a degree, whereas his real magnitude far surpasses that of the earth; for the sun being a globe, his diameter is estimated to be about 790,000 English miles, while the diameter of the earth is only 7912 English miles.

29th July 1760.

LETTER XXXIV.—OF THE ASSISTANCE WHICH JUDGMENT LENDS TO VISION.

WHAT I have now submitted to you on the phenomenon of vision, belongs to optics, which is a branch of mixed mathematics, and which likewise holds a considerable rank in physics. Beside colours, the nature of which I have endeavoured to explain, it is the business of optics to treat of the manner in which vision is performed, and of the different angles under which objects are seen.

You must have already remarked, that the same object may be viewed, sometimes under a greater visual angle, sometimes under a smaller, as it is less or more distant from us. I say farther, that a small object may be viewed under the same angle as a great one, when the former is very near, and the latter very distant. A small dish may be placed before the eye in such a manner, as to cover the whole body of the sun; and, in reality, a plate of half a foot diameter, at the distance of 54 feet, exactly covers the sun, and is seen under the same angle; and yet what a prodigious difference is there between the size of a plate and that of the sun: The full moon appears to us under nearly the same visual angle as the sun, and of consequence, nearly as great, though really much smaller; but it is to be considered, that the sun is almost 400 times more remote from us than the moon.

The visual angle is a point of so much the more importance in optics, that the images of the objects which paint themselves on the bottom of the eye, depend upon it. The greater or less the visual angle is, the greater or less they (the objects) are great or little. And as we see objects out of ourselves, only so far as their images are painted on the bottom of the eye, they constitute the immediate object of vision or sensation. One of these images, therefore, leads us to the knowledge only of three things. First, its figure and its colours conduct to the conclusion, that there is, out of us, a similar object, of such a figure, and such a colour. Secondly, its magnitude discovers the visual angle under which the object appears to us; and, finally, its place on the bottom of the eye makes us sensible of the direction of the external object, relatively to us, or that in which the rays emitted from it reach our eyes.

In these three particulars consists the phenomenon of vision; and we only perceive, 1st, the figure and colours; 2dly, the visual angle, or the apparent magnitude; and, 3dly, the direction, or the place in which we conclude that the object exists. Vision, then, discovers to us nothing respecting either the real magnitude of objects, or their distances. Though we frequently imagine, that we can determine by the eye the magnitude and distance of an object, this is not an act of vision, but of the understanding. The other senses, and habits of long standing, enable us to calculate at what distance an object is from us. But this faculty extends only to objects at no great distance. Whenever their distance becomes considerable, our judgment cannot exercise itself with certainty; and if sometimes we venture to hazard a decision, it is generally very remote from the truth.

Thus, no one can pretend to say that he sees the magnitude or the distance of the moon; and when the vulgar imagine they can judge of the first, by considering it as equal to that of the terrestrial bodies which are seen under the same angle, it is not by vision they are deceived, but by their judgment, which they want to apply to an object far beyond their reach. It is certain, therefore, that the eyes alone can determine nothing respecting the distance and magnitude of objects.

To this subject may be referred the very remarkable case of a man born blind, who obtained sight, by means of an operation, at an advanced period of life.* This person was at first dazzled; he could distinguish nothing as to the magnitude and distance of objects. Every thing appeared so near, that he wanted to handle them. A considerable time, and long practice, were requisite to bring him to the real use of sight. He was under the necessity of serving a long apprenticeship, such as we perform during the term of childhood, and of which we afterwards preserve no recollection.

This it is which instructed us, that an object appears to us so much the more clear and distinct as it is nearer; and reciprocally, than an object which appears clear and distinct is near; and when it appears obscure and indistinct, that it is at a distance. It is thus that painters, by weakening the tints of the objects which they wish to appear remote, and strengthening those which they would represent as nearer, are enabled to determine our judgment, conformably to the effect which they mean to produce. And they succeed so perfectly, that we consider some of the objects represented in painting as more distant than others—an illusion which could not take place, if vision discovered to us the real distance and magnitude of objects.

---

* This was the young man, blind from cataract, on whom our countryman *Chesselden* performed the operation of couching. An account of this interesting case, which is so often referred to, will be found in the *Philosophical Transactions* for 1728, vol. xxxv. p. 447.—Ed.

1*st August* 1760.

Letter XXXV.—Explanation of certain Phenomena relative to Optics.

You have just seen, that vision alone discovers to us nothing respecting either the real magnitude or the distance of objects; and that all we imagine we see, whether as to the distance or magnitude of any object, is the effect of judgment. We must carefully distinguish that which the senses represent to us, from what judgment adds, in which we frequently deceive ourselves. Many philosophers, who have declaimed against the accuracy of the senses, and who meant thence to infer the uncertainty of all human knowledge, have confounded the proper representations of our senses with judgment.

This is their mode of reasoning: We see the sun no bigger than a trencher, though it be infinitely greater; therefore the sense of seeing deceives us; therefore all our senses deceive us; at least, we cannot depend on them; therefore, all the knowledge we acquire by means of the senses, is uncertain, and probably false: We, therefore, know nothing. Such is the reasoning of these sceptics, who boast so vaingloriously of their ingenuity; though there be nothing so easy as to say, that every thing is uncertain; and the greatest dunce may make a shining figure in this sublime philosophy. But it is absolutely false, that the sight represents to us the sun no bigger than a pewter plate; it determines nothing whatever respecting his magnitude; it is our judgment alone that deceives us. When the objects, however, are not very distant, we can pronounce with tolerable exactness on their dimensions and distances; and the other senses joined to the degree of clearness with which we see these same objects, render our judgments sufficiently certain. Now, as soon as we have the idea of the distance of an object, we form to ourselves, likewise, that of its real magnitude, knowing that it depends on that distance. Hence, the more distant we reckon an object to be, the greater we conclude is its magnitude; and reciprocally, the nearer we conclude it is, the smaller we suppose it. We, of course, frequently take one body for another of much greater magnitude, when a suspension of judgment prevents our taking distance into the account. The reason is, that a very large body may be seen at a great distance, under the same angle as a small object placed near us.

There is another phenomenon well known to every one, and which has given occasion to many disputes among the learned, and which it is now perfectly easy to explain. The full moon appears to every eye at the time of her rising to be much greater than when she has got to a considerable height above the horizon, though the visual angle of the apparent magnitude be the same. The sun, too, at the time of rising and setting, appears to every one greater than at noon. What then is the foundation of this judgment, so universal, and so false? It is undoubtedly because we judge the sun and the moon in the horizon to be at a greater distance from us than when they have got to a considerable height.

But how come we to form such a judgment? The common answer is, that when the sun and the moon are in the horizon, we perceive a great many objects between them and us which seem to increase their distance; whereas when the sun and moon have

risen to a great height, we perceive nothing between them and us, and therefore conclude that they are nearer. I know not whether this explanation will be satisfactory. It may be objected, that an empty apartment appears greater than one completely furnished, though the size be exactly the same; several intervening objects, therefore, do not always lead us to imagine that one more remote is at a greater distance than is really the case. I flatter myself that the following solution will be deemed more natural, and better founded.

Let the circle A (PLATE I. *Fig.* 13.) represent the earth, and the dotted circle the atmosphere or air with which the earth is surrounded; suppose yourself stationed at the point A, if the moon is in the horizon, the rays will reach you in the direction of the line B A; but in her extreme height, the rays will descend in the line C A. In the first case the rays pass through the greater space B A, and in the second case through the smaller space C A. Now you will please to recollect, that the rays of light which pass through a transparent medium have their force diminished in proportion to the length of the passage. The atmosphere or air, then, being a transparent medium, the ray B A must in its passage lose much more of its force than the ray C A. Hence it follows in general, that all the celestial bodies appear much less brilliant in the horizon than when fully risen and elevated. We are able to look directly even at the sun when he is in the horizon; but when once he has gained a certain height, the eye is constrained to shrink from his lustre.

I conclude from this that the moon, too, appears less brilliant in the horizon than when elevated.*

---

* A more complete explanation of this phenomenon will be found in Dr. Smith's *Optics*, vol. i. p. 63. He shows that the apparent figure of the sky resembles B F E D (PLATE I. *Fig.* 32.), being much less than a

Now you will recollect what I said a little above, in speaking of effect in painting, that the same object appears to us more distant when its light is weakened: the moon, then, being in the horizon, must appear more distant than at any point of elevation. The consequence is obvious; as we judge the distance of the moon greater in the horizon, we must likewise judge her magnitude greater. And in general all the stars, when near the horizon, appear to us greater, because their apparent distance is greater.

3d August 1760.

Letter XXXVI.—Of Shadow.

I have endeavoured to explain almost all that is usually treated of in optics. All that remains is to speak of shadow. You already know too well what is meant by *shade* or *shadow*, to render it necessary for me to dwell long on the subject. Shadow always supposes two things: a luminous body, and an opaque body, which does not transmit the rays of light. The opaque body, then, prevents the rays of

---

hemisphere; and considering that the moon at $m\,n$ subtends an angle $m\,O\,n$ equal to the angle $o\,O\,p$, which it subtends at $o\,p$, he concludes that the moon must appear much larger at $o\,p$ than at $m\,n$, in consequence of its being supposed to be at a much greater distance. When a star seemed to be half way between the horizon and the zenith, Dr. Smith found its real altitude to be only 23°; and upon this principle he constructed the following table:—

Sun or Moon's altitude, in degrees.	Apparent Diameters, or Distances.
0	100
15	68
30	50
45	40
60	34
75	31
90	30

Ed.

a luminous body from getting behind it, and the space which the rays cannot reach from this interception, is called the shadow of the opaque body; or, what comes to the same thing, shadow includes all that space in which the luminous body is not to be seen, because the opaque body obstructs its rays.

Let A (Plate I. *Fig.* 14.) be a luminous point, and B C D E an opaque body. Draw the extreme rays A B M, A D N, touching the opaque body. It is evident that no ray of light proceeding from A can penetrate into the space M B E D N; and in whatever point within that space the eye may be placed, at O, for example, it will not see the luminous body. This space is the shadow of the opaque body; and we see that it is continually increasing, and may extend to infinity. But if the body from which the rays proceed be itself of great magnitude, the determination of the shadow is somewhat different. There are three cases which demand consideration; the first is, when the luminous body is less than the opaque; the second, when they are equal; and the third, when the luminous body is the greater. The first case is that which we have now been considering, in which the light is smaller than the opaque body.

The second is represented in (Plate I. *Fig* 15.), where the luminous body A is of the same magnitude with the opaque body B C E D. If you draw the extreme rays A B M, A E N, the space M B E N will be shaded, and through the whole of that space it will be impossible to see the luminous body. You see likewise that the lines B M and E N are parallel, and that the shadow extends to infinity, always preserving the same breadth.

The third case is exhibited in (Plate I. *Fig*. 16), where the luminous body A A is greater than the opaque body B C E D. The extreme rays touching the opaque body in B and E, if produced, will meet in the point O, and the space of the shadow B O E becomes finite, and terminates in O. The shade in this case is termed conical. It is only into this space that the light has no admission, and in which it is impossible to see the luminous body. To this third case belong the shadows of the celestial bodies, which are much smaller than the luminous body which enlightens them, namely, the sun.

We have here, then, another display of the Creator's wisdom. For if the sun were smaller than the planets, their shadows would not be terminated, but extend to infinity, which would deprive immense spaces of the benefit of the sun's light. But the magnitude of that luminary surpassing by so many times that of the planets, their shadows are contracted to very narrow bounds, from which alone the light of the sun is excluded.

It is thus that the earth and the moon project their conical shadows; and the moon may occasionally plunge into the shadow of the earth either partially or totally. When this takes place, we say the moon is eclipsed, either wholly or in part. In the former case we call it a total eclipse of the moon; in the other, a partial eclipse. The moon, likewise, projects her shadow, but it is smaller than that of the earth. It may happen, however, that the shadow of the moon should extend as far as to the earth; and then those who are involved in that shadow, undergo an eclipse of the sun. An eclipse of the sun, then, takes place when the moon, interposing, prevents our seeing the sun wholly, or in part. We see not the sun by night, though there be no eclipse; but we are then in the shadow of the earth, which causes our greatest obscurity.

Hitherto we have considered only the cases in which the rays of light are transmitted in straight lines, which is the professed object of optics. But

it has been already remarked, that the rays of light are sometimes reflected, and sometimes broken or refracted. You will recollect, that when the rays fall on a well-polished surface, such as a mirror, they are reflected from that surface; and when they pass from one transparent medium to another, they undergo refraction, and are in some sense broken. Hence arise two other sciences. That which considers vision in reference to reflected rays, is called *Catoptrics;* and that which has for its object vision, in reference to broken or refracted rays, is termed *Dioptrics.* Optics treat of vision relatively to direct rays of light. I shall present you with a summary of these two sciences, catoptrics and dioptrics, as they disclose phenomena which are every day presenting themselves, and of which it is of importance to investigate the causes and the properties. Every thing relating to the subject of vision is, beyond contradiction, an object highly worthy of exciting curiosity, and of engaging attention.

5th August 1760.

LETTER XXXVII.—OF CATOPTRICS, AND THE REFLECTION OF RAYS FROM PLAIN MIRRORS.

CATOPTRICS treat of vision relatively to reflected rays. When rays of light fall on a well-polished surface, they are reflected in such a manner that the angles on all sides are equal among themselves.

To set this in a clear light, let A B (PLATE I. *Fig.* 17.) be the surface of a common mirror, and P a luminous point, whose rays P Q, P M, P *m*, fall upon the mirror. Of all these rays, let P Q be that which falls perpendicularly on the mirror, and which has this particular and remarkable property, that it is reflected upon itself in the direction of Q P; just as on a billiard table, when the ball is struck perpendicularly against the ledge, it is repelled in the selfsame direction. But every other ray, as P M, is reflected in the line M N, in such a manner, as to make the angle A M N equal to the angle B M P; in which it is to be remarked, that the ray P M is named the incident ray, and M N the reflected ray. In like manner, to the incident ray P *m*, will correspond the reflected ray *m n*; and, consequently, because of the reflection, the ray P M is continued in the direction of the line M N, and the ray P *m* in the direction of *m n*, so that we have the angle A M N, equal to B M P, and the angle A *m n*, equal to the angle B *m* P. This property is thus enounced: *The angle of reflection is always equal to the angle of incidence.*

I have already taken notice of this striking property; but my design, at present, is to show what the phenomena in vision are, which result from it. First, it is evident, that an eye, placed at N, will receive from the luminous point P, the reflected ray M N; thus the ray which excites in that eye the sensation of the body from whence it proceeded, comes in the direction M N, just as if the object P were in some point of that line; hence it follows that the eye must see the object P in the direction N M.

In order the more clearly to elucidate this fact, we must have recourse to geometry; and you will recollect with pleasure the propositions on which the following reasoning is founded. Let the perpendicular ray P Q be produced on the other side the mirror to R, so that Q R shall be equal to P Q; I will show you that all the reflected rays, M N, and *m n* being produced behind the mirror, must meet in that point. For, taking the two triangles P Q M and R Q M, they have first the side M Q common to both; then the side Q R was made equal to the side P Q; and, finally, the angle P Q M being a right angle, its adjacent angle R Q M must likewise be a right angle (Euclid's Elements, Book I. Prop. 13.) Therefore these two triangles, having each an equal angle contained by two equal sides, shall be every way equal (Euclid, Book I. Prop. 4.), and consequently the angle P M Q equal to the angle R M Q. But the angle A M N, and the angle R M Q, being vertical, are equal to each other (Euclid, Book I. Prop. 15.), therefore also the angle A M N shall be equal to the angle P M Q; that is, the angle of reflection shall be equal to the angle of incidence.

In the same manner it is demonstrated, that the reflected ray *m n* being produced, would likewise pass through the point R, and consequently produce in the eye the same effect as if the object P were actually placed behind the mirror at R, this point being in the perpendicular P Q R, at the same distance as P from the surface of the mirror, but on different sides. This will enable you to comprehend clearly why mirrors represent objects as if they were behind them; and why we judge that these objects are placed as far behind the surface of the mirror as they really are before it. It is thus that the mirror transports objects into another place, without changing their appearance. To distinguish in the mirror that apparent object from the real, we name the apparent object the image, and we say that the images represented by reflected rays are behind the mirror. This denomination serves to distinguish real objects from the images of them represented in mirrors; and the images which we see in mirrors are perfectly equal and similar to the objects, with this exception, that what in the object is on the left appears in the image on the right, and reciprocally. Thus a person wearing his sword on the left side, appears with it in the mirror on his right.

From what has been said, it is always easy to settle the image of any object whatever behind the mirror.

For A B (PLATE I. *Fig.* 18.) being a mirror, and E F an object, say an arrow: draw from the points E and F the perpendiculars E G and F H, to the surface of the mirror, and produce these to *e* and *f*, so that E G shall be equal to *e* G, and F H to *f* H, *e f* will be the image sought, which will be equal to the object E F, because the quadrilateral figure G *e f* H is in all respects equal to the quadrilateral figure G E F H. It must be still farther remarked, that were you even to cut off from the mirror a part, as C B, and A C was the mirror, the image *e f* would not be changed. And consequently when the mirror is not sufficiently large to admit the falling of the perpendiculars E G and F H upon it, we must suppose the plane of the mirror to be extended, as we produce lines in geometry when we want to let fall perpendiculars upon them. What I have said respects only common mirrors, whose surface is perfectly plain. Convex and concave mirrors produce different effects.

7th August 1760.

LETTER XXXVIII.—REFLECTION OF RAYS FROM CONVEX AND CONCAVE MIRRORS. BURNING MIRRORS.

EVERY thing relating to the reflection of rays is reduced, as you have seen, to two things; the one of which is the place of the image which the reflected rays represent; and the other the relation of the image to the object. In ordinary or plain mirrors, the image of the object is behind the mirror, at a distance equal to that of the object before the mirror, and it is equal and similar to the object. To both of these circumstances we must attend when the mirror is not plain; but when its surface is convex or concave; for in either case the image is, for the most part, strangely disfigured. You must frequently have remarked that on presenting any object before a spoon very highly polished, you see its image greatly disfigured, whether reflected from its interior surface, which is concave, or from its exterior, which is convex.

A globe of silver, finely polished, represents objects with sufficient accuracy, but in miniature. If the interior surface of the globe is well polished, objects appear upon it magnified; provided always that they are not too distant. For the same objects may likewise appear smaller and inverted, if they are removed far from the mirror. There is no occasion to take a whole globe; any part of its surface whatever produces the same effect. These mirrors are denominated spherical; and there are two sorts of them. The one is convex and the other concave, according as they are taken on the exterior or interior surface of the sphere. They are compounded of various metals, susceptible of a fine polish; whereas plain mirrors are made of a plate of glass, and covered on one side with a preparation of mercury, designed to stop the passage of the rays, and to reflect them. I begin with convex mirrors.

Let A C B (PLATE I. *Fig.* 19.) be a mirror, the segment of a sphere, whose centre is G. If you place before this mirror an object E, at a great distance, its image will appear behind the mirror, at the point D, the middle point of the radius of the sphere C G; and the magnitude of this image will be to that of the object in the relation of the lines C D and C E: it will therefore be in this case much smaller than the object, as the line C D is in effect much smaller than the line C E. If the object E approaches to the mirror, so likewise will its image. This is all demonstrable on geometrical principles, by supposing that any incident ray whatever, say E M, is reflected in the direction of M N, so that the angle B M N may be equal to the angle C M E. Thus, when the eye is at N, receiving the reflected ray M N, it will see the object E, according to that direction, and will observe it in the mirror at the point D; or, in other words, D will be the image of the object placed at E, but smaller. It is likewise easy to see, that the smaller the sphere is, of which the mirror is a segment, the more likewise is the image diminished.

I proceed to concave mirrors, the use of which is very common on many occasions. Let A C B (PLATE I. *Fig.* 20.) be a mirror, forming part of a sphere, whose centre is G, and G C a radius. Let us suppose an object E very distant from the mirror, its image will appear before the mirror at D, the middle point of the radius C G; for any ray of light whatever, E M, from the object E, falling on the surface of the mirror at the point M, will be reflected thence in such a manner as to pass through the point D; and when the eye is placed at N, it will see the object at D; but this image will be to the object in the ratio of C D to C E, and consequently in this case smaller than it. And when you bring the object nearer to the mirror, the image retires; the object being placed even at the centre G, the image is there likewise. If you bring the object still forward to D, the image will retire infinitely beyond E. But if the object be placed still farther forward, between C and D, the image will fall behind the mirror, and appear greater than the object.

When you look at yourself in such a mirror, at some point between D and C, your face will appear frightfully large. This is explained by the nature of reflection, in virtue of which the angle of incidence E M A is always equal to the angle of reflection C M N. To this species must be referred burning mirrors, and every concave mirror may be employed to burn. This remarkable property merits a more particular explanation.

Let A B C (PLATE I. *Fig.* 21.) be a concave mirror, whose centre is G, and instead of the object, let the sun be at E; his reflected rays will represent the image of the sun at D, the middle point between C and G. Now, the magnitude of this image will be determined by the extreme rays S C, S C. This image of the sun will be accordingly very small; and as all the rays of the sun which fall on the mirror A B C are reflected in this image, they will be collected there, and will have so much more force, as the image D is smaller than the surface of the mirror. But the rays of the sun are endowed with the property of heating the bodies on which they fall, as well as that of illuminating them; hence it follows, that there must be at D a great degree of heat; and when the mirror is sufficiently large, this heat may become stronger than the most ardent fire. In fact, by means of such a mirror you may burn in an instant any combustible body, and even melt metals of every kind. It is the image of the sun alone which produces these surprising effects. This image is usually denominated the focus of the mirror; it falls always in the middle point of the radius C G, between the mirror and its centre G.

You must carefully distinguish *burning mirrors* from *burning glasses*, of which I shall give some account in my next letter.

9th August 1760.

LETTER XXXIX.—OF DIOPTRICS.

HAVING explained the principal phenomena of *Catoptrics*, which result from the reflection of the rays of light, I proceed to treat of *Dioptrics*, whose object is to unfold the phenomena of the refraction of rays, which takes place when they pass through different transparent mediums. A ray of light does not pursue the same straight line, unless it continues its progress through the same medium. As soon as it enters another transparent medium, it changes its direction more or less, according as it falls upon it more or less obliquely. There is only one case in which it pursues a rectilinear course, namely, when it enters the other medium perpendicularly.

The instruments principally to be considered in dioptrics, are the glasses employed in the construction of telescopes and microscopes. These glasses are of a circular form, but with two faces. Every thing relating to them is reducible to the figure of these two faces, which may be plain, or convex, or concave. Their convexity, or concavity, is always equal to that of a sphere, of which the radius must be known, it being considered as the measure of the curve of those surfaces. This being laid down, we shall have several kinds of dioptric glasses.

The first species, No. I. (PLATE I. *Fig*. 22.), is that whose two faces are plain. By cutting a circular piece out of a plate of glass of equal thickness, we shall have one of this species, which makes no change on objects either as to magnitude or distance. Glass No. II. has one of its surfaces plain, and the other convex; and such are termed *plano-convex.* The third species, No. III., has one face plain, and the other concave; and these are called *plano-concave.* The fourth, No. IV., has two convex surfaces; and is called *double-convex.* No. V. has two concave surfaces, and is called *double-concave.* The species Nos. VI. VII. have one surface convex, and the other concave; and we give them the name of *meniscus.* All these lenses are reducible to two classes; the one containing those in which convexity prevails, as Nos. II. IV. VI.; in the other, concavity is predominant, namely, Nos. III. V. VII. The former class is simply denominated convex, and the latter concave. These two classes are distinguished by the following property.

Let A B (PLATE I. *Fig*. 23.) be a convex glass, exposed to a very distant object, E F, whose rays, G A, G C, G B, fall on the glass, and passing through it, undergo a refraction, which will take place in such a manner, that the rays proceeding from the point G shall meet on the other side of the glass in the point *g*. The same thing will happen to the rays which proceed from every point of the object. By this alteration all the refracted rays, A *l*, B *m*, C *n*, will pursue the same direction as if the object were at *e*, *g*, *f*, and inverted; and it will appear as many times smaller as the distance C *g* shall be contained in the distance C G. We say, then, that such a glass represents the object E F behind it at *e f;* and this representation is called the *image*, which is consequently inverted, and is, with the object itself, in the ratio of the distances of the glass from the image, and of the glass from the object.

It is clear, then, that if the sun were the object, the image represented at *e f* would be that of the sun; though very small, it will be so brilliant as to dazzle the eye, for all the rays which pass through the glass meet in this image, and they exercise their double power of giving light and heat. The heat there is nearly as many times greater as the surface of the glass exceeds in magnitude the image of the sun, named its *focus*, from which, if the glass be very great, you may produce the greatest effects of heat. Combustible substances placed in the focus of such a glass, are instantly consumed. Metals are melted, and even vitrified by it; and other effects are produced far beyond the reach of the most active and intense fire.

The reason is the same as in the case of burning mirrors. In both, the rays of the sun, diffused over the whole surface of the mirror or glass, are collected in the small space of the sun's image. The only difference is, that in mirrors the rays are collected by reflection, and in glasses by refraction. Such is the effect of convex glasses, which are thicker in the middle than at the extremities, and which I have represented in Nos. II. IV. and VI. Those represented in Nos. III. V. and VII. are thicker at the extremities than at the middle; and being all comprehended under the term concave, produce a contrary effect.

Let A C B (Plate I. *Fig.* 24.) be a glass of this form. If you expose to it, at a great distance, the object E G F, the rays G A, G C, G B, proceeding from the point G, will undergo a refraction, on leaving the glass in the direction of A *l*, C *m*, and B *n*, as if they had issued from the point *g*; and an eye placed behind the glass, at *m*, for example, will see the object just as if it were placed at *e g f*, and in a situation similar to that in which it is at the point G, but as many times smaller as the distance C G exceeds the distance G *g*. Convex glasses, then, represent the image of a very distant object behind them, concave glasses represent it before them; the former represent it inverted, and the latter in its real situation. In both the image is as many times smaller as the distance of the object from the glass exceeds that of the glass from the image. On this property of glasses is founded the construction of telescopes, spectacles, and microscopes.

11*th August* 1760.

LETTER XL.—CONTINUATION. OF BURNING GLASSES, AND THEIR FOCUS.

Convex glasses furnish some farther remarks, which I beg leave to lay before you. I speak here of those glasses in general which are thicker in the middle than at the extremities; whether both surfaces be convex, or one plain and the other convex; or, finally, one concave and the other convex; provided, however, that the convexity exceed the concavity, or that the thickness be greater at the middle than at the extremities. It is farther supposed, that the glasses have a spherical figure.

They have first this property, that being exposed to the sun, they present behind them a focus, which is the image of that luminary, and which is endowed, like it, with the property of illuminating and burning. The reason is, that all the rays issuing from the sun, and falling on this surface, are collected by the refraction of the glass into a single point. The same thing happens, whatever be the object exposed to such a glass; it always presents the image of it, which you see instead of the object itself. The following figure will render what I have said more intelligible.

Let A B C D (Plate I. *Fig.* 25.) be a convex glass, before which is placed an object E G F, of which it will be sufficient to consider the three points E, G, F. The rays which, from the point E, fall upon the glass, are contained in the space A E B; and are all collected in the space A *e* B by refraction, so as to meet in the point *e*. In the same manner the rays from the point G, which fall on the glass, and which fill the space A G B, are comprehended by means of refraction in the space A *g* B, and meet in the point *g*. Finally, the rays from the point F, which fall on the glass in the angle A F B, are refracted so as to meet in the point *f*. Thus we shall have the image *e g f* in an inverted position behind the glass; and an eye placed at O, behind the image, will be affected in the same manner as if the object were at *e g f* inverted, and as many times smaller as the distance D *g* is smaller than the distance C G.

In order to determine the place of the image *e g f*, we must attend as well to the form of the glass as to the distance of the object. As to the first, it may be remarked, that the more convex the glass is, in other words, the more that the thickness of the middle C D exceeds that of the extremities, the nearer the image will be to its surface. With regard to the distance, if you bring the object E F nearer to the glass, its image *e f* retires from it, and reciprocally. The image cannot be nearer to the glass than when the object is at a very great distance from it; it is then at the same distance as that of the sun would be, which is denominated the focus of the lens. When the object, then, is very distant, the image falls in the very focus; and the nearer you bring the object to the glass, the farther the image retires from it, and that in conformity to a law in dioptrics, by means of which you can always determine the place of the image, for every distance of the object, provided you know the focus of the glass, that is, the distance at which it collects the rays of the sun, in a space sufficiently small to set on fire a body exposed to it.

The point where the rays meet is, as has been said, the place of the image. Now, this point is easily found by experience. The different denominations of glasses are derived from it, as when we say, such a glass has its focus at the distance of an inch, another at the distance of a foot, another at the distance of ten feet, and so on; or, more concisely, a glass of an inch, a foot, or ten feet focus. Long telescopes require glasses of a very distant focus, and it is extremely difficult to make them exact. I once paid 150 crowns for one lens, which I sent to the academy of Petersburg; it has its focus at the distance of 600 feet.* I am convinced it was of no great value; but they wished to have it on account of its rarity.

To be satisfied that the representation of the image *e g f*, in Figure 25, is real, you have only to hold at that place a piece of white paper, the particles of which are susceptible of the different kinds of vibrations on which colours depend. Then all the rays from the point E of the object, on meeting at the point *e*, will put the particles of the paper into a movement of vibration similar to that which the point E has, and consequently you will see the point *e* of the same colour as the point E. In like manner the points *g* and *f* will have the same colours as the points G and F of the object; and you will likewise see on the paper all the points of the object expressed in their natural colours; which will represent the most exact and the most beautiful picture of the object. This will succeed perfectly well in a dark room, by applying a convex lens to a hole made in the shutter. You will then see on a sheet

---

* The largest lenses ground by Campani of Bologna, had a focal length of 100 and 136 feet. Huygens presented to the Royal Society two lenses, one of which was 120, and the other 123 feet in focal length.—ED.

of white paper, placed opposite to the aperture in the shutter, all the external objects so exactly painted, that you may trace them with a pencil. Painters make use of such a machine for designing landscapes and other views.*

13th August 1760.

Letter XLI.—Of Vision, and the Structure of the Eye.

I am now enabled to explain the phenomena of vision, which is undoubtedly one of the greatest operations of nature that the human mind can contemplate. Though we are very far short of a perfect knowledge of the subject, the little we do know of it is more than sufficient to convince us of the power and wisdom of the Creator. We discover in the structure of the eye perfections which the most exalted genius could never have imagined.

---

* The theory of light adopted and illustrated by Euler in the preceding letters, was originally proposed by Huygens, in his *Traité de la Lumiere*, published in 1690. In this ingenious work he has shown how all the phenomena of refraction and reflection may be explained and calculated, by the hypothesis, that light consists of undulations of an ethereal medium; and he considers it as supported by the phenomena of double refraction. Notwithstanding the attempts of Euler to revive this theory, it fell into total neglect, and was received in no part of Europe as a branch of sound physics.

About the year 1800, Dr. Thomas Young ventured to maintain it, almost single-handed, against the rest of the philosphical world. He pointed out its applicability to explain a great variety of natural phenomena, that could not be referred to any general principle; and by his discovery of the law of interference, he may be said to have established the theory of undulations. The singular phenomena of the polarization, and the double refraction of light, which were afterwards discovered, have successively found an explanation in the theory of undulations; and some of the recent discoveries in that branch of optics may be considered as placing it upon the firmest basis.

The Newtonian doctrine, of the emanation of luminous particles, we have always regarded as the true one. A partiality for the name of its great founder,—the simplicity with which it explains the general phenomena, and perhaps a portion of national feeling, have conspired to give it permanency in this country. The force of truth, however, compels us to acknowledge, that the theory of undulations is likely to be soon adopted by every philosopher who has studied the vast variety of phenomena which it embraces and explains. An account of the Huygenian theory of light will be found in the *Edinburgh Encyclopædia*, Art. Optics, vol. xv. p. 524.—Ed.

I shall not detain you at present with an anatomical description of the eye. It is sufficient to remark, that the exterior membrane *a* A *b* (Plate I. *Fig.* 26.) is transparent, and is called the *Cornea* of the eye; behind this, on the inside, is another membrane *a′ m*, *b′ m*, circular and coloured, which we call the *Iris*, in the middle of which is an aperture *m m*, called the *Pupil*, which appears to us to be black. We find behind this aperture, the *Crystalline humour*, *b* B C *a*, which is a body somewhat resembling in form a small burning glass; it is perfectly transparent, and is covered with a thin membrane, called its *Capsule*. Behind the crystalline humour the cavity of the eye is filled with a transparent jelly, called the *vitreous humour*. The anterior space between the thick coat *a* A *b*, and the crystalline *a b*, contains a fluid like water, which, for that reason, is called the *Aqueous humour*.

Here, then, are four transparent substances, through which the rays of light that enter into the eye must pass: 1, the anterior coat, or *cornea*; 2, the *aqueous humour*, between A and B; 3, the *crystalline* *b* B C *a*; 4, the *vitreous humour*. These four substances differ as to density; and the rays passing from one to another, undergo a particular refraction; and they are so arranged, that the rays coming from a point of any object, are still collected within the eye in a point, and there present an image.

The bottom of the eye at E G F, or the *retina*, is furnished with a whitish tissue, adapted to the reception of images: and it is thus, you will please to recollect, that the images of objects may be represented on a white ground. Conformably to the same principle, all the objects, whose rays enter into the eye, are found painted on the retina. Take the eye of an ox, and having removed the exterior parts which cover the retina, you will see all the objects painted there so exactly, that no artist could surpass it, or even arrive at such a degree of perfection. And in order to see any object whatever, the object must always be painted on the retina; and when, unfortunately, any of the parts of the eye are injured, or lose their transparency, the person becomes blind.

But it is not sufficient, in order to our seeing objects, that their images should be painted on the retina; some are blind, though this takes place. Hence we see that images painted on the retina are not, after all, the immediate object of vision, and that the perception of the soul is communicated some other way. The retina is a reticulated contexture of nerves the most subtile, communicating with a great nerve, which, coming from the brain, enters the eye at O, and is denominated the *optic nerve*. These small nerves of the retina are agitated by the rays of light which form the image at the bottom of the eye; and this agitation is transmitted by the optic nerve to the brain. It is there, undoubtedly, that mental perception is formed; but the most dexterous anatomist is unable to pursue these nerves to their source—the union of the soul with the body must for ever remain a mystery.

15*th August* 1760.

LETTER XLII.—CONTINUATION. WONDERS DISCOVERABLE IN THE STRUCTURE OF THE EYE.

IT will not be disagreeable to you, I hope, to contemplate with me, somewhat more attentively, the wonders discoverable in the structure of the eye.

And, first, the pupil presents an object highly worthy of admiration. It is that aperture which we find in the middle of the iris or star *m m*, by which the rays pass into the inside of the eye, and which appears black. The larger it is, the greater quantity of rays can enter into the eye, to form on the retina the image which appears painted there; thus the more the pupil is opened, the more brilliant this image will be.

On carefully examining the human eye, we observe that the aperture of the pupil is sometimes greater and sometimes smaller. It is generally remarked, that the pupil is contracted when exposed to a very strong light; and, on the contrary, very much dilated when the light is faint. This variation is absolutely necessary to the perfection of vision. When we are in a very strong light, the rays being more powerful, fewer of them are wanted to agitate the nerves of the retina; the pupil, accordingly, is then more contracted. Were it more dilated, and consequently admitted more rays, their force would agitate the nerves too violently, and occasion pain. It is for this reason we are unable to look upon the sun without being dazzled, and without experiencing a sensible pain in the bottom of the eye.

Were it possible for us to contract the pupil still more, so as to admit only a very small quantity of rays, we should not be very greatly incommoded by it; but the contraction of the pupil is not in our own power. Eagles possess this advantage, and are able to look directly at the sun; it is accordingly remarked, that their pupil is then so much contracted, as to appear reduced to a point—a clear light requiring a very small dilatation of the pupil. In proportion as the light decreases, the pupil dilates, and in the dark it is so enlarged, as almost to occupy the whole of the iris. If it remained in the same state of contraction as in the light, the rays which enter into it would be too weak to agitate the nerves as much as is necessary to vision; the rays must, therefore, be then admitted in greater abundance, in order to produce a sensible effect.

Were it in our power to open the pupil still more,* we should be able to see in a greater degree of darkness. To this purpose we are told of a person, who, having received a blow on his eye, the pupil was so dilated by it, that he could read and distinguish the minutest objects in the dark. Cats, and several other animals which roam in the dark, have the faculty of enlarging the pupil much more than the human species; and owls have theirs at all times too much dilated to bear even a moderate degree of light.

Now, when the pupil of the human eye dilates or contracts, it is not by an act of the will; man not having the power of dilating or contracting the pupil at pleasure. As soon as he enters into a luminous situation, it spontaneously contracts, and dilates on his return to darkness. But this change is not produced in an instant; it requires a little time for this organ to accommodate itself to circumstances.

---

* Although we cannot do this by muscular exertion, yet by putting a drop of the juice of the Belladonna, or of the Hyoscyamus, upon the eye, the pupil will dilate itself in an extraordinary degree, and retain itself in that state for *one* or *two* hours.—Ed.

You must, no doubt, have remarked, that as often as you make a very sudden transition from a clear light to a dark place, as in the theatre, you could not at first distinguish the company. The pupil was still too narrow to permit the few feeble rays which it admitted to make a sensible impression; but it gradually dilated to receive a sufficiency of rays. The contrary happens when you pass suddenly from darkness to a clear light. The pupil being then very much expanded, the retina is struck in a lively manner, you are quite dazzled, and under the necessity of shutting your eyes.

It is then a very remarkable circumstance, that the pupil should dilate and contract according as vision requires, and that this change should take place almost spontaneously and independently of any act of the will. Philosophers who examine the structure and the functions of the human body, are greatly divided in opinion as to this subject; and there is little appearance that we shall ever have a satisfactory solution of this wonderful phenomenon. The variability of the pupil is, however, an object essentially necessary to vision; and without which it would be very imperfect. But various other particulars are discoverable, equally entitled to admiration.

17*th August* 1760.

LETTER XLIII.—FARTHER CONTINUATION.—ASTONISHING DIFFERENCE BETWEEN THE EYE OF AN ANIMAL, AND THE ARTIFICIAL EYE, OR CAMERA OBSCURA.

THE principle on which the structure of the eye is founded, is in general the same as that according to which I explained the representation of ob-