to be conceived, that the surfaces of their parts should be all plain, and the plains of the superficial parts always kept looking all the same way, notwithstanding that they are in perpetual motion. And yet without these two suppositions, the superficies of fluids could not be so regularly reflexive as they are, were the reflexion done by the parts themselves, and not by an aethereal superficies evenly overspreading the fluid.

Further, concerning the regular motion of light, it might be suspected, whether the various vibrations of the fluid, through which it passes, may not much disturb it: but that suspicion, I suppose, will vanish, by considering, that if at any time the foremost part of an oblique wave begin to turn it awry, the hindermost part, by a contrary action, must soon set it straight again.

Lastly, because without doubt there are, in every transparent body, pores of various sizes, and I said, that aether stands at the greatest rarity in the smallest pores; hence the aether in every pore should be of a differing rarity, and so light be refracted in its passage out of every pore into the next, which would cause a great confusion, and spoil the body's transparency. But considering that the aether, in all dense bodies, is agitated by continual vibrations, and these vibrations cannot be performed without forcing the parts of aether forward and backward, from one pore to another, by a kind of tremor, so that the aether, which one moment is in a greater pore, is the next moment forced into a less; and on the contrary, this must evenly spread the aether into all the pores not exceeding some certain bigness, suppose the breadth of a vibration, and so make it of an even density throughout the transparent body, agreeable to the middle sort of pores. But where the pores exceed a certain bigness, I suppose the aether suits its density to the bigness of the pore, or to the medium within it; and so being of a diverse density from the aether that surrounds it, refracts or reflects light in its superficies, and so make the body, where many such interstices are, appear opake."

from I Newton, "*Hypothesis explaining the properties of light*"
(1675, paper read before the Royal Society)
Published in: Thomas Birch, The History of the Royal Society, vol. 3 (London: 1757), pp. 247-305.

The two key ideas that are being discussed here are that (i) the variation of aetherial density between different objects will allow one to explain the diverse aspects of light propagation; and (ii) that the interaction between light corpuscles and wave in the aether will also explain a numebr of interesting phenomena which are observed in Nature. Newton begins by noting how difficult it is to force two solid bodies together, and infers from this that light will have great difficulty getting into the narrow speaces between nearby bodies, or into thin films, where he argues that the aether will be more rigid. This leads him to an important question, viz., how is it possble for light particles to be both reflected and refracted from the interface between two different material media? We saw that Huyghens gave a very natural explanation of this in terms of wave propagation. Newton argues that there will be surface waves in the interface, excited by the passage of the light particles (and that indeed these waves will also propagate into the two surrounding media). He further argues that this process would be what we would now call a 'resonant coupling', ie., that the particles excite the interface waves periodically in time, so that the amplitude of the oscillations increases with time to very large values (as in the excitation of a child's swing when regularly pushed). The picture he then wants us to believe is that when the interface is strongly compressed by these oscillations, the aether becomes rigid, so that light particles may not pass and are thus reflected from the interface; whereas in a 'rarefraction' of the interface (ie., that part of the oscillation in which the density is low) the light particles pass easily through, so we see a refracted ray.

Needless to say, no details are given of how it is that the angle of the refracted ray takes a unique value (the most natural assumption would be that the surface oscillations would scatter the light corpuscles in a whole range of directions, but Newton is having none of this - he simply wants them to behave as a kind of gate-keeper, either letting them through in one single direction, or reflecting them back in one single direction). The discussion is noteworthy for one other thing, viz., Newton's idea that very fast-moving waves in the aether, caused by light corpuscles, could actually propagate influences very rapidly between differetn parts of a material body - indeed he states that quite generally, the aether and waves in it are the most efficient way of transporting interactions between light corpuscles and matter. Thus he saw the aether as the main intermediary between light corpuscles and matter.

One utterly obvious question that one can ask at this point is how it is that matter is then able to move without hindrance through the aether (in, eg., empty space), or vice-versa. It is rather astonishing that Newton, author of his '3rd law' of particle dynamics (according to which every force must be accompanied by an equal and opposite reactive force), does not address this question here. He does address it in the *Opticks*, and so we will return to this topic again in the next sub-section.

The rest of the passage above is concerned with the explanation of how it is that light can pass in a completely regular way through a medium like glass, even though it is obvious that the density of the glass must vary quite radically at the microscopic scale, in the same way that the density of an object made of fine sand particles varies very strongly at the scale of the sand particles (with small gaps and 'pores' between the sand particles), whereas the density on a much larger 'coarse-grained' scale is quite uniform. Newton's rather vague argument is that, even though the aether must be highly inhomogeneous at this micoscopic scale, nevertheless vibrations of the aether will smooth everything out, and make rays propagate in straight lines without lots of internal reflection.

Newton wrote a number of papers on optics and light in this intermediate period. However almost none of this work appeared beyond the confines of the Royal Society, and eventually he turned his attetion to other things. It was not until much later that he returned to the subject, and then it was with the publication of his major work, the *Opticks*, in 1704. We are then dealing with a Newton at the height of his scientific fame, with a very large reputation both in England and on the continent.

3(c) The IDEAS in the "OPTICKS"

With the death of Hooke, Newton felt that it was time to summarize all of the work he had done on optics and light, into the second book he published in his career. This book was of a very different kind from the *Principia*. The latter was very much concerned with the development of a real theory, with a set of well-defined principles and a lengthy development of their empirical consequences. Thus, although Newtons spent a lot of time on astronomical and tidal observations in the *Principia*, his main task was the development of the theory. On the other hand in the *Opticks* he was much more concerned with the experimental observations he had made, and with a systematic exposition of these. Only at certain points in the book, and then at the end in his 'Queries', does he allow himself to give a more general discussion of what he thinks is actually going on.

There seems little doubt that the main reason for this reticence on Newton's part is that he knew that he did not have a good theory of light, and that much of what he did know could only be fit together into a rather incoherent set of speculations, which he was unable to substantiate. What was then left was the large corpus of experimental investigations, and his main purpose in the *Opticks* was to give a good account of these. In what follows we will pass over the elaborate and rather technical discussion he gives of all these experiments, pausing only briefly to look at his work on 'Newton's rings'. We then go immediately to the discussion at the end of the work, where Newton posits a long series of 'Queries', in which he again allows himself to speculate on the causes of light, and indeed on diverse other topics.

(i) Experiments on "Newton's Rings": The most interesting parts of the *Opticks*, from a modern point of view, are the discussions of diffraction and of the "Newton's Rings' phenomenon. Diffraction was important to Newton, and he investigated it in some detail, and yet he never deduced the wave-like nature of light propagation from his studies. Why this is something of a mystery, and we shall leave it as such in these notes.

Even more interesting was the pattern of light which he found to exist when light was passed through an arrangement in which a transparent glass plate with a flat surface was brought into contact with a curved concave lens. The precise shape of the lans is not crucial, because what matters is that it curve away from the point of contact with the flat glass plate in a parabolic fashion, and this will be true of almost any curved lens if one is sufficiently close to the point of contact. The parabolicity of the shape near the point of contact means that the distance y separating the glass plate from the lens is proportional to the square of the distance x one is from the point of contact, ie., $y \sim x^2$.

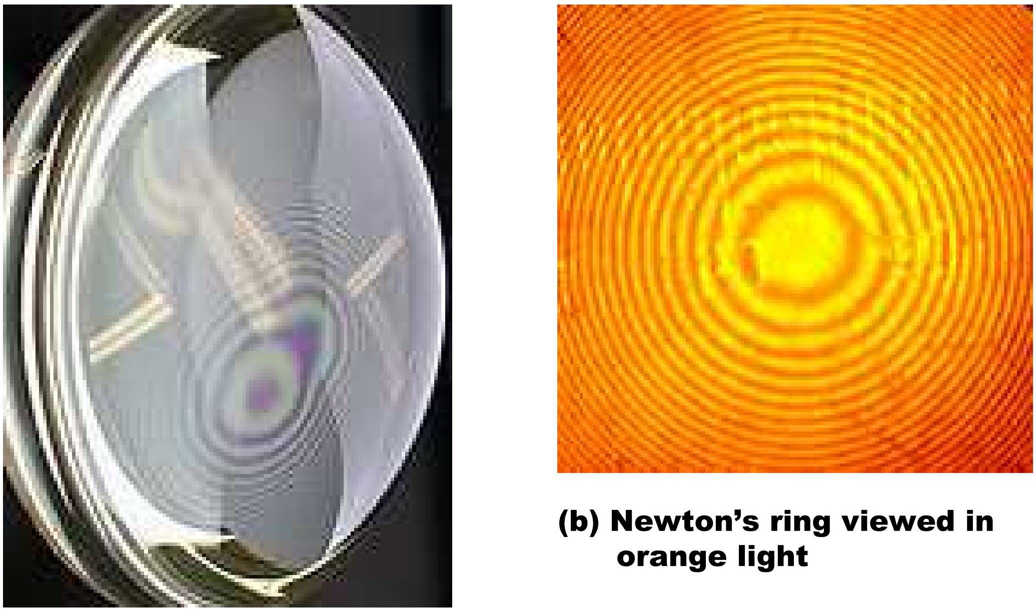


FIG. 4: Photographs of Newton's rings. In (a) we see the pattern of light from a convex lens, held against a flat glass plate, in sunlight. In (b) the same arragement is illuminated by a monochrome orange light, and we see the pattern of light transmitted through the lens. For further description see the text.

What one then observes is perhaps not surprising to most people, who will have noticed the coloured patterns in, eg., oil slicks on the road, soap bubbles, or in other transparent objects that are very thin. A pattern of coloured rings separated by darker regions is seen - in the vicinity of the point of contact of the plate and the lens, one sees a dark roughly circular region, surrounded by the rings; and as one moves away from the point of contact, the rings are more and more closely spaced. In Figure 4(a) we see this pattern for white light - the light we see has been transmitted through from the other side of the lens arrangement. What happens if light of a single colour is then shone through the arrangement is shown in Fig. 4(b), where light of a single colour is shone through the same arrangement. Then the rings become much clearer, and one sees that the regions between the rings are really very dark.

It was already obvious to workers at the time of Newton that these patterns were related to the iridescent colours often seen in Nature - one example that particularly excited the interest of people at that time was that of peacock feathers, and Newton also spent some time investigating soap bubbles. It was clear that the colours were related to the existence of refractive interfaces that were very close to each other (as in thin films). Newton had the great advantage over most other scientists at the time of having done extensive experiments on colour, and his elucidation of the spectrum of light, and his success in separatng off single colours, easily allowed him to repeat the experiemnts with single colours (which allowed him to discover that individual colours were associated with particular lengths - what we now know to be the wavelengths of different colors).

It is interesting to see how Newton described his observations - the way in which he 'unfolded' the details is actually a model of reporting of experimental observation. We have no space here to recount all of this, but some excerpts make it clear. We begin with the discussion of the phenomenon itself, for the reflection of white light from the system:

"*Next to the pellucid central Spot made by the contact of the Glasses succeeded blue, white, yellow, and red. The* *blue was so little in quantity, that I could not discern it in the Circles made by the Prisms, nor could I well distinguish any violet in it, but the yellow and red were pretty copious, and seemed about as much in extent as the white, and four or five times more than the blue. The next Circuit in order of Colours immediately encompassing these were violet, blue, green, yellow, and red: and these were all of them copious and vivid, excepting the green, which was very little in quantity, and seemed much more faint and dilute than the other Colours. Of the other four, the violet was the least in extent, and the blue less than the yellow or red. The third Circuit or Order was purple, blue, green, yellow, and red; in which the purple seemed more reddish than the violet in the former Circuit, and the green was much more conspicuous, being as brisk and copious as any of the other Colours, except the yellow, but the red began to be a little faded, inclining very much to purple. After this succeeded the fourth Circuit of green and red. The green was very copious and lively, inclining on the one side to blue, and on the other side to yellow. But in this fourth Circuit there was neither violet, blue, nor yellow, and the red was very imperfect and dirty. Also the succeeding Colours became more and more imperfect and dilute, till after three or four revolutions they ended in perfect whiteness.*"

from I. Newton, *Opticks*, 2nd book, Part I

From these and subsequent observations the obvious next step is to try and quantify the size of the rings. His first remark on this topic is a little technical, and illustrates his immediate understanding of the geometric content of the observations:

"*And from these Measures I seem to gather this Rule: That the Thickness of the Air is proportional to the Secant of an Angle, whose Sine is a certain mean Proportional between the Sines of Incidence and Refraction. And that mean Proportional, so far as by these Measures I can determine it, is the first of an hundred and six arithmetical mean Proportionals between those Sines counted from the bigger Sine, that is, from the Sine of Refraction when the Refraction is made out of the Glass into the Plate of Air, or from the Sine of Incidence when the Refraction is made out of the Plate of Air into the Glass.*"

from I. Newton, *Opticks*, 2nd book, Part I

Now since Newton had himself elucidated the spectral characteristics of white light, the obvious next step was to use light of a single colour in the experiments. This circumvented the problem mentioned above by him, viz., that the different colours all mixed together as one went to higher and higher rings. In his own words:

"Obs. 12. *These Observations were made in the open Air. But farther to examine the Effects of colour'd Light falling on the Glasses, I darken'd the Room, and view'd them by Reflexion of the Colours of a Prism cast on a Sheet of white Paper, my Eye being so placed that I could see the colour'd Paper by Reflexion in the Glasses, as in a Looking-glass. And by this means the Rings became distincter and visible to a far greater number than in the open Air. I have sometimes seen more than twenty of them, whereas in the open Air I could not discern above eight or nine.....*"

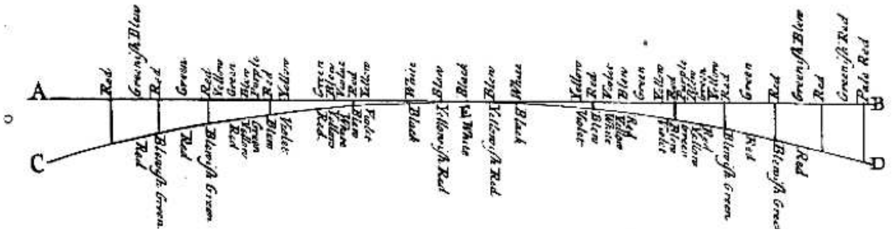
"*.......Obs. 16. The Squares of the Diameters of these Rings made by any prismatick Colour were in arithmetical Progression, as in the fifth Observation. And the Diameter of the sixth Circle, when made by the citrine yellow, and viewed almost perpendicularly was about 58/100 parts of an Inch, or a little less, agreeable to the sixth Observation.*"

from I. Newton, *Opticks*, 2nd book, Part I

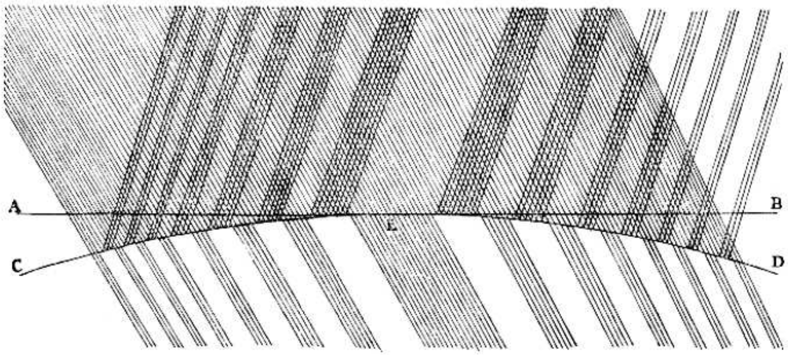
Here was the key, if Newton had only realized, to the whole business. The first extract above, what Newton called "Observation 12", was simply the result shown in Fig. 4(b) above, viz., the clear observtion of a large number of distinct rings in monochromatic light. The second extract, of very great importance, describes how the size of these rings follows a strict rule, which in modern language we can express by saying that $R_n^2 = \lambda x$, where R_n is the radius of the n-th ring, and x is the distance from the centre of the ring pattern. The constant λ is a length, and we now know it is simply the wavelength of the light.

Newton immediately realized that this simple formula was connected to the separation y between the lens and the glass plate - in fact, that the number of rings was simply proportional to this, so that one had the crucial result that $2y = N\lambda$, ie., that the distance between the two pieces of glass, at a point P at some distance from the point of contact, was proportional to the number of rings that one would count, going out from the point of contact to the point P .

The question then was - how to interpret this result? What it basically was saying was that bright rings would appear whenever the distance between the lens and the plate was given by an integral multiple of the basic length λ that was associated with the light ray. That this length λ varied with the colour of the light was obvious - it was larger for red light than for green, and large for green than for blue. Newton composed a map of the different lengths associated with different colours (see Fig. 5(a)), and also tabulated the lengths extensively in his book.



(a) Colours observed by Newton in his rings



(b) Pattern of refractions & reflections hypothesized by Newton

FIG. 5: The experimental results reported by Newton on his 'rings'. A flat glass plate is places on top of a curved lens (of roughly spherical shape). Figure (a) shows the pattern of rings and their colours that Newton observed. Fig. (b) shows the pattern of reflected and refracted light that he inferred from this. For further description see the text.

This and other experiments led Newton, in the first instance, to the idea that what was occuring here was a set of multiple reflections and refractions in the system. A light ray coming in through the flat plate could be both reflected back where it came from off the surface of the plate, or go through the surface and strike the lens. When it arrived at the surface of the lens, it could also be reflected back, or simply continue on through into the lens. If it was reflected back, it faced the choice of either passing back through the plate surface to its origin, or being reflected for yet a third time towards the lens again. And so this process can be iterated: the light ray can be reflected over and over again, so that both the final transmitted ray, eventually emerging from the opposite side of the lens, and the reflected ray, emerging from the glass plate in the direction from which it had originally come, were really the sum of multiple reflections inside the system, between the plate end the lens, as well as a simple transmitted ray which propagated through the system without any reflection at all. His construction of this is shown in Fig. 5(b), and his explanation of what is going on is as follows:

"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.

This is manifest by the 5th, 9th, 12th, and 15th Observations. For by those Observations it appears, that one and the same sort of Rays at equal Angles of Incidence on any thin transparent Plate, is alternately reflected and transmitted for many Successions accordingly as the thickness of the Plate increases in arithmetical Progression of the Numbers, 0, 1, 2, 3, 4, 5, 6, 7, 8, etc., so that if the first Reflexion (that which makes the first or innermost of the Rings of Colours there described) be made at the thickness 1, the Rays shall be transmitted at the thicknesses 0, 2, 4, 6, 8, 10, 12, etc. and thereby make the central Spot and Rings of Light, which appear by transmission, and be reflected at the thickness 1, 3, 5, 7, 9, 11, etc., and thereby make the Rings which appear by Reflexion. And this alternate Reflexion and Transmission, as I gather by the 24th Observation, continues for above an hundred vicissitudes, and by the Observations in the next part of this Book, for many thousands, being propagated from one Surface of a Glass Plate to the other, though the thickness of the Plate be a quarter of an Inch or above: So that this alternation seems *to be propagated from every refracting Surface to all distances without end or limitation*

This alternate Reflexion and Refraction depends on both the Surfaces of every thin Plate, because it depends on their distance. By the 21st Observation, if either Surface of a thin Plate of Muscovy Glass be wetted, the Colours caused by the alternate Reflexion and Refraction grow faint, and therefore it depends on them both. It is therefore perform'd at the second Surface; for if it were perform'd at the first, before the Rays arrive at the second, it would not depend on the second.

It is also influenced by some action or disposition, propagated from the first to the second, because otherwise at the second it would not depend on the first. And this action or disposition, in its propagation, intermits and returns by equal Intervals, because in all its progress it inclines the Ray at one distance from the first Surface to be reflected by the second, at another to be transmitted by it, and that by equal Intervals for innumerable vicissitudes.

.......What kind of action or disposition this is; Whether it consists in a circulating or a vibrating motion of the Ray, or of the Medium, or something else, I do not here enquire. Those that are averse from assenting 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 or reflecting 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 or reflecting 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 impedes 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."

from I. Newton, *Opticks*, 2nd book, part III

The first part of the above passage (which occurs as part of 'Proposition 12" of the 3rd part of Book 2 of the *Opticks* is essentially a description of how Newton saw the physical process of refelction and refraction from a surface. Curiously, he did not see the successive reflections as independet of each other, as would be the case if light was a simple set of particles: in his opinion there had to be some sort of physical connection between these, some kind of 'action or disposition', which made successive reflections dependent on each other. But what could this connection be?

Yet again Newton surprises us in his answer. One might have guessed, given that he was opposed to the use of a wave theory of light, that he would have then resorted to waves through the aether to explain the remarkable rule that he had discovered. For there is no question that a wave theory gives an extremely natural explanation of these observations. If one assumes that the length λ is just the wavelength of the wave, then one can explain the bright rings by noting the waves reflected back from the lens, and then reflected again forward from the plate, will have to travel an extra distance $2y$ (ie., twice the distance between lens and plate) as compared to a light ray which simply travels through without any reflection. If light is a wave, this simply mean that the waves will add together if $2y = \lambda$, or more generally if $2y = N\lambda$, where N is an integer (what is called 'constructive interference'), and we will see a bright ring. On the other hand, if $2y = \lambda/2$, or more generally if $2y = (N + 1/2)\lambda$, then a 'crest' in one wave will meet a 'trough' from the other, and they will cancel (ie., 'destructive interference'), so that almost no light comes through (a dark ring).

However Newton, astonishingly, does not resort to waves through the aether, but rather to waves through the solid body, to explain the observation! He was willing to concede that waves were involved - this much was pretty well forced upon him - but he was absolutely unwilling to give up his idea that light itself had to be particle-like. And, for reasons which are completely unclear, he wanted to have ordinary waves through the material medium to be responsible for the interference, rather than waves through the aether.

(ii) Fundamental Mechanisms - the 'Queries': So far so good. We have seen that Newton had arrived at a picture of light and the aether in which light was a set of particles which travelled through space extremely fast, motivated by some force, and interacting with the background aether, so that they traveled at a finite but very high velocity. The aether itself was everywhere, including in the vacuum, but its density was not uniform - it was at its highest density in the vacuum, and at its lowest in solid bodies, and in the very small spaces or 'pores' between solid bodies. The aether, being a continuous medium, could support wave-like disturbances, which would propagate through it - since the aether was supposed to be a stiff medium, almost incompressible, these waves moved very fast.

The question of how fast they propagated, and along which directions, was hardly discussed by Newton. Light, on the other hand, interacted with the aether in such a way that it was accelerated towards regions of lower density. This meant that it inevitably moved faster in dense material bodies, where the aetherial density was lowest.

This was the basis of his picture, and it was a rather complicated system, as he himself realized. Waves could not only move through the aether, but also through material bodies, and both of these could in principle interact with each other and also with the light particles. Newton would no doubt have been capable of carrying through a rather detailed analysis of the behaviour of these coupled systems if he had wanted to - after all, one was dealing with a set of particles and media interacting with each other, and so the problems posed were no different in principle from those he had addressed in the *Principia*. However he chose not to, and there seems little doubt that this was partly because he could see for himself how precarious was the picture he was advocating. Thus in the main body of the *Opticks*, he largely confines himself to discussion of experiments and the immediate deductions and inferences one can make from these.

Curiously, however, he could not restrain himself at the end of the book from trying to give a more detailed understanding of the underlying mechanisms involved in his basic picture. And so finally he tries to give a systematic expoiositon of this. However, it is done is a very peculiar fashion. Instead of the logico-deductive style of axioms and propositions that he had always used before, he developed his ideas in the form of a series of 'Queries', in which the answer was left open. The style is not altogether straightforward, since may of the questions are put in dogmatic style. Leaving aside the early Queries, let us go straight to those which lay out his theoretical picture. Since the key role is played by the aether, he spends some time redeveloping the picture we have already seen:

"Qu. 18: *If in two large tall cylindrical Vessels of Glass inverted, two little Thermometers be suspended so as not to touch the Vessels, and the Air be drawn out of one of these Vessels, and these Vessels thus prepared be carried out of a cold place into a warm one; the Thermometer in vacuo will grow warm as much, and almost as soon as the Thermometer which is not in vacuo. And when the Vessels are carried back into the cold place, the Thermometer in vacuo will grow cold almost as soon as the other Thermometer. Is not the Heat of the warm Room convey'd through the Vacuum by the Vibrations of a much subtiler Medium than Air, which after the Air was drawn out remained in the Vacuum? And is not this Medium the same with that Medium by which Light is refracted and reflected, and by whose Vibrations Light communicates Heat to Bodies, and is put into Fits of easy Reflexion and easy Transmission? And do not the Vibrations of this Medium in hot Bodies contribute to the intenseness and duration of their Heat? And do not hot Bodies communicate their Heat to contiguous cold ones, by the Vibrations of this Medium propagated from them into the cold ones? And is not this Medium exceedingly more rare and subtile than the Air, and exceedingly more elastick and active? And doth it not readily pervade all Bodies? And is it not (by its elastick force) expanded through all the Heavens?*"

"Qu. 19: *Doth not the Refraction of Light proceed from the different density of this thereal Medium in different places, the Light receding always from the denser parts of the Medium? And is not the density thereof greater in free and open Spaces void of Air and other grosser Bodies, than within the Pores of Water, Glass, Crystal, Gems, and other compact Bodies? For when Light passes through Glass or Crystal, and falling very obliquely upon the farther Surface thereof is totally reflected, the total Reflexion ought to proceed rather from the density and vigour of the Medium without and beyond the Glass, than from the rarity and weakness thereof.*"

"Qu. 20: *Doth not this Aethereal Medium in passing out of Water, Glass, Crystal, and other compact and dense Bodies into empty Spaces, grow denser and denser by degrees, and by that means refract the Rays of Light not in a point, but by bending them gradually in curve Lines? And doth not the gradual condensation of this Medium extend to some distance from the Bodies, and thereby cause the Inflexions of the Rays of Light, which pass by the edges of dense Bodies, at some distance from the Bodies?*"

from I. Newton, the "*Opticks*", 3rd Book.

Much of this we have seen already. Note that he is now adding the supposition that the aetherial density does not abruptly change when one passes suddenly between two material media across an interface - instead this is supposed to happen gradually. The reason Newton introduces this idea is that he wished to explain what we now call diffraction of light, in which the light rays are deflected when passing through a narrow aperture or around a sharp edge.

However, not content with merely discussing the role of the aether in controlling light propagation, Newton yet again extends his discussion to the motion of planets and other heavenly bodies, and eventually to electrical and magnetic phenomena, and to the human body:

"Qu. 21: *Is not this Medium much rarer within the dense Bodies of the Sun, Stars, Planets and Comets, than in the empty celestial Spaces between them? And in passing from them to great distances, doth it not grow denser and denser perpetually, and thereby cause the gravity of those great Bodies towards one another, and of their parts towards the*

Bodies; every Body endeavouring to go from the denser parts of the Medium towards the rarer? For if this Medium be rarer within the Sun's Body than at its Surface, and rarer there than at the hundredth part of an Inch from its Body, and rarer there than at the fiftieth part of an Inch from its Body, and rarer there than at the Orb of Saturn; I see no reason why the Increase of density should stop any where, and not rather be continued through all distances from the Sun to Saturn, and beyond. And though this Increase of density may at great distances be exceeding slow, yet if the elastick force of this Medium be exceeding great, it may suffice to impel Bodies from the denser parts of the Medium towards the rarer, with all that power which we call Gravity.

And that the elastick force of this Medium is exceeding great, may be gather'd from the swiftness of its Vibrations. Sounds move about 1140 English Feet in a second Minute of Time, and in seven or eight Minutes of Time they move about one hundred English Miles. Light moves from the Sun to us in about seven or eight Minutes of Time, which distance is about 70,000,000 English Miles, supposing the horizontal Parallax of the Sun to be about 12. And the Vibrations or Pulses of this Medium, that they may cause the alternate Fits of easy Transmission and easy Reflexion, must be swifter than Light, and by consequence above 700,000 times swifter than Sounds. And therefore the elastick force of this Medium, in proportion to its density, must be above 700000 x 700000 (that is, above 490,000,000,000) times greater than the elastick force of the Air is in proportion to its density. For the Velocities of the Pulses of elastick Mediums are in a subduplicate Ratio of the Elasticities and the Rarities of the Mediums taken together. As Attraction is stronger in small Magnets than in great ones in proportion to their Bulk, and Gravity is greater in the Surfaces of small Planets than in those of great ones in proportion to their bulk, and small Bodies are agitated much more by electric attraction than great ones; so the smallness of the Rays of Light may contribute very much to the power of the Agent by which they are refracted. And so if any one should suppose that Aether (like our Air) may contain Particles which endeavour to recede from one another (for I do not know what this Aether is) and that its Particles are exceedingly smaller than those of Air, or even than those of Light: The exceeding smallness of its Particles may contribute to the greatness of the force by which those Particles may recede from one another, and thereby make that Medium exceedingly more rare and elastick than Air, and by consequence exceedingly less able to resist the motions of Projectiles, and exceedingly more able to press upon gross Bodies, by endeavouring to expand it self."

"Qu. 22: *May not Planets and Comets, and all gross Bodies, perform their Motions more freely, and with less resistance in this Aethereal Medium than in any Fluid, which fills all Space adequately without leaving any Pores, and by consequence is much denser than Quick-silver or Gold? And may not its resistance be so small, as to be inconsiderable? For instance; If this Aether (for so I will call it) should be supposed 700000 times more elastick than our Air, and above 700000 times more rare; its resistance would be above 600,000,000 times less than that of Water. And so small a resistance would scarce make any sensible alteration in the Motions of the Planets in ten thousand Years. If any one would ask how a Medium can be so rare, let him tell me how the Air, in the upper parts of the Atmosphere, can be above an hundred thousand thousand times rarer than Gold. Let him also tell me, how an electrick Body can by Friction emit an Exhalation so rare and subtile, and yet so potent, as by its Emission to cause no sensible Diminution of the weight of the electrick Body, and to be expanded through a Sphere, whose Diameter is above two Feet, and yet to be able to agitate and carry up Leaf Copper, or Leaf Gold, at the distance of above a Foot from the electrick Body? And how the Effluvia of a Magnet can be so rare and subtile, as to pass through a Plate of Glass without any Resistance or Diminution of their Force, and yet so potent as to turn a magnetick Needle beyond the Glass?"*

"Qu. 23: *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.*

from I. Newton, the "*Opticks*", 3rd Book.

There are some fascinating speculations here. As we saw in the discussion of the debate between Newton and Leibniz, on the nature of the gravitational force, Newton was acutely aware of the difficulty with 'action at a distance', ie., with the idea that gravity could act through a vacuum. Now he is appealing to the aether as the medium though which graviational forces act. We see that the picture is getting very complex - for now the aether is playing a double role, both as the intermediary of very weak gravitational forces, and as the medium which guides light particles. Moreover it is supposed to interact with matter in mediating the interactions between light particles and matter. All of this is very confusing, particularly as he is also quite clear that the interaction between matter and the aether has to be very weak indeed - so weak that it in no way impedes the motion of massive planets through it. We are left wondering when Newton is going to *quantify* all of this, so that we can seehow big these forces are, and in what direction they act, etc., etc. But nowhere does he do this.

Indeed, not content with all this, Newton also wants the aether to play a role in mediating electrical and magnetic forces, and finally even to the senses of the human body. Again, we are left with no quantitative detail of any kind, except the remarks that indicate that the strength of electrical and magnetic forces is extremely large (at least compared to gravitational forces). All of this is extremely unsatisfactory.

And what of the wave theory of light, which Newton was by now very much aware of (Huyghens's book had been published 14 year before the *Opticks*)? This is discussed, and dispensed with, in a seies of later Queries, which are a little astonishing in their short-sightedness:

"Qu. 28: *Are not all Hypotheses erroneous, in which Light is supposed to consist in Pression or Motion, propagated through a fluid Medium? For in all these Hypotheses the Phaenomena of Light have been hitherto explain'd by supposing that they arise from new Modifications of the Rays; which is an erroneous Supposition.*

If Light consisted only in Pression propagated without actual Motion, it would not be able to agitate and heat the Bodies which refract and reflect it. If it consisted in Motion propagated to all distances in an instant, it would require an infinite force every moment, in every shining Particle, to generate that Motion. And if it consisted in Pression or Motion, propagated either in an instant or in time, it would bend into the Shadow. For Pression or Motion cannot be propagated in a Fluid in right Lines, beyond an Obstacle which stops part of the Motion, but will bend and spread every way into the quiescent Medium which lies beyond the Obstacle. Gravity tends downwards, but the Pressure of Water arising from Gravity tends every way with equal Force, and is propagated as readily, and with as much force sideways as downwards, and through crooked passages as through strait ones. The Waves on the Surface of stagnating Water, passing by the sides of a broad Obstacle which stops part of them, bend afterwards 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 streight ones. But Light is never known to follow crooked Passages nor to bend into the Shadow. For the fix'd Stars by the Interposition of any of the Planets cease to be seen. And so do the Parts of the Sun by the Interposition of the Moon, Mercury or Venus. The Rays which pass very near to the edges of any Body, are bent a little by the action of the Body, as we shew'd above; but this bending is not towards but from the Shadow, and is perform'd only in the passage of the Ray by the Body, and at a very small distance from it. So soon as the Ray is past the Body, it goes right on.

To explain the unusual Refraction of Island Crystal by Pression or Motion propagated, has not hitherto been attempted (to my knowledge) except by Huygens, who for that end supposed two several vibrating Mediums within that Crystal. But when he tried the Refractions in two successive pieces of that Crystal, and found them such as is mention'd above; he confessed himself at a loss for explaining them. For Pressions or Motions, propagated from a shining Body through an uniform Medium, must be on all sides alike; whereas by those Experiments it appears, that the Rays of Light have different Properties in their different Sides. He suspected that the Pulses of ther in passing through the first Crystal might receive certain new Modifications, which might determine them to be propagated in this or that Medium within the second Crystal, according to the Position of that Crystal. But what Modifications those might be he could not say, nor think of any thing satisfactory in that Point. And if he had known that the unusual Refraction depends not on new Modifications, but on the original and unchangeable Dispositions of the Rays, he would have found it as difficult to explain how those Dispositions which he supposed to be impress'd on the Rays by the first Crystal, could be in them before their Incidence on that Crystal, and in general, how all Rays emitted by shining Bodies, can have those Dispositions in them from the beginning. To me, at least, this seems inexplicable, if Light be nothing else than Pression or Motion propagated through Aether.

And it is as difficult to explain by these Hypotheses, how Rays can be alternately in Fits of easy Reflexion and easy Transmission; unless perhaps one might suppose that there are in all Space two Aethereal vibrating Mediums, and that the Vibrations of one of them constitute Light, and the Vibrations of the other are swifter, and as often as they overtake the Vibrations of the first, put them into those Fits. But how two Aethers can be diffused through all Space, one of which acts upon the other, and by consequence is re-acted upon, without retarding, shattering, dispersing and confounding one anothers Motions, is inconceivable. And against filling the Heavens with fluid Mediums, unless they be exceeding rare, a great Objection arises from the regular and very lasting Motions of the Planets and Comets in all manner of Courses through the Heavens. For thence it is manifest, that the Heavens are void of all sensible Resistance, and by consequence of all sensible Matter."

from I. Newton, the "*Opticks*", 3rd Book.

The first part of this passage simply repeats the objection that waves in a medium would be diffracted around corners, and that this is not observed with light except through very small angles. It is very surprising that Newton, who knew how short the wavelengths would have to be if light was indeed a wave disturbance (he had measured the lengthscales in his experiments on Newton's rings), did not see immediately see that very short wavelength waves would necessarily be deflected through very small angles.

The second part of his objection to waves, explicitly directed against the Huyghens theory, is that it cannot fully explain birefringence in Iceland Spar. Newton notes that Huyghens had hypothesized two media, through which light travelled at different velocities, and that this led him to problems in explaining all the features of the light propagation through Iceland Spar. Newton then gives his fundamental objection to the idea of two different aethers - that they would act upon each other in a completely disruptive way, so that one would lose all the properties one wished of an aether. He further adds that if one had several aethers, the heavenly bodies would no longer be able to move freely through a vacuum.

These objections seem rather cavalier to us. One wonders if Newton would have made them so easily if either Huyghens or Hooke had been alive. For the obvious objection to his remarks is that his own ideas are equally susceptible to the same criticisms. He has two media which interact with each other (the aether and the material world), and which moreover each interact with light particles, which are themselves subject to another force which drives them. Why then is there no disruption here of the properties of the aether? And why is it that material objects can move freely through a vacuum, given these various interactions?

One is left feeling disappointed that Newton had not taken the Huyghens theory more seriously. For the idea of two different velocities of propagation for light was indeed the key to understanding birefringence - and if Newton had taken it and the wave theory more seriously, there is every chance he might have ended up hypothesizing the existence of two kinds of oscillation in the aether - a step which Huyghens also failed to make.

(iii) Final Reflections: Newtonian Credo and Methodology: It is exceedingly interesting to ask what fundamental set of core beliefs lay behind all of Newton's work on optics and light (and indeed his work in all the other spheres in which he speculated). The last paragraphs of the *Opticks* were essentially Newton's last words on the whole body of his work, summarizing both his general beliefs on the nature and construction of the world, and on how one should best approach this world in an attempt to understand it. This was not the first time that Newton had unburdened himself on these topics (he had liberally sprinkled the *Principia* with similar reflections); but it was perhaps the most forthright of his attempts, and he never went back on it (merely contenting himself in later years with slight revisions).

Let us first look at his general beliefs, which as we might expect for the time in which he lived, amalgamated both religious and scientific ideas:

"*All these things being consider'd, it seems probable to me, that God in the Beginning form'd Matter in solid, massy, hard, impenetrable, moveable Particles, of such Sizes and Figures, and with such other Properties, and in such Proportion to Space, as most conduced to the End for which he form'd them; and that these primitive Particles being Solids, are incomparably harder than any porous Bodies compounded of them; even so very hard, as never to wear or break in pieces; no ordinary Power being able to divide what God himself made one in the first Creation. While the Particles continue entire, they may compose Bodies of one and the same Nature and Texture in all Ages: But should they wear away, or break in pieces, the Nature of Things depending on them, would be changed. Water and Earth, composed of old worn Particles and Fragments of Particles, would not be of the same Nature and Texture now, with Water and Earth composed of entire Particles in the Beginning. And therefore, that Nature may be lasting, the Changes of corporeal Things are to be placed only in the various Separations and new Associations and Motions of these permanent Particles; compound Bodies being apt to break, not in the midst of solid Particles, but where those Particles are laid together, and only touch in a few Points.*

It seems to me farther, that these Particles have not only a Vis inertiae, *accompanied with such passive Laws of Motion as naturally result from that Force, but also that they are moved by certain active Principles, such as is that of Gravity, and that which causes Fermentation, and the Cohesion of Bodies. These Principles I consider, not as occult Qualities, supposed to result from the specifick Forms of Things, but as general Laws of Nature, by which the Things themselves are form'd; their Truth appearing to us by Phnomena, though their Causes be not yet discover'd. For these are manifest Qualities, and their Causes only are occult. And the Aristotelians gave the Name of occult Qualities, not to manifest Qualities, but to such Qualities only as they supposed to lie hid in Bodies, and to be the unknown Causes of manifest Effects: Such as would be the Causes of Gravity, and of magnetick and electrick Attractions, and of Fermentations, if we should suppose that these Forces or Actions arose from Qualities unknown to us, and uncapable of being discovered and made manifest. Such occult Qualities put a stop to the Improvement of natural Philosophy, and therefore of late Years have been rejected. To tell us that every Species of Things is endow'd with an occult specifick Quality by which it acts and produces manifest Effects, is to tell us nothing: But to derive two or three general Principles of Motion from Phaenomena, and afterwards to tell us how the Properties and Actions of all corporeal Things follow from those manifest Principles, would be a very great step in Philosophy, though the Causes of those Principles were not yet discover'd: And therefore I scruple not to propose the Principles of Motion* *above-mention'd, they being of very general Extent, and leave their Causes to be found out.*

Now by the help of these Principles, all material Things seem to have been composed of the hard and solid Particles above-mention'd, variously associated in the first Creation by the Counsel of an intelligent Agent. For it became him who created them to set them in order. And if he did so, it's unphilosophical to seek for any other Origin of the World, or to pretend that it might arise out of a Chaos by the mere Laws of Nature; though being once form'd, it may continue by those Laws for many Ages. For while Comets move in very excentrick Orbs in all manner of Positions, blind Fate could never make all the Planets move one and the same way in Orbs concentrick, some inconsiderable Irregularities excepted, which may have risen from the mutual Actions of Comets and Planets upon one another, and which will be apt to increase, till this System wants a Reformation. Such a wonderful Uniformity in the Planetary System must be allowed the Effect of Choice. And so must the Uniformity in the Bodies of Animals, they having generally a right and a left side shaped alike, and on either side of their Bodies two Legs behind, and either two Arms, or two Legs, or two Wings before upon their Shoulders, and between their Shoulders a Neck running down into a Back-bone, and a Head upon it; and in the Head two Ears, two Eyes, a Nose, a Mouth, and a Tongue, alike situated. Also the first Contrivance of those very artificial Parts of Animals, the Eyes, Ears, Brain, Muscles, Heart, Lungs, Midriff, Glands, Larynx, Hands, Wings, swimming Bladders, natural Spectacles, and other Organs of Sense and Motion; and the Instinct of Brutes and Insects, can be the effect of nothing else than the Wisdom and Skill of a powerful ever-living Agent, who being in all Places, is more able by his Will to move the Bodies within his boundless uniform Sensorium, and thereby to form and reform the Parts of the Universe, than we are by our Will to move the Parts of our own Bodies. And yet we are not to consider the World as the Body of God, or the several Parts thereof, as the Parts of God. He is an uniform Being, void of Organs, Members or Parts, and they are his Creatures subordinate to him, and subservient to his Will; and he is no more the Soul of them, than the Soul of Man is the Soul of the Species of Things carried through the Organs of Sense into the place of its Sensation, where it perceives them by means of its immediate Presence, without the Intervention of any third thing. The Organs of Sense are not for enabling the Soul to perceive the Species of Things in its Sensorium, but only for conveying them thither; and God has no need of such Organs, he being every where present to the Things themselves. And since Space is divisible in infinitum, and Matter is not necessarily in all places, it may be also allow'd that God is able to create Particles of Matter of several Sizes and Figures, and in several Proportions to Space, and perhaps of different Densities and Forces, and thereby to vary the Laws of Nature, and make Worlds of several sorts in several Parts of the Universe. At least, I see nothing of Contradiction in all this."

In modern terms, we see that Newton is advocating a philosophy of 'intelligent design'. There was of course nothing new about this - and Newton was by the standards of any time a sophisticated scholar of biblical history, and aware of the many arguments that had been used over the years to argue for the existence of an intelligent designer (notably those of Aquinas). We note also that Newton, as in so many things, followed the ideas of his British contemporaries like Locke, and earlier writers like Bacon, in condemning the Aristotelian mathod of investing 'occult qualities' in objects. By this he simply meant that the invocation of hidden properties of objects, in order to provide explanations of their behaviour, was in fact to provide no explanation at all unless some set of underlying principles could be developed which unified and explained these qualities. This in essence is what he felt he was doing in developing his Laws of Nature.

However this left open the question of the cause of these Laws of Nature, and here Newton was quite unambiguous in invoking a Creator - he felt that to suppose that the universe with all its regularities had arisen from a mindless Chaos (as is supposed in, eg., the tradition of Greek mythology) was too improbable. His arguments against the idea include (i) the inherent instability of a solar system in which interactions exist between all the planets as well as with the comets - when in fact what we see is a set of near circular planetary orbits which have apparently remained stable for a long time; (ii) the extraordinary improbabilty of the sophistication of the world of living things, unless some designer had been around to orchestrate this world.

There was of course nothing controversial in this set of beliefs - the only thing that is unusuial is the achievements of the person advocating them. For Newton felt that he had indeed gone some way to revealing part of the pattern of design of the Creator. And he thus finally felt impelled to say how it was that he had done this, and what attitude and method ought to be adopted if one were to extract some understanding of the universe and its occult qualities. The following extract ends the *Opticks*, and forms a suitable epitaph to the remarkable work of Newton, both in his scientific work and on other topics - for he recognized no boundaries between the different spheres of human understanding, and spent most of his life trying to unveil what lay behind the world of experience:

"*As in Mathematicks, so in Natural Philosophy, the Investigation of difficult Things by the Method of Analysis, ought ever to precede the Method of Composition. This Analysis consists in making Experiments and Observations, and in drawing general Conclusions from them by Induction, and admitting of no Objections against the Conclusions, but such as are taken from Experiments, or other certain Truths. For Hypotheses are not to be regarded in experimental*

Philosophy. And although the arguing from Experiments and Observations by Induction be no Demonstration of general Conclusions; yet it is the best way of arguing which the Nature of Things admits of, and may be looked upon as so much the stronger, by how much the Induction is more general. And if no Exception occur from Phnomena, the Conclusion may be pronounced generally. But if at any time afterwards any Exception shall occur from Experiments, it may then begin to be pronounced with such Exceptions as occur. By this way of Analysis we may proceed from Compounds to Ingredients, and from Motions to the Forces producing them; and in general, from Effects to their Causes, and from particular Causes to more general ones, till the Argument end in the most general. This is the Method of Analysis: And the Synthesis consists in assuming the Causes discover'd, and establish'd as Principles, and by them explaining the Phnomena proceeding from them, and proving the Explanations.

In the two first Books of these Opticks, I proceeded by this Analysis to discover and prove the original Differences of the Rays of Light in respect of Refrangibility, Reflexibility, and Colour, and their alternate Fits of easy Reflexion and easy Transmission, and the Properties of Bodies, both opake and pellucid, on which their Reflexions and Colours depend. And these Discoveries being proved, may be assumed in the Method of Composition for explaining the Phnomena arising from them: An Instance of which Method I gave in the End of the first Book. In this third Book I have only begun the Analysis of what remains to be discover'd about Light and its Effects upon the Frame of Nature, hinting several things about it, and leaving the Hints to be examin'd and improv'd by the farther Experiments and Observations of such as are inquisitive. And if natural Philosophy in all its Parts, by pursuing this Method, shall at length be perfected, the Bounds of Moral Philosophy will be also enlarged. For so far as we can know by natural Philosophy what is the first Cause, what Power he has over us, and what Benefits we receive from him, so far our Duty towards him, as well as that towards one another, will appear to us by the Light of Nature. And no doubt, if the Worship of false Gods had not blinded the Heathen, their moral Philosophy would have gone farther than to the four Cardinal Virtues; and instead of teaching the Transmigration of Souls, and to worship the Sun and Moon, and dead Heroes, they would have taught us to worship our true Author and Benefactor, as their Ancestors did under the Government of Noah and his Sons before they corrupted themselves."

The exhortation to proceed from visible phenomena to extract general principles, and thereby to arrive at a set of laws of Nature which can be used to explain the world, and expand our understanding of it, is by now accepted as commonplace. The idea that this process takes us one step closer to the most general and deepest understanding of Nature is also probably accepted by most scientists, although nowadays we are perhaps less optimistic about the existence of a 'final theory' of everything. The idea that this ultimate explanation lies in a Creator is much less widely accepted - and the examples that Newton gave to support his idea of an intelligent designer (the stability of the solar system, and the existence of life and all its regularities) have now received very different explanations than the one envisaged by Newton.

And yet, one can only stand in admiration of his attempts at a complete worldview, and his faith that by attempting to decipher the world, one attained a more complete moral perspective on things. This view is not much different from the beliefs of Plato, 2000 years before him, or Einstein, over 200 years later.