TREATISE ON LIGHT

In which are explained

The causes of that which occurs

In REFLEXION, & in REFRACTION

And particularly

In the strange REFRACTION

OF ICELAND CRYSTAL

By

CHRISTIAAN HUYGENS

Rendered into English

By

SILVANUS P. THOMPSON

PREFACE

I wrote this Treatise during my sojourn in France twelve years ago, and I communicated it in the year 1678 to the learned persons who then composed the Royal Academy of Science, to the membership of which the King had done me the honour of calling, me. Several of that body who are still alive will remember having been present when I read it, and above the rest those amongst them who applied themselves particularly to the study of Mathematics; of whom I cannot cite more than the celebrated gentlemen Cassini, Römer, and De la Hire. And, although I have since corrected and changed some parts, the copies which I had made of it at that time may serve for proof that I have yet added nothing to it save some conjectures touching the formation of Iceland Crystal, and a novel observation on the refraction of Rock Crystal. I have desired to relate these particulars to make known how long I have meditated the things which now I publish, and not for the purpose of detracting from the merit of those who, without having seen anything that I have written, may be found to have treated [Pg vi]of like matters: as has in fact occurred to two eminent Geometricians, Messieurs Newton and Leibnitz, with respect to the Problem of the figure of glasses for collecting rays when one of the surfaces is given.

One may ask why I have so long delayed to bring this work to the light. The reason is that I wrote it rather carelessly in the Language in which it appears, with the intention of translating it into Latin, so doing in order to obtain greater attention to the thing. After which I proposed to myself to give it out along with another Treatise on Dioptrics, in which I explain the effects of Telescopes and those things which belong more to that Science. But the pleasure of novelty being past, I have put off from time to time the execution of this design, and I know not when I shall ever come to an end if it, being often turned aside either by business or by some new study. Considering which I have finally judged that it was better worth while to publish this writing, such as it is, than to let it run the risk, by waiting longer, of remaining lost.

There will be seen in it demonstrations of those kinds which do not produce as great a certitude as those of Geometry, and which even differ much therefrom, since whereas the Geometers prove their Propositions by fixed and incontestable Principles, here the Principles are verified by the conclusions to be drawn from them; the nature of these things not allowing of this being done otherwise.

It is always possible to attain thereby to a degree of probability which very often is scarcely less than complete proof. To wit, when things which have been demonstrated by the Principles that have been assumed correspond perfectly to the phenomena which experiment has brought under observation; especially when there are a great number of [Pg vii]them, and further, principally, when one can imagine and foresee new phenomena which ought to follow from the hypotheses which one employs, and when one finds that therein the fact corresponds to our prevision. But if all these proofs of probability are met with 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 must be ill if the facts are not pretty much as I represent them. I would believe then that those who love to know the Causes of things and who are able to admire the marvels of Light, will find some satisfaction in these various speculations regarding it, and in the new explanation of its famous property which is the main foundation of the construction of our eyes and of those great inventions which extend so vastly the use of them.

I hope also that there will be some who by following these beginnings will penetrate much further into this question than I have been able to do, since the subject must be far from being exhausted. This appears from the passages which I have indicated where I leave certain difficulties without having resolved them, and still more from matters which I have not touched at all, such as Luminous Bodies of several sorts, and all that concerns Colours; in which no one until now can boast of having succeeded. Finally, there remains much more to be investigated touching the nature of Light which I do not pretend to have disclosed, and I shall owe much in return to him who shall be able to supplement that which is here lacking to me in knowledge. The Hague. The 8 January 1690.[Pg viii] [Pg ix]

TREATISE ON LIGHT

CHAPTER I

ON RAYS PROPAGATED IN STRAIGHT LINES

s happens in all the sciences in which Geometry is applied to matter, the demonstrations concerning Optics are founded on truths drawn from experience. Such are that the rays of light are propagated in straight lines; that the angles of reflexion and of incidence are equal; and that in refraction the ray is bent according to the law of sines, now so well known, and which is no less certain than the preceding laws.

The majority of those who have written touching the various parts of Optics have contented themselves with presuming these truths. But some, more inquiring, have desired to investigate the origin and the causes, considering these to be in themselves wonderful effects of Nature. In which they advanced some ingenious things, but not however such that the most intelligent folk do not wish for better and more satisfactory explanations. Wherefore I here desire to propound what I have meditated on the sub[Pg 2]ject, so as to contribute as much as I can to the explanation of this department of Natural Science, which, not without reason, is reputed to be one of its most difficult parts. I recognize myself to be much indebted to those who were the first to begin to dissipate the strange obscurity in which these things were enveloped, and to give us hope that they might be explained by intelligible reasoning. But, on the other hand I am astonished also that even here these have often been willing to offer, as assured and demonstrative, reasonings which were far from conclusive. For I do not find that any one has yet given a probable explanation of the first and most notable phenomena of light, namely why it is not propagated except in straight lines, and how visible rays, coming from an infinitude of diverse places, cross one another without hindering one another in any way.

I shall therefore essay in this book, to give, in accordance with the principles accepted in the Philosophy of the present day, some clearer and more probable reasons, firstly of these properties of light propagated rectilinearly; secondly of light which is reflected on meeting other bodies. Then I shall explain the phenomena of those rays which are said to suffer refraction on passing through transparent bodies of different sorts; and in

this part I shall also explain the effects of the refraction of the air by the different densities of the Atmosphere.

Thereafter I shall examine the causes of the strange refraction of a certain kind of Crystal which is brought from Iceland. And finally I shall treat of the various shapes of transparent and reflecting bodies by which rays are collected at a point or are turned aside in various ways. From this it will be seen with what facility, following our new Theory, we find not only the Ellipses, Hyperbolas, and [Pg 3]other curves which Mr. Des Cartes has ingeniously invented for this purpose; but also those which the surface of a glass lens ought to possess when its other surface is given as spherical or plane, or of any other figure that may be.

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, [Pg 4]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.

To see then whether the spreading of light takes time, let us consider first whether there are any facts of experience which can convince us to the contrary. As to those which can be made here on the Earth, by striking lights at great distances, although they prove that light takes no sensible time to pass over these distances, one may say with good [Pg 5]reason that they are too small, and that the only conclusion to be drawn from them is that the passage of light is extremely rapid. Mr. Des Cartes, who was of opinion that it is instantaneous, founded his views, not without reason, upon a better basis of experience, drawn from the Eclipses of the Moon; which, nevertheless, as I shall show, is not at all convincing. I will set it forth, in a way a little different from his, in order to make the conclusion more comprehensible.
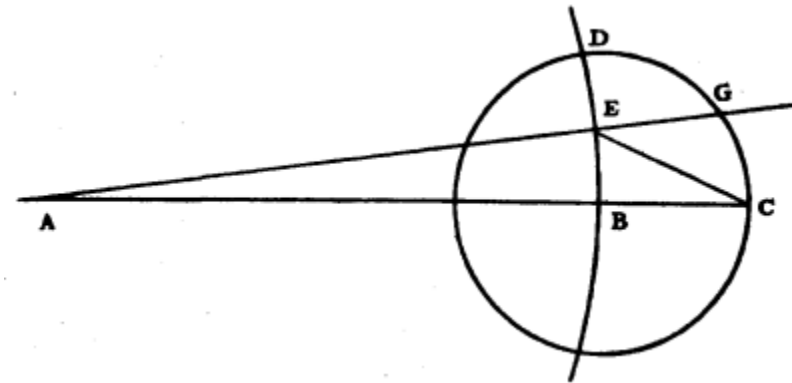
Let A be the place of the sun, BD a part of the orbit or annual path of the Earth: ABC a straight line which I suppose to meet the orbit of the Moon, which is represented by the circle CD, at C.

Now if light requires time, for example one hour, to traverse the space which is between the Earth and the Moon, it will follow that the Earth having arrived at B, the shadow which it casts, or the interruption of the light, will not yet have arrived at the point C, but will only arrive there an hour after. It will then be one hour after, reckoning from the moment when the Earth was at B, [Pg 6]that the Moon, arriving at C, will be obscured: but this obscuration or interruption of the light will not reach the Earth till after another hour. Let us suppose that the Earth in these two hours will have arrived at E. The Earth then, being at E, will see the Eclipsed Moon at

C, which it left an hour before, and at the same time will see the sun at A. For it being immovable, as I suppose with Copernicus, and the light moving always in straight lines, it must always appear where it is. But one has always observed, we are told, that the eclipsed Moon appears at the point of the Ecliptic opposite to the Sun; and yet here it would appear in arrear of that point by an amount equal to the angle GEC, the supplement of AEC. This, however, is contrary to experience, since the angle GEC would be very sensible, and about 33 degrees. Now according to our computation, which is given in the Treatise on the causes of the phenomena of Saturn, the distance BA between the Earth and the Sun is about twelve thousand diameters of the Earth, and hence four hundred times greater than BC the distance of the Moon, which is 30 diameters. Then the angle ECB will be nearly four hundred times greater than BAE, which is five minutes; namely, the path which the earth travels in two hours along its orbit; and thus the angle BCE will be nearly 33 degrees; and likewise the angle CEG, which is greater by five minutes.

But it must be noted that the speed of light in this argument has been assumed such that it takes a time of one hour to make the passage from here to the Moon. If one supposes that for this it requires only one minute of time, then it is manifest that the angle CEG will only be 33 minutes; and if it requires only ten seconds of time, [Pg 7]the angle will be less than six minutes. And then it will not be easy to perceive anything of it in observations of the Eclipse; nor, consequently, will it be permissible to deduce from it that the movement of light is instantaneous.

It is true that we are here supposing a strange velocity that would be a hundred thousand times greater than that of Sound. For Sound, according to what I have observed, travels about 180 Toises in the time of one Second, or in about one beat of the pulse. But this supposition ought not to seem to be an impossibility; since it is not a question of the transport of a body with so great a speed, but of a successive movement which is passed on from some bodies to others. I have then made no difficulty, in meditating on these things, in supposing that the emanation of light is accomplished with time, seeing that in this way all its phenomena can be explained, and that in following the contrary opinion everything is incomprehensible. For it has always seemed to me that even Mr. Des Cartes, whose aim has been to treat all the subjects of Physics intelligibly, and who assuredly has succeeded in this better than any one before him, has said nothing that is not full of difficulties, or even inconceivable, in dealing with Light and its properties.

But that which I employed only as a hypothesis, has recently received great seemingness as an established truth by the ingenious proof of Mr. Römer which I am going here to relate, expecting him himself to give all that is needed for its confirmation. It is founded as is the preceding argument upon celestial observations, and proves not only that Light takes time for its passage, but also demonstrates how much time it takes, and

that its velocity is even at least six times greater than that which I have just stated.

[Pg 8]For this he makes use of the Eclipses suffered by the little planets which revolve around Jupiter, and which often enter his shadow: and see what is his reasoning. Let A be the Sun, BCDE the annual orbit of the Earth, F Jupiter, GN the orbit of the nearest of his Satellites, for it is this one which is more apt for this investigation than any of the other three, because of the quickness of its revolution. Let G be this Satellite entering into the shadow of Jupiter, H the same Satellite emerging from the shadow.
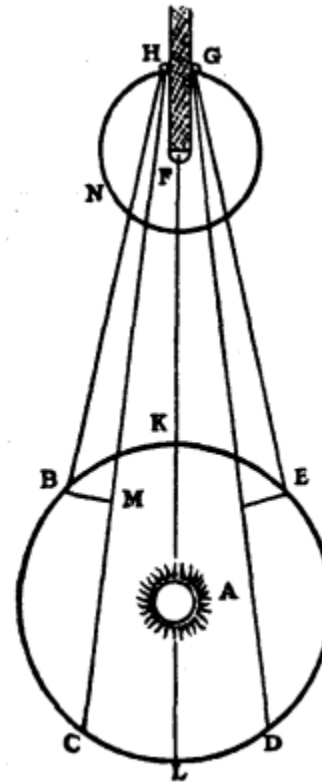
Let it be then supposed, the Earth being at B some time before the last quadrature, that one has seen the said Satellite emerge from the shadow; it must needs be, if the Earth remains at the same place, that, after 42-1/2 hours, one would again see a similar emergence, because that is the time in which it makes the round of its orbit, and when it would come again into opposition to the Sun. And if the Earth, for instance, were to remain always

at B during 30 revolutions of this Satellite, one would see it again emerge from the shadow after 30 times 42-1/2 hours. But the Earth having been carried along during this time to C, increasing thus its distance from Jupiter, it follows that if Light requires time for its passage the illumination of the little planet will be perceived later at [Pg 9]C than it would have been at B, and that there must be added to this time of 30 times 42-1/2 hours that which the Light has required to traverse the space MC, the difference of the spaces CH, BH. Similarly at the other quadrature when the earth has come to E from D while approaching toward Jupiter, the immersions of the Satellite ought to be observed at E earlier than they would have been seen if the Earth had remained at D.

Now in quantities of observations of these Eclipses, made during ten consecutive years, these differences have been found to be very considerable, such as ten minutes and more; and from them it has been concluded that in order to traverse the whole diameter of the annual orbit KL, which is double the distance from here to the sun, Light requires about 22 minutes of time.

The movement of Jupiter in his orbit while the Earth passed from B to C, or from D to E, is included in this calculation; and this makes it evident that one cannot attribute the retardation of these illuminations or the anticipation of the eclipses, either to any irregularity occurring in the movement of the little planet or to its eccentricity.

If one considers the vast size of the diameter KL, which according to me is some 24 thousand diameters of the Earth, one will acknowledge the extreme velocity of Light. For, supposing that KL is no more than 22 thousand of these diameters, it appears that being traversed in 22 minutes this makes the speed a thousand diameters in one minute, that is 16-2/3 diameters in one second or in one beat of the pulse, which makes more than 11 hundred times a hundred thousand toises; since the diameter of the Earth contains 2,865 leagues, reckoned at 25 to the degree, and each [Pg 10]each league is 2,282 Toises, according to the exact measurement which Mr. Picard made by order of the King in 1669. But Sound, as I have said above, only travels 180 toises in the same time of one second: hence the velocity of Light is more than six hundred thousand times greater than that of Sound. This, however, is quite another thing from being instantaneous, since there is all the difference between a finite thing and an infinite. Now the successive movement of Light being confirmed in this way, it follows, as I have said, that it spreads by spherical waves, like the movement of Sound.

But if the one resembles the other in this respect, they differ in many other things; to wit, in the first production of the movement which causes them; in the matter in which the movement spreads; and in the manner in which it is propagated. As to that which occurs in the production of Sound, one knows that it is occasioned by the agitation undergone by an entire body, or by a considerable part of one, which shakes all the contiguous air. But the movement of the Light must originate as from each point of the luminous object, else we should not be able to perceive all the different parts of that object, as will be more evident in that which follows. And I do not believe that this movement can be better explained than by supposing that all those of the luminous bodies which are liquid, such as flames, and apparently the sun and the stars, are composed of particles which float in a much more subtle medium which agitates them with great rapidity, and makes them strike against the particles of the ether which surrounds them, and which are much smaller than they. But I hold also that in luminous solids such as charcoal or metal made red hot in the fire, this same movement is caused by the violent [Pg 11]agitation of the particles of the metal or of the wood; those of them which are on the surface striking similarly against the ethereal matter. The agitation, moreover, of the particles which engender the light ought to be much more prompt and more rapid than is that of the bodies which cause sound, since we do not see that the tremors of a body which is giving out a sound are capable of giving rise to Light, even as the movement of the hand in the air is not capable of producing Sound.

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 [Pg 12]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.

But the extreme velocity of Light, and other properties which it has, cannot admit of such a propagation of motion, [Pg 13]and I am about to show here the way in which I conceive it must occur. For this, it is needful to explain the property which hard bodies must possess to transmit movement from one to another.

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.

But it is still certain that this progression of motion is not instantaneous, but successive, and therefore must take time. For if the movement, or the disposition to movement, if you will have it so, did not pass successively through all these spheres, they would all acquire the movement at the same time, and hence would all advance together; which does not happen. For the last one leaves the whole row and acquires the speed of the one which was pushed. Moreover there are experiments which demonstrate that all the bodies which we reckon of the hardest kind, such as quenched steel, glass, and agate, act as springs and bend somehow, not only when extended as rods but also when they are in the form of spheres or of other shapes. That is to say they yield a little in themselves at the place where they are struck, and immediately regain their former figure. For I have found that on striking with a ball of glass or of agate against a large and quite thick [Pg 14]thick piece of the same substance which had a flat surface, slightly soiled with breath or in some other way, there remained round marks, of smaller or larger size according as the blow had been weak or strong. This makes it evident that these substances yield where they meet, and spring back: and for this time must be required.

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 [Pg 15]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.
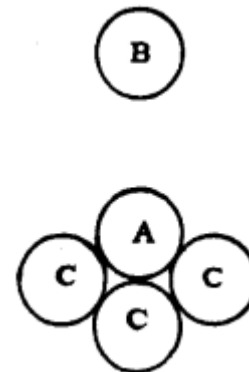
And it must be known that although the particles of the ether are not ranged thus in straight lines, as in our row of spheres, but confusedly, so that one of them touches several others, this does not hinder them from transmitting their movement and from spreading it always forward. As to this it is to be remarked that there is a law of motion serving for this propagation, and verifiable by experiment. It is that when a sphere, such as A here, touches several other similar spheres CCC, if it is struck by another sphere B in such a way as to exert an impulse against all the spheres CCC which touch it, it transmits to them the whole of its movement, and remains after that motionless like the sphere B. And without supposing that the ethereal particles are of spherical form (for I see indeed no need to suppose them so) one may well understand that this property of communicating an impulse [Pg 16]does not fail to contribute to the aforesaid propagation of movement.

Equality of size seems to be more necessary, because otherwise there ought to be some reflexion of movement backwards when it passes from a smaller particle to a larger one, according to the Laws of Percussion which I published some years ago.

However, one will see hereafter that we have to suppose such an equality not so much as a necessity for the propagation of light as for rendering that propagation easier and more powerful; for it is not beyond the limits of probability that the particles of the ether have been made equal for a purpose so important as that of light, at least in that vast space which is beyond the region of atmosphere and which seems to serve only to transmit the light of the Sun and the Stars.

I have then shown in what manner one may conceive Light to spread successively, by spherical waves, and how it is possible that this spreading is accomplished with as great a velocity as that which experiments and celestial observations demand. Whence it may be further remarked that although the particles are supposed to be in continual movement (for there are many reasons for this) the successive propagation of the waves cannot be hindered by this; because the propagation consists nowise in the transport of those particles but merely in a small agitation which they cannot help communicating to those surrounding, notwithstanding any movement which may act on them causing them to be changing positions amongst themselves.

But we must consider still more particularly the origin of these waves, and the manner in which they spread. And, first, it follows from what has been said on the production [Pg 17]of Light, that each little region of a luminous body, such as the Sun, a candle, or a burning coal, generates its own waves of which that region is the centre. Thus in the flame of a candle, having distinguished the points A, B, C, concentric circles described about each of these points represent the waves which come from them. And one must imagine the same about every point of the surface and of the part within the flame.

But as the percussions at the centres of these waves possess no regular succession, it must not be supposed that the waves themselves follow one another at equal distances: and if the distances marked in the figure appear to be such, it is rather to mark the progression of one and the same wave at equal intervals of time than to represent several of them issuing from one and the same centre.

After all, this prodigious quantity of waves which traverse one another without confusion and without effacing one another must not be deemed inconceivable; it being certain that one and the same particle of matter can serve for many waves coming from different sides or even from contrary directions, not only if it is struck by blows which follow one another closely but even for those which act on it at the same instant. It can do so because the spreading of the movement is successive. This may be proved by the row of equal spheres of hard matter, spoken of above. If against this row there are pushed from two opposite sides at the same time two similar spheres A and [Pg 18]D, one will see each of them rebound with the same velocity which it had in striking, yet the whole row will remain in its place, although the movement has passed along its whole length twice over. And if these contrary movements happen to meet one another at the middle sphere, B, or at some other such as C, that sphere will yield and act as a spring at both sides, and so will serve at the same instant to transmit these two movements.
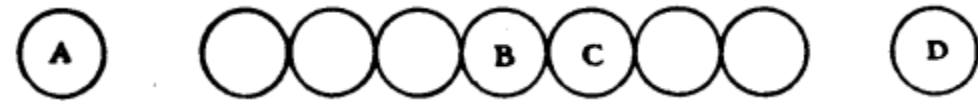
But what may at first appear full strange and even incredible is that the undulations produced by such small movements and corpuscles, should spread to such immense distances; as for example from the Sun or from the Stars to us. For the force of these waves must grow feeble in proportion as they move away from their origin, so that the action of each one in particular will without doubt become incapable of making itself felt to our sight. But one will cease to be astonished by considering how at a great distance from the luminous body an infinitude of waves, though they have issued from different points of this body, unite together in such a way that they sensibly compose one single wave only, which, consequently, ought to have enough force to make itself felt. Thus this infinite number of waves which originate at the same instant from all points of a fixed star, big it may be as the Sun, make practically only one single wave which may well have force enough to produce an impression on our eyes. Moreover

from each luminous point there may come many thousands of waves in the smallest imaginable time, by the frequent percussion of the corpuscles which strike the [Pg 19]Ether at these points: which further contributes to rendering their action more sensible.
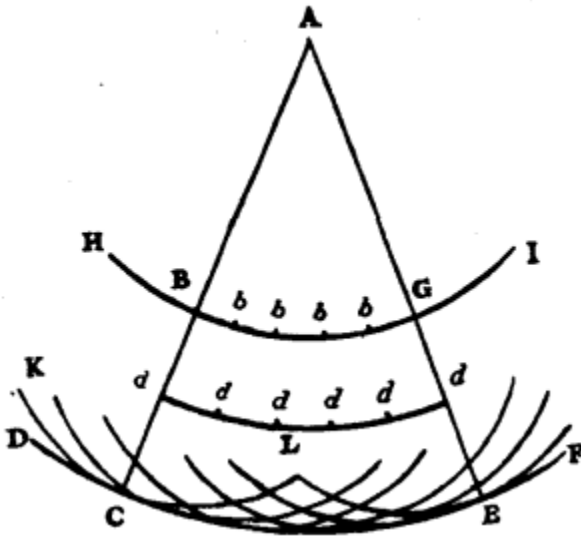
There is the further consideration in the emanation of these waves, that each particle of matter in which a wave spreads, ought not to communicate its motion only to the next particle which is in the straight line drawn from the luminous point, but that it also imparts some of it necessarily to all the others which touch it and which oppose themselves to its movement. So it arises that around each particle there is made a wave of which that particle is the centre. Thus if DCF is a wave emanating from the luminous point A, which is its centre, the particle B, one of those comprised within the sphere DCF, will have made its particular or partial wave KCL, which will touch the wave DCF at C at the same moment that the principal wave emanating from the point A has arrived at DCF; and it is clear that it will be only the region C of the wave KCL which will touch the wave DCF, to wit, that which is in the straight line drawn through AB. Similarly the other particles of the sphere DCF, such as bb, dd, etc., will each make its own wave. But each of these waves can be infinitely feeble only as compared with the wave DCF, to the composition of which all the others contribute by the part of their surface which is most distant from the centre A.

[Pg 20]One sees, in addition, that the wave DCF is determined by the distance attained in a certain space of time by the movement which started from the point A; there being no movement beyond this wave, though there will be in the space which it encloses, namely in parts of the

particular waves, those parts which do not touch the sphere DCF. And all this ought not to seem fraught with too much minuteness or subtlety, since we shall see in the sequel that all the properties of Light, and everything pertaining to its reflexion and its refraction, can be explained in principle by this means. This is a matter which has been quite unknown to those who hitherto have begun to consider the waves of light, amongst whom are Mr. Hooke in his *Micrographia*, and Father Pardies, who, in a treatise of which he let me see a portion, and which he was unable to complete as he died shortly afterward, had undertaken to prove by these waves the effects of reflexion and refraction. But the chief foundation, which consists in the remark I have just made, was lacking in his demonstrations; and for the rest he had opinions very different from mine, as may be will appear some day if his writing has been preserved.

To come to the properties of Light. We remark first that each portion of a wave ought to spread in such a way that its extremities lie always between the same straight lines drawn from the luminous point. Thus the portion BG of the wave, having the luminous point A as its centre, will spread into the arc CE bounded by the straight lines ABC, AGE. For although the particular waves produced by the particles comprised within the space CAE spread also outside this space, they yet do not concur at the same instant to compose a wave which terminates the [Pg 21]movement, as they do precisely at the circumference CE, which is their common tangent.

And hence one sees the reason why light, at least if its rays are not reflected or broken, spreads only by straight lines, so that it illuminates no object except when the path from its source to that object is open along such lines.

For if, for example, there were an opening BG, limited by opaque bodies BH, GI, the wave of light which issues from the point A will always be terminated by the straight lines AC, AE, as has just been shown; the parts of the partial waves which spread outside the space ACE being too feeble to produce light there.

Now, however small we make the opening BG, there is always the same reason causing the light there to pass between straight lines; since this opening is always large enough to contain a great number of particles of the ethereal matter, which are of an inconceivable smallness; so that it appears that each little portion of the wave necessarily advances following the straight line which comes from the luminous point. Thus then we may take the rays of light as if they were straight lines.

It appears, moreover, by what has been remarked touching the feebleness of the particular waves, that it is not needful that all the particles of the Ether should be equal amongst themselves, though equality is more apt for the propagation of the movement. For it is true that inequality will cause a particle by pushing against another larger one to strive to recoil with a part of its movement; but it will thereby merely generate backwards towards the luminous point some partial waves incapable of causing light, and not a wave compounded of many as CE was.

Another property of waves of light, and one of the most [Pg 22]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.

CHAPTER II

ON REFLEXION

aving explained the effects of waves of light which spread in a homogeneous matter, we will examine next that which happens to them on encountering other bodies. We will first make evident how the Reflexion of light is explained by these same waves, and why it preserves equality of angles.

[Pg 23]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.
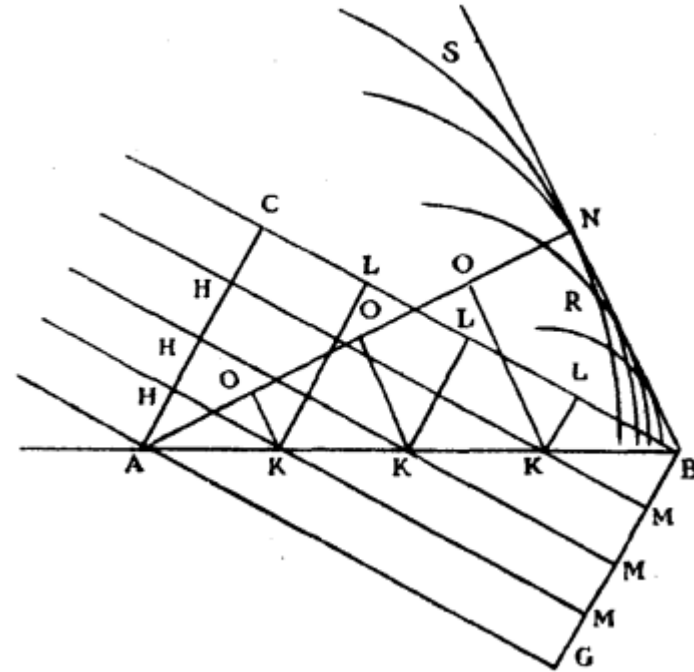
The piece C of the wave AC, will in a certain space of time advance as far as the plane AB at B, following the straight line CB, which may be supposed to come from the luminous centre, and which in consequence is perpendicular to AC. Now in this same space of time the portion A of the same wave, which 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 [Pg 24]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,

spheres of reflexion, of which we have spoken, are almost in one uniform plane, and that thus the common tangent can fit to them as perfectly as is requisite for the production of light. And this alone is requisite, in our method of demonstration, to cause equality of the said angles without the remainder of the movement reflected from all parts being able to produce any contrary effect.

CHAPTER III

ON REFRACTION

n the same way as the effects of Reflexion have been explained by waves of light reflected at the surface of polished bodies, we will explain transparency and the phenomena of refraction by waves which spread within and across diaphanous bodies, both solids, such as glass, and liquids, such as water, oils, etc. But in order that it may not seem strange to suppose this passage of waves in the interior of these bodies, I will first show that one may conceive it possible in more than one mode.

First, then, if the ethereal matter cannot penetrate transparent bodies at all, their own particles would be able to communicate successively the movement of the waves, the same as do those of the Ether, supposing that, like those, they are of a nature to act as a spring. And this is [Pg 29]easy to conceive as regards water and other transparent liquids, they being composed of detached particles. But it may seem more difficult as regards glass and other transparent and hard bodies, because their solidity does not seem to permit them to receive movement except in their whole mass at the same time. This, however, is not necessary because this solidity is not such as it appears to us, it being probable rather that these bodies are composed of particles merely placed close to one another and held together by some pressure from without of some other matter, and by the irregularity of their shapes. For primarily their rarity is shown by the facility with which there passes through them the matter of the vortices of the magnet, and that which causes gravity. Further, one cannot say that these bodies are of a texture similar to that of a sponge or of light bread, because the heat of the fire makes them flow and thereby changes the situation of the particles amongst themselves. It remains then that they are, as has been said, assemblages of particles which touch one another without constituting a continuous solid. This being so, the movement which these particles receive to carry on the waves of light, being merely communicated from some of them to others, without their going for that purpose out of their places or without derangement, it may very well produce its effect without prejudicing in any way the apparent solidity of the compound.

By pressure from without, of which I have spoken, must not be understood that of the air, which would not be sufficient, but that of some other more subtle matter, a pressure which I chanced upon by experiment long ago, namely in the case of water freed from air, which remains suspended in a tube open at its lower end, notwithstanding [Pg 30]that the air has been removed from the vessel in which this tube is enclosed.

One can then in this way conceive of transparency in a solid without any necessity that the ethereal matter which serves for light should pass through it, or that it should find pores in which to insinuate itself. But the truth is that this matter not only passes through solids, but does so even with great facility; of which the experiment of Torricelli, above cited, is already a proof. Because on the quicksilver and the water quitting the upper part of the glass tube, it appears that it is immediately filled with ethereal matter, since light passes across it. But here is another argument which proves this ready penetrability, not only in transparent bodies but also in all others.

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 [Pg 31]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 [Pg 32]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 [Pg 33]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 [Pg 34]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.
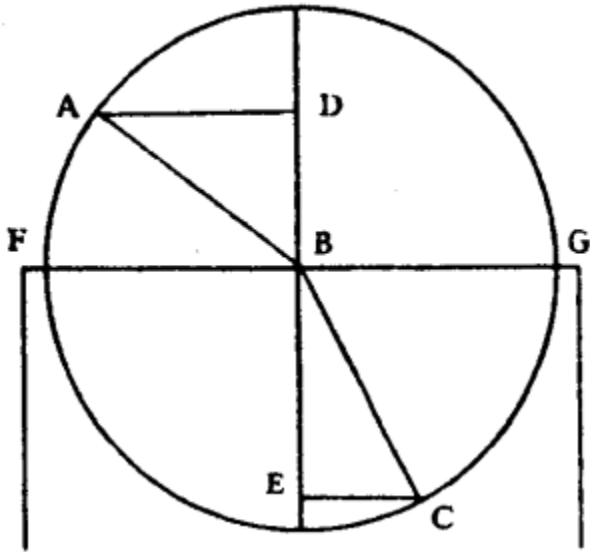
Let us pass now to the explanation of the effects of Refraction, assuming, as we have done, the passage of waves of light through transparent bodies, and the diminution of velocity which these same waves suffer in them.

The chief property of Refraction is that a ray of light, such as AB, being in the air, and falling obliquely upon the polished surface of a transparent body, such as FG, is [Pg 35]broken at the point of incidence B, in such a way that with the straight line DBE which cuts the surface perpendicularly it makes an angle CBE less than ABD which it made with the same perpendicular when in the air. And the measure of these angles is found by describing, about the point B, a circle which cuts the radii AB, BC. For the perpendiculars AD, CE, let fall from the points of intersection upon the straight line DE, which are called the Sines of the angles ABD, CBE, have a certain ratio between themselves; which ratio is always the same for all inclinations of the incident ray, at least for a given transparent body. This ratio is, in glass, very nearly as 3 to 2; and in water very nearly as 4 to 3; and is likewise different in other diaphanous bodies.

Another property, similar to this, is that the refractions are reciprocal between the rays entering into a transparent body and those which are leaving it. That is to say that if the ray AB in entering the transparent body is refracted into BC, then likewise CB being taken as a ray in the interior of this body will be refracted, on passing out, into BA.
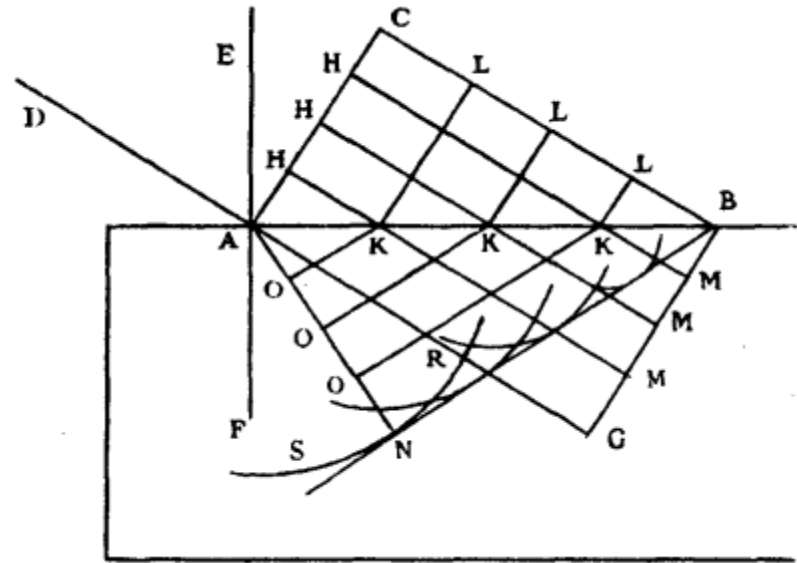
To explain then the reasons of these phenomena according to our principles, let AB be the straight line which [Pg 36]represents a plane surface bounding the transparent substances which lie towards C and towards N. When I say plane, that does not signify a perfect evenness, but such as has been understood 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 [Pg 37]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 [Pg 38]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.

To see, consequently, what the refraction will be when the waves of light pass into a substance in which the movement travels more quickly than in

that from which they emerge (let us again assume the ratio of 3 to 2), it is only necessary to repeat all the same construction and demonstration which we have just used, merely substituting everywhere 3/2 instead of 2/3. And it will be found by the same reasoning, in this other figure, that when the piece C of the wave AC shall have reached the surface AB at B, [Pg 39]all the portions of the wave AC will have advanced as far as BN, so that BC the perpendicular on AC is to AN the perpendicular on BN as 2 to 3. And there will finally be this same ratio of 2 to 3 between the Sine of the angle BAD and the Sine of the angle FAN.

Hence one sees the reciprocal relation of the refractions of the ray on entering and on leaving one and the same transparent body: namely that if NA falling on the external surface AB is refracted into the direction AD, so the ray AD will be refracted on leaving the transparent body into the direction AN.
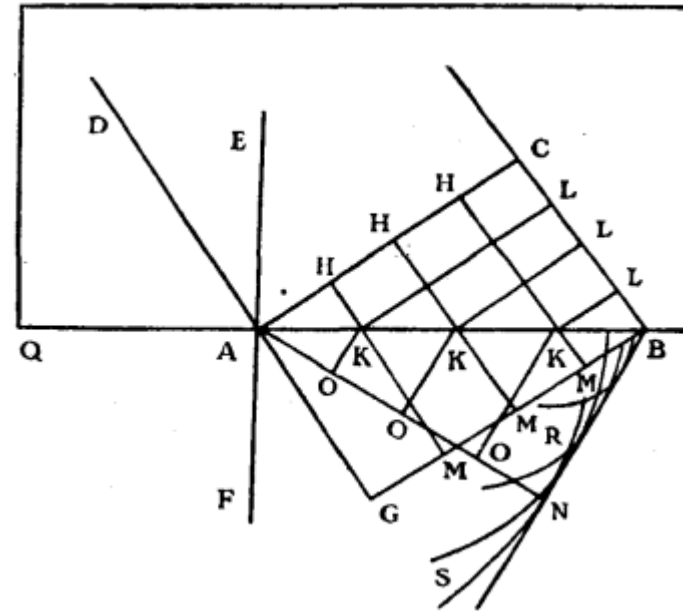
One sees also the reason for a noteworthy accident which happens in this refraction: which is this, that after a certain obliquity of the incident ray DA, it begins to be quite unable to penetrate into the other transparent substance. For if the angle DAQ or CBA is such that in the triangle ACB, CB is equal to 2/3 of AB, or is greater, then AN cannot form one side of the triangle ANB, since it becomes equal to or greater than AB: so that the portion of wave BN cannot be found anywhere, neither consequently can AN, which ought to be perpendicular to it. And thus the incident ray DA does not then pierce the surface AB.

[Pg 40]When the ratio of the velocities of the waves is as two to three, as in our example, which is that which obtains for glass and air, the angle DAQ must be more than 48 degrees 11 minutes in order that the ray DA may be able to pass by refraction. And when the ratio of the velocities is as 3 to 4, as it is very nearly in water and air, this angle DAQ must exceed 41 degrees 24 minutes. And this accords perfectly with experiment.

But it might here be asked: since the meeting of the wave AC against the surface AB ought to produce movement in the matter which is on the other side, why does no light pass there? To which the reply is easy if one remembers what has been said before. For although it generates an infinitude of partial waves in the matter which is at the other side of AB, these waves never have a common tangent line (either straight or curved) at the same moment; and so there is no line terminating the propagation of the wave AC beyond the plane AB, nor any place where the movement is gathered together in sufficiently great quantity to produce light. And one will easily see the truth of this, namely that CB being larger than 2/3 of AB, the waves excited beyond the plane AB will have no common tangent if about the centres K one then draws circles having radii equal to 3/2 of the lengths LB to which they correspond. For all these circles will be enclosed in one another and will all pass beyond the point B.

Now it is to be remarked that from the moment when the angle DAQ is smaller than is requisite to permit the refracted ray DA to pass into the other transparent substance, one finds that the interior reflexion which occurs at the surface AB is much augmented in brightness, as [Pg 41]is easy to realize by experiment with a triangular prism; and for this our theory can afford this reason. When the angle DAQ is still large enough to enable the ray DA to pass, it is evident that the light from the portion AC of the wave is collected in a minimum space when it reaches BN. It appears also that the wave BN becomes so much the smaller as the angle CBA or DAQ is made less; until when the latter is diminished to the limit indicated a little previously, this wave BN is collected together always at one point. That is to say, that when the piece C of the wave AC has then arrived at B, the wave BN which is the propagation of AC is entirely reduced to the same point B. Similarly when the piece H has reached K, the part AH is entirely reduced to the same point K. This makes it evident that in proportion as the wave CA comes to meet the surface AB, there occurs a great quantity of movement along that surface; which movement ought also to spread within the transparent body and ought to have much re-enforced the partial waves which produce the interior reflexion against the surface AB, according to the laws of reflexion previously explained.
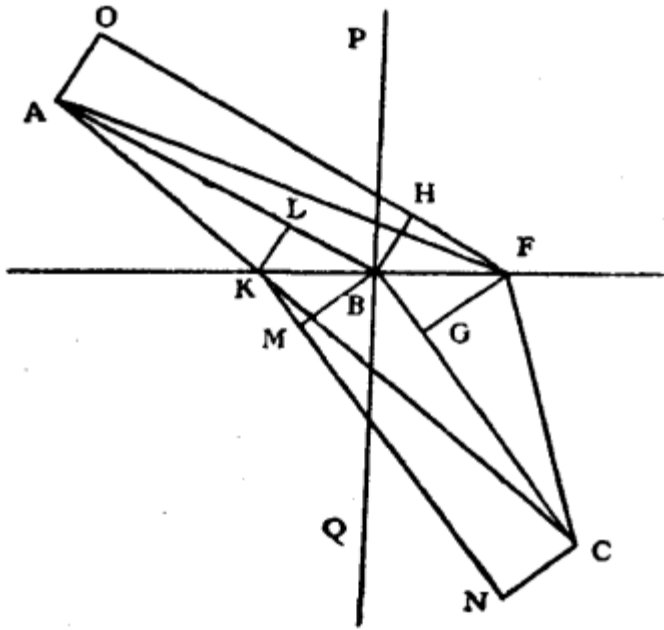
And because a slight diminution of the angle of incidence DAQ causes the wave BN, however great it was, to be reduced to zero, (for this angle being 49 degrees 11 minutes in the glass, the angle BAN is still 11 degrees 21 minutes, and the same angle being reduced by one degree only the angle BAN is reduced to zero, and so the wave BN reduced to a point) thence it comes about that the interior reflexion from being obscure becomes suddenly bright, so soon as the angle of incidence is such that it no longer gives passage to the refraction.

[Pg 42]Now as concerns ordinary external reflexion, that is to say which occurs when the angle of incidence DAQ is still large enough to enable the refracted ray to penetrate beyond the surface AB, this reflexion should occur against the particles of the substance which touches the transparent body on its outside. And it apparently occurs against the particles of the air or others mingled with the ethereal particles and larger than they. So on the other hand the external reflexion of these bodies occurs against the particles which compose them, and which are also larger than those of the ethereal matter, since the latter flows in their interstices. It is true that there remains here some difficulty in those experiments in which this interior reflexion occurs without the particles of air being able to contribute to it, as in vessels or tubes from which the air has been extracted.

Experience, moreover, teaches us that these two reflexions are of nearly equal force, and that in different transparent bodies they are so much the stronger as the refraction of these bodies is the greater. Thus one sees manifestly that the reflexion of glass is stronger than that of water, and that of diamond stronger than that of glass.

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 [Pg 43]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. His demonstration, which may be seen in his printed works, and in the volume of letters of Mr. Des Cartes, is very long; wherefore I give here another which is simpler and easier.