Dioptrics

René Descartes

1637

First Discourse
On Light

All the conduct of our lives depends on our senses, among which the sense of sight being the most universal and most noble, there is no doubt that the inventions which serve to augment its power are the most useful that could be made. And it is difficult to find any of these inventions that has done as much good as the discovery of those marvelous telescopes, which, being in use for only a short time, have already revealed more new stars in the sky, and numerous other objects above the Earth, than we had seen before: such that, projecting our vision much farther than the imagination of our ancestors was accustomed to go, they seem to have opened the path for us to come to a much greater and more perfect knowledge of nature than they had. But, to the shame of our sciences, this invention, so useful and so admirable, was first found only by experiment and good fortune.

It was around thirty years ago that a certain Jacques Métius, from the city of Alcmar in Holland, a man who had never studied, although he had a father and brother who were professional mathematicians, but who took a particular joy in making mirrors and burning lenses, even making some out of ice in the winter, as experiment has shown it possible to do; having on this occasion several lenses of different shapes, by chance he had a mind to look through two of them, one of which was thicker in the middle than at the extremities, and the other was much thicker at the extremities than in the middle, and he so fortunately placed them at the two ends of a tube: thus the first of the telescopes of which we speak was created. And it is only on this model that all the others that we have seen have been made, without anyone that I know of having sufficiently determined the shapes that the lenses ought to have.[1] For, although there have since been many minds who had greatly pondered this matter, and who had found several things about optics worth more than what the ancients left us, all the same, because somewhat difficult inventions do not achieve their final degree of perfection in the first attempt, there have still remained enough difficulties on this topic to give me something to write about. And, inasmuch as the execution of the things of which I shall speak will depend upon the industry of artisans, who ordinarily have not done much studying, I shall attempt to make myself intelligible to everyone, without omitting anything or assuming anything known from other sciences. This is why I shall begin with the explanation of light and of its rays; then, having made a brief description of the parts of the eye, I will specifically say how vision operates, and then, having remarked on all the techniques that can make it more perfect, I will teach how the field of these techniques may be broadened by the inventions which I will describe.

Now, having no other occasion to speak of light here, except to explain how its rays enter the eye, and how they can be deflected by the various bodies they encounter, there is no need for me to attempt to say what its true nature is, and I believe that it will suffice for me to make use of two or three comparisons which aid in conceiving it in the manner which seems to me the most correct to explain all of its properties that experience has made known to us, and then to deduce all the other properties which cannot so easily be noticed. In this I will be imitating the astronomers, who, although their assumptions be almost all false or uncertain, nonetheless, because they agree with many observations that they have made, never cease to allow the derivation of many very true and well-assured consequences.[2]

It has no doubt sometimes happened to you, while walking during the night without a light through difficult paths, you have had need of a stick to help direct yourself, and from this you have been able to remark that you feel, through the medium of the stick, the various objects which you encounter around yourself, and that you could distinguish if there were trees, or rocks, or sand, or water, or grass, or mud or some other similar thing. It is true that this sort of sensation is somewhat confused and obscure for those who are not used to it, but consider it for those who, being born blind, have used it all their lives, and you will find that they use it so perfectly and so exactly that it may almost be said that they see with their hands, or that

[1] What about Kepler?

[2] And to think that he is writing this after Kepler!

their stick is the organ of a sixth sense which was given to them instead of sight. And to make a comparison with this, I would have you think that light is nothing other, in bodies that we call luminous, than a certain movement, or a very quick and strong action which moves towards our eyes through the medium of the air and other transparent bodies in the same fashion as the movement or the resistance of bodies encountered by this blind person pass to his hand by the intermediary of the stick. This example will prevent you from thinking it strange that light can extend its rays in an instant from the sun to us; for you know that the action by which one end of the stick is moved must thus pass in an instant to the other, and that light must pass in the same way between the Earth and the heavens, even though there would be more distance.

Nor will you find it strange that, by means of it, we can see all sorts of colors; and perhaps you will even believe that these colors are nothing other in the bodies that we call colored than the different ways in which these bodies receive light and send it back to our eyes: if you consider that the differences that a blind person notices between trees, stones, water, and other things, by the intermediary of his stick, seem no more the same to him than the differences we see between red, yellow, green, and all the other colors; and nonetheless these differences are nothing other than the different ways of moving, or resisting the movements of, this stick. From which it follows that you will have occasion to judge that there is no need to assume that something material passes between the objects and our eyes to let us see colors and light, nor that there is anything in these objects which is similar to the ideas or the sensations that we have of them: just as nothing comes out from the bodies that a blind person senses which must pass along the stick to his hand, and just as the resistances or movements of the bodies, which are the sole cause of the perceptions that he has of them, are nothing at all like the ideas that he has of them.[3] And by this means, your mind will be freed of all these images fluttering through the air, named *intentional species*, which have so worked up the imagination of philosophers. You can even easily decide the question among them concerning the origin of the action that causes the sense of sight. For, as our blind person can sense bodies which are around him, not only by the action of these bodies when they move against his stick, but also by the action of his hand when they only resist his motion, thus, we must maintain that the objects of vision can be sensed not only by

[3] There is nothing in the objects similar to the sensations that we have of them.

means of the action which, being within them, tends towards the eyes, but also by means of that which, being in the eyes, tends towards them. Still, because this action is nothing other than light, it must be said that it is only in the eyes of those who can see in the shadows of the night, such as cats, in which it is found: and that, ordinarily for humans, they only see by the action which comes from objects, for experience shows us that these objects must be luminous or illuminated to be seen, rather than our eyes luminous or illuminated to see them. But, since there is a great difference between this blind person's stick and air or other transparent bodies by means of which we see, I must make use of still another comparison here.

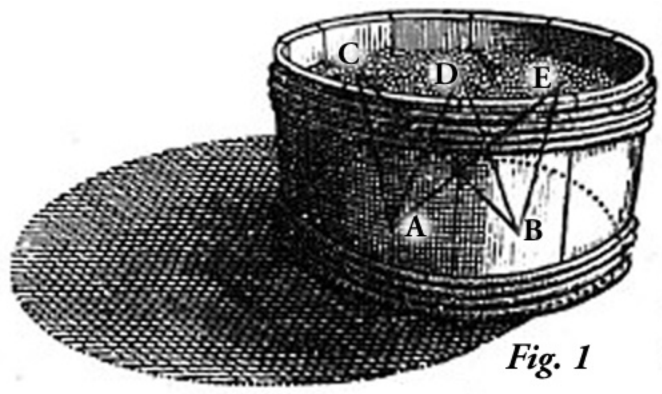


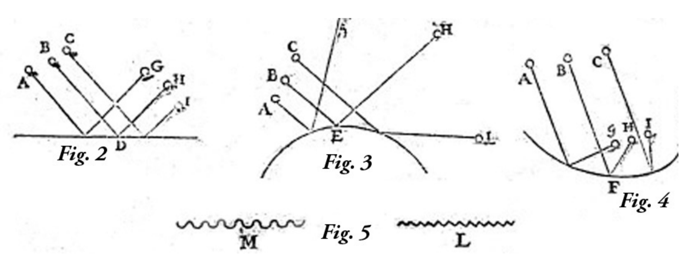
Fig. 1

Picture a vat, at the time of vintage full of half-pressed grapes, and in the bottom of the vat, a hole or two, A and B, have been made through which the soft wine that it contains may flow. Then imagine that, there being no vacuum in nature, as almost all the philosophers maintain, and there being nonetheless many pores in all the bodies that we see around us, as experience shows us quite clearly, it is necessary that these pores be filled with some very subtle and very fluid matter, which extends from the stars to us without interruption. Now comparing this subtle matter with the wine of this vat, and comparing the less fluid or heavier parts, both of air and of other transparent bodies, with the bunches of grapes which it is among, you will easily understand that, since the parts of this wine, which are for example near C, tend to descend in a straight line through hole A at the very moment that it is opened, and through hole B at the same time; and that those parts which are near D and E also tend at the same time to descend through these two holes without one of these actions being prevented by the other, nor by the resistance of the bunches which are in this vat, notwithstanding that these bunches, being supported by each other, do not at all tend to descend through these holes A and B as does the wine, and that they can even be moved in various other ways by those which press upon them. Thus all the parts of the subtle matter which are touched by the side of the sun which faces us, tend in a straight line towards our eyes at the very moment that they are opened, without impeding each other and even without being impeded by the heavier parts of the transparent bodies which are between the two: whether these bodies move in other ways, as does air, which is almost always agitated by some wind, or if they be without motion as are perhaps glass and crystal.

And note here that a distinction must be made between the movement, and the action or inclination to move; for one can very easily believe that the parts of the wine which are for example near C tend towards B, and also towards A, notwithstanding that they cannot actually be moved towards these two sides at the same time, and that they tend exactly in a straight line towards B or A, notwithstanding that they cannot move so precisely towards A in a straight line, due to the bunches of grapes which are between the two: and in the same way, thinking that it is not so much the movement as the action of the luminous bodies that must be taken to be their light, you must judge that the rays of this light are nothing other than the lines along which this action tends. So that there are an infinite number of such rays which come from all the points of the luminous bodies towards all the points of the bodies that they illuminate, in the same way as you can imagine an infinite number of straight lines, along which the actions that come from all the points of the surface CDE of the wine tend towards A; and an infinite number of others, along which the actions which come from these same points also tend towards B without the one preventing the other.

Moreover, these rays must always be imagined to be completely straight, when they pass only through one transparent body that is everywhere uniform; but when they encounter some other bodies, they are subject to being deflected by them, or weakened in the same way as the movement of a ball or a stone thrown in the air is weakened by those bodies that it encounters; for it is quite easy to believe that the action or inclination to move, which I have said light must be taken to be, must follow in this the same laws as movement. And, in order to explain this third comparison completely, consider that the bodies which can be encountered in this way by a ball which passes in air are either soft, hard, or liquid; and that, if they are soft, they will stop and soften its movement altogether, as when it is thrown against linens, or sand, or mud; whereas if they are hard, they will redirect it in another direction without stopping it,[4] and will do so in different ways: for either their surface is completely even and smooth, or rough and uneven; and moreover if it is smooth, it is either flat or curved: and being rough, either its roughness consists only in its composition of many different curved parts, of which each is smooth in itself; or rather it consists, besides this, in having many different angles or points, or some parts harder than others, or which move in a thousand imaginable variations. And it must be noted that the ball, aside from its simple and ordinary movement, which carries it from one place to another, can also have a second which makes it turn about its center, and that the speed of this latter can have many different proportions with the speed of the former. Now, when many balls, coming from the same direction, encounter a body whose surface is completely smooth and uniform, they reflect equally and in the same order, such that, if this surface is totally flat, they maintain the same distance between each other after having encountered it, that they had before; and if it is curved inward or outward, they will approach or move away from each other, more or less, in the same order, depending on the ratio of this curvature.

Here you see balls A, B, C (*figs.* 2, 3, 4), which, after having encountered the surfaces of bodies D, E, F, reflect towards G, H, I. And, if these balls encounter an uneven surface, such as L or M (*fig.* 5), they reflect in different directions, each according to the situation of the location of this surface that they touch.



And they do not change anything besides this in the manner of their movement when its unevenness consists only in its parts being differently curved. But it can also consist in many other things, and by these means can bring it about that, if these balls had earlier had only a simple rectilinear motion, they will lose a part of it and acquire instead a circular motion, which can

[4] Descartes held that a perfect rebound would involve no change in speed: rather, the ball would instantaneously change its direction.

have a different proportion with that that they retain of their rectilinear motion, accordingly as the surface of the body which they encounter can be differently disposed. Those who play tennis prove this sufficiently when their ball encounters uneven ground, or when they hit it obliquely with their racket, which they call, I believe, cutting or grazing. Finally, consider that, if a moving ball encounters obliquely the surface of a liquid body through which it can pass more or less easily than through that which it is leaving, it is deflected and changes its course when it enters: as, for example, if, being in the air at point A (*fig.* 6), it is impelled towards B, it will indeed go in a straight line from A to B, if neither its weight nor some other particular cause prevent it; but, at point B, where I suppose it to encounter the surface of the water CBE, it is deflected and takes a path towards I, going moreover in a straight line from B to I, as is easy to verify by experiment.

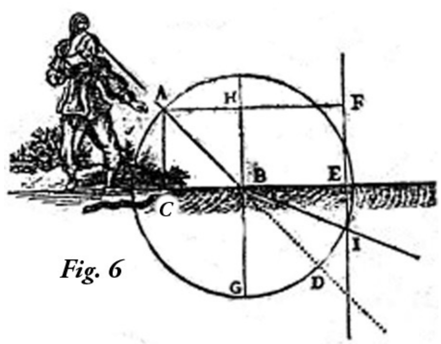


Fig. 6

Now it is necessary to think in the same way that there are bodies which, being encountered by rays of light, dampen these rays' motion and remove all of their force, namely those bodies which we name black, which have only the color of shadows; and that there are others which reflect them in the same order that they received them, namely those which, having their surfaces completely polished, can be used as mirrors, both flat as well as curved, and the others reflect them confusedly in many directions. Among these latter, some cause rays to reflect without causing any other change in their action, namely those that we call white; and others bring with this reflection a change similar to that received by the movement of a ball when it is grazed, namely those which are red, or yellow, or blue, or of any other such color. For I think it possible to determine what the nature of each of these colors consists of, and make it known by experiment; but this goes beyond the bounds of my subject. And it is enough here for me to show you that the rays which fall on bodies which are colored and unpolished ordinarily reflect in all directions, even when they come from only one direction. As, even though those which fall upon the surface of a white body AB (*fig.* 7) come only from flame C, they are still reflected in all directions such that in any location where one puts one's eye, as for example near D, there are always found many rays coming from each location of this surface AB which tend towards it. And the same is true, if we assume this body to be quite thin, like a sheet of paper, or a cloth, such that light passes through it, even though the eye is on the side opposite the flame, such as towards E, some rays of each of the parts of the body will still be reflected towards it.

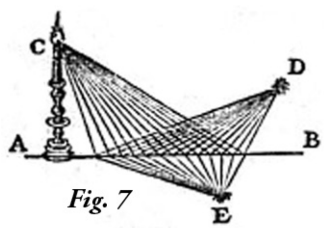


Fig. 7

Finally, consider that the rays are also deflected in the same way as was said of a ball when they encounter obliquely the surface of a transparent body through which they penetrate more or less easily than through the body from which they came, and in these bodies this manner of being deflected is called refraction.

Second Discourse
On Refraction

Inasmuch as we will later need to know the quantity of this refraction exactly, and since it can be understood easily enough by the comparison which I have just used, I believe that it is appropriate that I try here to explain it all at once, and that I first speak of reflection, in order to make the understanding of refraction so much the easier.

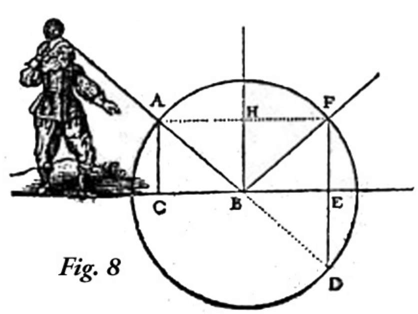


Fig. 8

Let us think then, that a ball being impelled from A towards B, meets at point B the surface of the earth CBE, which, preventing it from passing through, is the cause that it turns away, and let us see in which direction it does so. But in order not to be tripped up by new difficulties, let us assume that the ground is completely flat and solid, and that the ball always has an equal speed, both in descending and in ascending, without inquiring into the power which continues to move it after it is no longer touched by the racket, nor shall we consider any effect of its weight, nor its size, nor its shape; for here there is no question of looking at it so closely, and none of these things are of relevance to the action of light, to which this inquiry must correspond. It must only be noted that the power that causes the movement of the ball to continue, whatever it may be, is different from that which determines it to go towards one direction rather than another, as it is easy to know from the fact that its movement depends on the force by which it was pushed by the racket, and that this force could just as easily have moved it towards any other direction instead of B; although it is the position of this racket which determines that it will tend towards B, and which could have determined it in the same way even had another force moved it; which already shows that it is not impossible that this ball be diverted by its encounter with the earth, and thus that the determination that it had to move towards B be changed, without there being any change in the force of its movement, since these are two different things, and consequently one need not imagine that it is necessary for it to stop for some time at B before returning towards F, as many of our philosophers say: for, if its movement was halted by this stop, there would be no cause for it to start moving again.

Furthermore, it must be noted that the determination to move in one direction can, just as movement, and in general any sort of quantity, be divided into all the parts of which we imagine it is composed, and that we can easily imagine that the motion of the ball which moves from A towards B is composed of two others, one causing it to descend from the line AF towards the line CE, and the other at the same time causing it to go from the left AC to the right FE, such that these two combined direct it towards B along straight line AB. And then, it is easy to understand that the encounter with the ground can only prevent one of these two determinations, and not in any way the other: for it must prevent that which causes the ball to descend from AF towards CE, because it occupies all the space below CE; but why would it hinder the other which causes it to advance towards the right, considering that it is in no way opposed to this direction? Therefore to truly find in which direction the ball must rebound, let us describe a circle with center B, passing through point A, and let us say that in as much time as it will take to move from A to B, it must undoubtedly return from B to some point on the circumference of the circle, since all the points which are equally distant from B, such as A, are found on the circumference, and assuming that the movement of the ball is always equally fast. Then, in order to know precisely to which among all the points of the circle it will return, let us draw three straight lines AC, HB and FE, perpendicular to CE, and in such a way that there is neither more nor less distance between AC and HB as between HB and FE; and let us say that in as much time as the ball has taken to advance to the right from A (one of the points on the line AC) to B (one of the points on line HB), it must also advance from line HB to some point on line FE: for each of the points of this line FE are as far from HB in this direction as any other, and are as far from HB as line AC is, and it is also just as determined to advance towards that side as it was before. Now, it is a fact that it cannot arrive at the same time at a certain point on the line FE and at a certain point on the circumference of circle AFD, unless it is at point D or F, inasmuch as it is only these two where they [the line and the circumference] intersect each other, and since the earth prevents its going to D, it must be concluded that it indubitably goes towards F. And thus you easily see how reflection occurs, to wit: along an angle always equal to that which is named the angle of incidence; just as if a ray coming from point A falls upon point B on the surface of a flat mirror CBE, is reflected towards F, such that the angle of reflection FBE is neither larger nor smaller than the angle of incidence ABC.

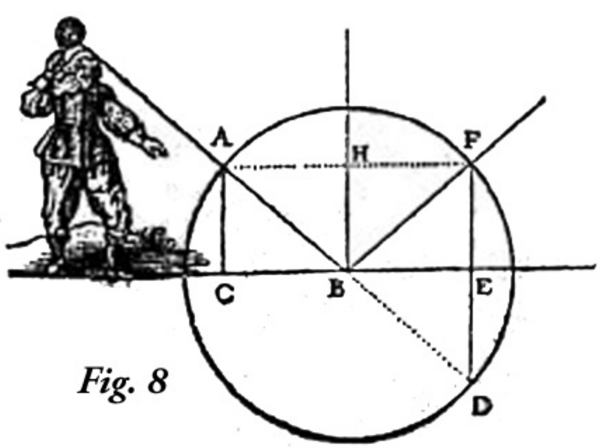


Fig. 8

Now we come to refraction; and we will first suppose that a ball (*fig.* 6) impelled from A towards B intersects at point B, not the surface of the earth, but a cloth CBE, which is so feeble and loosely woven that this ball has the force to break it and pass right through it, while losing only a part of its speed, one half for example. Now, under this hypothesis, in order to know which path it must follow, let us consider afresh that its movement differs entirely from its determination to move more in one direction rather than another, from which it follows that their quantities must be examined separately; and let us also consider that of the two parts of which we can imagine this determination is composed, it is only that which makes the ball move from high to low that can be changed in some fashion by the encounter with the cloth, and that by which it is made to move towards the right always remains the same as it has been, because the cloth is in no way opposed to motion in that direction.

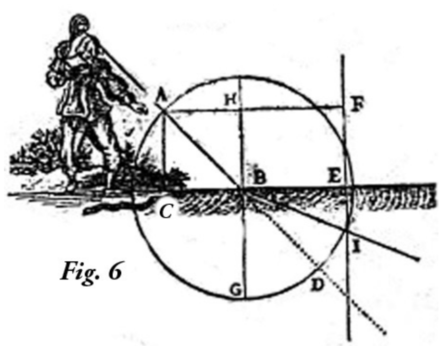


Fig. 6

Then having described the circle AFD around center B, and having drawn at right angles to CBE the lines AC, HB, FE, such that there be twice as much distance between FE and HB as between HB and AC, we will see that this ball must tend towards point I. For, since it loses half its speed in passing through the cloth CBE, it must take twice as much time to pass below B to a point on the circumference of the circle AFD as it took above to pass from A to B: and, since it loses none of its determination to move towards the right, in twice the time that it took to pass from line AC to line HB, it must move twice as much towards this side, and consequently arrive at some point on the line FE at the same time that it also arrives at some point on the circumference of circle AFD; which would be impossible if it did not go towards I, since it is the only point below the cloth CBE where the circle

AFD and the straight line FE intersect.[5]

Now let us consider that the ball which comes from A towards D encounters at point B, no longer a cloth, but rather water, whose surface CBE takes half its speed just as the cloth did; and the rest hypothesized as before, I say that this ball must pass from B in a straight line, not towards D, but rather towards I: first because it is certain that the surface of the water must divert it just as the cloth did, since it takes away just as much of its force, and is opposed to it in the same direction. Then, as for the rest of the body of water that fills the entire space between B and I, although it resists the light more or less than did the air that we hypothesized earlier, this is not to say that it must divert it more or less: for it can open to allow passage just as easily in one direction as in another; at least if we still assume, as we have, that neither the heaviness nor the lightness of this ball, nor its size, nor its shape, nor any other such foreign cause, changes its course;[6] and it can be noted here that it is diverted by the surface of the water or the cloth, to the degree that it encounters it more obliquely; such that if it meets it at a right angle, as when it is impelled from H towards B (*fig.* 9), it must pass through on a straight line towards G, without being diverted at all; but if it is moved on a line such as AB, which is very much inclined to the surface of the water or the canvas CBE, that the line FE being drawn as before does not cut the circle AD at all, this ball must not at all penetrate it, but must rebound from the surface B towards the air L, just as if it had hit the earth.

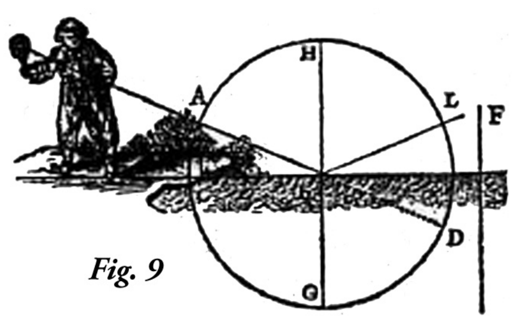


Fig. 9

Regretfully, some people have sometimes performed an experiment of shoot-

[5] So for Descartes, if f_i and f_r were the "forces" of light of incidence and refraction, then the condition that the horizontal determinations were to be the same, would be expressed as $f_i sin(i) = f_r sin(r)$, giving $\frac{f_i}{f_r} = \frac{sin(r)}{sin(i)}$. Isn't that convenient?

[6] So, what is not a foreign cause? Apparently, anything that real balls do is considered foreign.

ing off pieces of artillery for amusement, aiming at the bottom of a river, and injuring those who were on the shore on the other side.

But let us make yet another assumption here, and let us consider that the ball, having first been impelled from A towards B (*fig.* 10), is impelled anew, once at point B, by the racket CBE,[7] which increases the force of its movement by, for example, a third, such that it afterwards traverses the same distance in two moments of time that it earlier traversed in three, which will have the same effect as if it encountered at point B a body of such a nature that it passed through the surface CBE a third more easily than through air. And it obviously follows from what I have already demonstrated that, if we describe the circle AD as before, and the lines AC, HB, FE such that there is a third less distance between FE and HB than between HB and AC, the point I, where the line FE and the circumference AD intersect, will designate the location towards which this ball, being at point B, must be deflected.

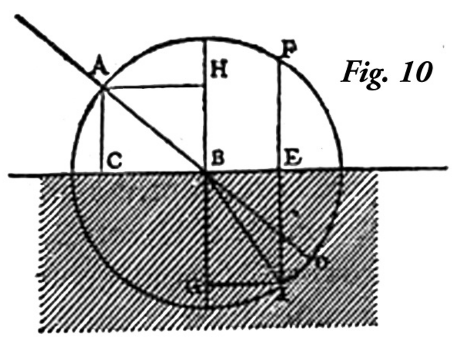


Fig. 10

Now we can also take the reverse of this conclusion, and say that, since the ball which comes from A in a straight line to B will be deflected at point B and take its course from there towards I, this signifies that the force or facility by which it enters into the body CBEI is to that with which it leaves the body ACBE, as the distance between AC and HB is to that between HB and FI, that is, as CB is to BE.

Finally, inasmuch as the action of light follows in this respect the same laws as the movement of this ball, it must be said that, when its rays pass obliquely from one transparent body into another, which receives them more or less easily than the first, they are deflected in such a way that they always

[7]Yes, Descartes really is creating the image of a tennis racket appearing out of nowhere to whack the ball downwards as it enters the water! It seems that, in the mind of Descartes, this racket is not a "foreign cause."

find themselves less inclined to the surface of these bodies on the side which receives them more easily; and this is in the same proportion as they are more easily received on one side than on the other side. Only, care must be taken that this inclination be measured by the quantity of straight lines, like CB or AH, and EB or IG, and similar lines, compared one with the other, rather than being measured by the quantity of the angles, like ABH and GBI, nor still less by the quantity of angles similar to DBI, which are named the angles of refraction. For the ratio or proportion which is between these angles varies at all the many inclinations of the rays, whereas that between lines AH and IG, or similar lines, remains the same in all the refractions caused by the same bodies. As, for example, if a ray travels through the air from A towards B, which, meeting the surface of lens CBR at point B, is deflected towards I in the lens, and if another comes from K towards B which deflects towards L, and another from P towards R which deflects towards S, there must be the same proportion between the lines KM and LN, as between AH and IG; but not the same between angles KBM and LBN as between ABH and IBG.

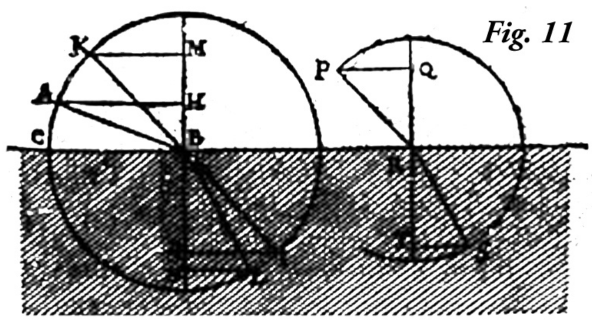


Fig. 11

It is good that now you see how different refractions must be measured; and although it is necessary to use experience to determine their quantities (inasmuch as they depend on the particular nature of the bodies in which they occur), we are nonetheless able to do so reasonably certainly and easily, since all refractions are thus reduced to the same measure; for it suffices to examine them with a single ray to know all those [refractions] which occur at the same surface, and one can avoid all error, if several others are examined as well. Thus if we would like to know the quantity of those which are made at surface CBR, which separates the air AK from the lens LI, we have only to find it for ray ABI, by looking for the proportion between lines AH and IG. Then, if we fear that we have failed in this experiment, it must also be tested for some other rays, like KBL; and finding the same proportion between KM and LN as between AH and IG, we will have no more occasion to doubt the truth.

But perhaps you will be shocked while making these experiments, to find that the rays of light are more inclined in air than in water, on the surfaces where they refract; and still more so in water than in glass, quite contrary to a ball, which inclines more in water than in air, and cannot pass through glass at all: since, for example, if a ball, being impelled in the air from A to B (*fig.* 10), encounters at point B the surface of the water CBE, it will be deflected from B towards V; and if it is a ray, it will on the contrary go from B towards I.

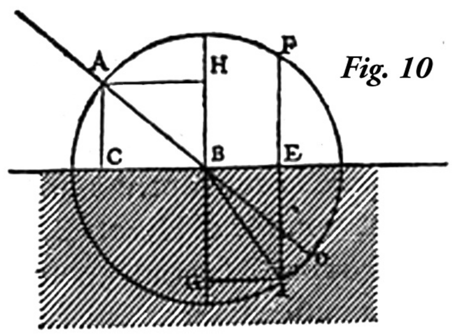
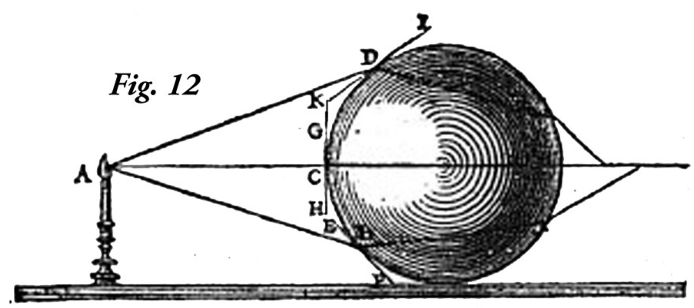


Fig. 10

You will cease to this find strange, if you remember the nature that I attributed to light, when I said that it is nothing other than a certain movement or an action, received in a very subtle material that fills the pores of other bodies; and if you would consider that, as a ball loses more of its agitation in running against a soft body than against a hard one, and that it rolls less easily on a carpet than upon a smooth table, thus the action of this subtle material can be much more impeded by the parts of air, which are soft and poorly joined and do not make much resistance, than by those of water which give more [resistance]; and still more by those of water than by those of glass or crystal: such that to the extent that the small pieces of a transparent body are harder and firmer, so much the easier will they allow light to pass, for this light does not have to drive them out of their places as does a ball in displacing the parts of water in order to find passage between them.

Moreover, knowing thus the cause of refractions which are made in water and in glass, and commonly in all other transparent bodies which are around us, one can note that they must all be the same when the rays leave the bodies as when they enter: as, if the ray which goes from A to B is deflected at B towards I by passing from air into glass, that which returns from I towards B must also deflect at B towards A. Still, other bodies can be found, principally in the heavens, where refractions, proceeding from other causes, are not reciprocal in this way. And certain cases can also be found where rays must curve, although they only pass through a single transparent body; in the same way as the movement of a ball curves, since it is deflected towards one direction by its weight, and towards another by the action with which it has been impelled, or for many other reasons. For, finally, I dare to say that the three comparisons which I have just used are so proper, that all the particularities which can be remarked about them correspond to others which are completely similar for light; but I have only sought to explain those which were the most relevant for my subject. And I do not wish to make you consider other things here, except that the surfaces of transparent bodies which are curved deflect rays which pass through each of their points, in the same way as would flat surfaces that could be imagined touching these bodies at the same points: as, for example, the refraction of the rays AB, AC, AD, which, coming from candle A (*fig.* 12), fall on the curved surface of the crystal ball BCD, must be considered as though AB fell upon the flat surface EBF, and AC upon GCH, and AD upon IDK, and so on for the others.

Fig. 12



From this, you see that the rays can be brought together or spread apart, accordingly as they fall upon surfaces which are curved in various ways. And it is time that I begin to describe to you the structure of the eye, in order that you will be able to understand how rays which enter into it dispose themselves there to cause the sensation of sight.