of soft iron P might likewise be applied there, the better to keep up the current; and in this manner you may easily and speedily magnetize as many double bars as you please.

28th November 1761.

LETTER LXX.—THE METHOD OF COMMUNICATING TO BARS OF STEEL A VERY GREAT MAGNETIC FORCE, BY MEANS OF OTHER BARS WHICH HAVE IT IN A VERY INFERIOR DEGREE.

THOUGH this method of magnetizing by *the double touch* be preferable to the preceding, the magnetic power, however, cannot be carried beyond a certain degree. Whether we employ a natural loadstone, or two magnetic bars, for rubbing other bars, these last will never acquire so much force as the first; it being impossible that the effect should be greater than the cause.

If the bars with which we rub have little force, those which are rubbed will have still less: the reason is evident; for as bars destitute of magnetic force never could produce it in others, so a moderate degree of force is incapable of producing one greater than itself, at least by the method which I have been describing.

But this rule is not to be taken in the strict interpretation of the words, as if it were literally impossible to produce a greater magnetic force by the assistance of a smaller. I am going to point out a method by which the magnetic power may be increased almost as far as you please, beginning with the smallest degree possible. This is a late discovery, which merits so much the more attention that it throws much light on a very difficult subject—the nature of magnetism.

Supposing that I am possessed of a very feeble loadstone, or, for want of a natural magnet, of bars of iron rendered somewhat magnetic merely by the vortex of the earth, as I explained it in a preceding letter, I then provide myself with eight bars of steel, very small, and not hardened, in order the more easily to receive the small degree of magnetic power which the feeble loadstone, or slightly magnetized bars, are capable of communicating, by rubbing each pair or couple in the manner I formerly described. Having then eight bars, magnetic, but in a very small degree, I take two pair, which I join together in the manner represented in *Fig.* 26.

By uniting the two bars by the poles of the same name, I form but one of double the thickness, and with which I form the compass A C and B D; the better to keep up the magnetic current, a piece of soft iron P may be applied at the top C D. The legs of the compass may be separated as far as is judged proper, and I rub with them, one after the other, the remaining bars, which will thereby acquire more power than they had before, because the powers of the first are now united. I have now only to join these two pair newly rubbed in the same manner, and by rubbing with them, one after the other, the two pair first employed, and the power of these will be considerably increased. I afterwards join these two pair together, and go on rubbing others, in order to augment their magnetic force, and still two pair with two pair alternately; and by repeating this operation, the magnetic power may be carried to such a degree as to become insusceptible of farther increase, even by continuing the operation. When we have more than four pair of such bars, instead of two pair, three may be joined together for the purpose of rubbing others; they will thereby be sooner carried to the highest degree possible.

The greatest obstacles are therefore surmounted; and by means of such bars, joined together by two or more pairs, we may rub others of steel properly hardened, and which may be either of the same size, or still greater than the first, to which the greatest power of which they are susceptible may be thus communicated.

Beginning with small bars such as I have described, these operations may be successively applied to bars of an enormous size, and made of the hardest steel, which is less liable to lose the magnetic power. Only it is to be observed, that for the purpose of rubbing large bars, several pairs ought to be joined together, whose united weight should be at least double that of the large one. But it would always be better to proceed by degrees, and to rub each species of bars with bars not much smaller than themselves, or it may be sufficient to join at most two pair: for when we are obliged to join more than two pair, the extremities with which the friction is performed will extend too far, and the magnetic matter which passes that way will itself prevent its being directed conformably to the direction of the bar that is rubbed; and then rather that it enters the bar perpendicularly, whereas it necessarily should take a horizontal direction.

In order to facilitate this change of direction, it is proper that the magnetic matter should be led to it in a small space, and in a direction already approaching to that which it ought to take within the bar which we are going to rub. The following method, I think, might be effectual for this purpose.

Plate V. Fig. 27. represents five pair of bars M M, N N, joined together, but not in the form of a compass. There is at top a bar of soft iron C D, to keep up the vortex; below, I do not rub immediately with the extremities of the bars, but I case these extremities on each side in a foot of soft iron, fastening them to it with screws marked O. Each foot is bent at A and B, so that the direction of the magnetic matter which freely pervades these feet, already has a considerable approximation to the horizontal; so that in the bar to be rubbed E F it has no need greatly to change its direction. I have no doubt, that by means of these feet the bar E F will receive a much greater magnetic power, than if we rubbed immediately by the extremities of the bars, the depth of whose vertical direction naturally opposes the formation of horizontal magnetic canals in the bar E F. It is likewise possible, in practising this method, to contract or extend the distance of the feet A and B at pleasure.

I must farther observe, that when these bars lose in time their magnetic power, it is easily restored by the same operation.

1*st December* 1761.

LETTER LXXI.—CONSTRUCTION OF ARTIFICIAL MAGNETS IN THE FORM OF A HORSE SHOE.

WHOEVER wishes to make experiments on the properties of the loadstone, ought to be provided with a great number of magnetic bars, from a very small, up to a very large size. Each may be considered as a particular magnet, having its two poles, the one north and the other south.

You must have considered it as extremely remarkable, that by the interposition of the magnetic power, the feeblest which can be supplied by a wretched natural loadstone, or by a pair of tongs in the chimney corner, which have acquired by length of time a small portion of magnetism, we should be enabled to increase that power to such a degree, as to communicate to the largest bars of steel the highest degree of magnetic force of which they are susceptible. It would be needless to add, that by this method we are enabled to construct the best magnetic needles, not only much larger than the common, but made of a steel hardened to the highest degree, which renders them more durable. I have only a few words to add on the construction of artificial magnets, which have usually the form of a horse-shoe, as you must no doubt have seen.

These artificial magnets answer the same purposes, on every occasion, as the natural ones, with this advantage in their favour, that we can have them much more powerful, by giving them a sufficient magnitude. They are made of well tempered steel, and the figure of a horse-shoe seems the most proper for keeping up the vortex. When the mechanic has finished his work, we communicate to it the greatest degree of magnetic power of which it is susceptible, by mea of the magnetic bars, of which I have given a description. It is evident, that the greater this magne is, the larger must be the bars we employ; and this is the reason why we should be provided with bars of all sizes.

In order to magnetize a horse-shoe HIG (PLATE V. *Fig*. 28.), which ought to be of steel well tempered, we place on the table a pair of magnetic bars A C and B D, with their supporters of soft iron applied on both sides, but of which the figure represents only one E F, the other having been removed to make way gradually for the application of the feet of the horse-shoe, as you see. In this state, the magnetic matter which pervades the bars will mak strong efforts to pass through the horse-shoe, the poles of the bars being adapted magnetically to thos of the horse-shoe; but considering the hardness of tempered steel, it will not be sufficient to arrang the pores, and open for itself a passage. The sam means, therefore, must be employed to this effec

which were prescribed for the magnetizing of bars. We take a compass formed of another pair of magnetic bars, and rub them in the same manner over the horse-shoe; magnetic canals will thereby be opened, and the subtile matter of the bars, by pervading it, will form the vortex of that fluid. Particular care must be taken, in this operation, that the legs of the compass, in passing over the horse-shoe, do not touch the extremities A and B of the bars; for this would disturb the current of the magnetic matter, which would pass immediately from the bars into the legs of the compass; or, the vortices of the bars and of the compass would mutually derange each other.

The horse-shoe will thereby acquire very great power, being pervaded by an impetuous magnetic current. All that remains to be done, is to detach the bars without deranging the current. If they are separated violently, the magnetic vortex will be destroyed, and the artificial magnet will retain very little power.

The canals being kept up no longer than the magnetic matter pervades them, it must be concluded, that the particles which form these canals are in a forced state, and that this state subsists only while the vortex acts; and that as soon as it ceases, these particles, by their elasticity, will deviate from their forced situation, and the magnetic canals will be interrupted and destroyed. This we clearly see in the case of soft iron, whose pores are quickly arranged on the approach of a magnetic vortex, but retain scarcely any magnetic power when removed out of the vortex. This proves that the pores of iron are moveable, but endowed with an elasticity which changes their situation as soon as force ceases. It requires length of time to fix certain pores in the position impressed on them by the magnetic force, which takes place chiefly in bars of iron long exposed to the vortex of the earth. The pores of steel are much less flexible, and better support the state into which they have been forced: they are however liable to some derangement, as soon as force ceases to act on them; but this derangement is less in proportion to the hardness of the steel. For this reason, artificial magnets ought to be made of the hardest steel: were they to be made of iron, they would immediately acquire, on being applied to magnetic bars, a very great degree of power; but the moment you detach them, all that power would disappear. Great precaution must therefore be employed in separating from the bars magnets composed of well tempered steel. For this purpose, before the separation, you press the supporter, which is of very soft iron, in the direction of the line M N, (Plate V. *Fig.* 29.) taking particular care not to touch the bars with it, for this would mar the whole process, and oblige you to repeat the operation. On the application of the supporter, a considerable portion of the magnetic matter which is circulating in the magnet G H I will make its way through the supporter, and form a separate vortex, which will continue after the magnet is detached from the bars.

Afterwards, you press the supporter slowly forward over the legs of the magnet to the extremities, as represented in the figure, and in this state permit it to rest for some time, that the vortex may be allowed to settle. The supporter is likewise furnished with a weight P, which may be increased every day; it being always understood, that the supporter is to be so perfectly adjusted to the feet of the magnet, as to touch them in all points.*

5th December 1761.

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* An account of Coulomb's improvements on the method of magnetizing bars of steel, will be found in the article *Magnetism*, of the *Edinburg* *Encyclopædia*, vol. xiii. p. 264.—Ed.

Letter LXXII.—On Dioptrics; Instruments which that science supplies: of Telescopes and Microscopes. Different figures given to Glasses or Lenses.

The wonders of dioptrics will now, I think, furnish a subject worthy of your attention. This science provides us with two kinds of instruments composed of glass, which serve to extend our sphere of vision, by discovering objects which would escape the naked eye.

There are two cases in which the eye needs assistance: the first is, when objects are too distant to admit of our seeing them distinctly; such are the heavenly bodies, respecting which the most important discoveries have been made by means of dioptrical instruments. You will please to recollect what I have said concerning the satellites of Jupiter, which assist us in the discovery of the longitude; they are visible only with the aid of good telescopes; and those of Saturn require telescopes of a still better construction.

There are, besides, on the surface of the earth objects very distant, which it is impossible for us to see, and to examine in detail, without the assistance of telescopes, which represent them to us in the same manner as if they were near. These dioptrical glasses or instruments, for viewing distant bodies, are denominated *Telescopes.*

The other case in which the eye needs assistance, is when the object, though sufficiently near, is too small to admit of a distinct examination of its parts. If we wished, for example, to discover all the parts of the leg of a fly, or of any insect still smaller;—if we were disposed to examine the minuter particles of the human body, such as the smallest fibres of the muscles, or of the nerves, it would be impossible to succeed without the help of certain instruments called *Microscopes*, which represent small objects in the same manner as if they were a hundred or a thousand times greater.

Here, then, are two kinds of instruments, *Telescopes* and *Microscopes*, furnished by dioptrics for assisting the weakness of our sight. A few ages only have elapsed since these instruments were invented; and from the era of that invention must be dated the most important discoveries in astronomy by means of the telescope, and in physics by the microscope.

These wonderful effects are produced merely by the figure given to bits of glass, and the happy combination of two or more glasses, which we denominate *Lenses*. Dioptrics is the science that unfolds the principles on which such instruments are constructed, and the uses to which they are applied; and you will please to recollect that it turns chiefly on the direction which rays of light take on passing through transparent media of a different quality; on passing, for example, from air into glass or water, and reciprocally, from glass or water into air.

As long as the rays are propagated through the same medium, as for example air, they preserve the same direction, in the straight lines LA, LB, LC, LD, (Plate V. *Fig.* 21.), drawn from the luminous point L, whence these rays issue; and when they any where meet an eye they enter into it, and there paint an image of the object from which they proceeded. In this case the vision is denominated simple, or natural; and represents to us the objects as they really are. The science which explains to us the principles of this vision, is termed *Optics*.

But when the rays, before they enter into the eye, are reflected on a finely polished surface, such as a mirror, the vision is no longer natural; as in this case we see the objects differently, and in a different place, from what they really are. The science which explains the phenomena presented to us by this vision from reflected rays, is termed *Catoptrics*. It, too, supplies us with instruments calculated to extend the sphere of our vision; and you are acquainted with such sorts of instruments, which, by means of one or two mirrors, render us the same services as those constructed with lenses. These are what we properly denominate *Telescopes*; but in order to distinguish them from the common perspectives, which are composed only of glasses, it would be better to call them catoptric or reflecting telescopes. This mode of expression would at least be more accurate; for the word telescope was in use before the discovery of reflecting instruments, and then meant the same thing with perspective.

I propose at present to confine myself entirely to dioptrical instruments, of which we have two sorts, telescopes and microscopes. In the construction of both we employ glasses formed after different manners, the various sorts of which I am going to explain. They are principally three, according to the figure given to the surface of the glass.

The first is the *plane*, when the surface of a glass is plane on both sides, as that of a common mirror. If you were to take, for example, a piece of looking-glass, and to separate from it the quicksilver which adheres to its farther surface, you would have a glass both of whose surfaces are *plane*, and of the same thickness throughout.

The second is the *convex*; a glass of this denomination is more raised in the middle than toward the edge.

The third is the *concave*; such a glass is hollow toward the middle, and rises toward the edge.

Of these three different figures which may be given to the surface of a glass, are produced the six species of glasses represented in PLATE VI. *Fig.* 2.

I. The *plane* glass has both its surfaces plane.

II. The *plano-convex* glass has one surface plane and the other convex.

III. The *plano-concave* has one surface plane and the other concave.

IV. The *convexo-convex* or *double convex*, has both surfaces convex.

V. The *convexo-concave*, or *meniscus*, has one surface convex, and the other concave.

VI. Finally, the *concavo-concave*, or *double concave*, has both surfaces concave.

It is proper to remark, that the figure represents the section of these glasses or lenses.

8th December 1761.

LETTER LXXIII.—DIFFERENCE OF LENSES WITH RESPECT TO THE CURVE OF THEIR SURFACES. DISTRIBUTION OF LENSES INTO THREE CLASSES.

FROM what I have said respecting the convex and concave surfaces of lenses, you will easily comprehend that their form may be varied without end, according as the convexity and concavity are greater or less. There is only one species of plane surfaces, because a surface can be plane in one manner only; but a convex surface may be considered as making part of a sphere, and according as the radius or diameter of that sphere is greater or less, the convexity will differ; and as we represent lenses on paper by segments of a circle, according as these circles are greater or less, the form of lenses must be infinite, with respect both to the convexity and concavity of their surfaces.

As to the manner of forming and polishing glasses, all possible care is taken to render their figure exactly circular or spherical; for this purpose we employ basins of metal formed by the turning machine, on a spherical surface, both inwardly and outwardly.

Let AEBDFC (PLATE V. *Fig.* 30.) be the form of such a basin, which shall have two surfaces, AEB and CFD, each of which may have its separate radius; when a piece of glass is rubbed on the concave side of the basin AEB, it will become convex; but if it is rubbed on the convex side CFD, it will become concave. Sand, or coarse emery, is at first used in rubbing the glass on the basin, till it has acquired the proper form; and after that a fine species of emery, or pumice stone, to give it the last polish.

In order to know the real figure of the surfaces of a lens, you have only to measure the radius of the surface of the basin on which that lens was formed; for the true measure of the convexity and concavity of surfaces, is the radius of the circle or sphere which corresponds to them, and of which they make a part.

Thus, when it is said that the radius of the convex surface AEB (PLATE VI. *Fig.* 2.) is three inches, the meaning is, that AEB is an arch of a circle described with a radius of three inches, the other surface AB being plane.

That I may convey a still clearer idea of the difference of convexities, when their radii are greater or less, I shall here present you with several figures of different convexity; (see PLATE VI. *Fig.* 1.)

From this you see, that the smaller the radius is, the greater is the curve of the surface, or the greater its difference from the plane; on the contrary, the greater the radius is, the more the surface approaches to a plane, or the arch of the circle to a straight line. If the radius were made still greater, the curve would at length become hardly perceptible. You scarcely perceive it in the arch MN (*Fig.* 2.), the radius of which is six inches, or half a foot; and if the radius were still extended to ten or a hundred times the magnitude, the curve would become altogether imperceptible to the eye.

But this is by no means the case as to dioptrics; and I shall afterwards demonstrate, that though the radius were a hundred or a thousand feet, and the curve of the lens absolutely imperceptible, the effect would nevertheless be abundantly apparent. The radius must indeed be inconceivably great, to produce a surface perfectly plane; from which you may conclude, that a plane surface might be considered as a convex surface whose radius is infinitely great, or as a concave of a radius infinitely great. Here it is that convexity and concavity are confounded, so that the plane surface is the medium which separates convexity from concavity. But the smaller the radii are, the greater and more perceptible do the convexities and concavities become; and hence we say, reciprocally, that a convexity or concavity is greater in proportion as its radius, which is the measure of it, is smaller.

However great in other respects may be the variety we meet with in lenses or glasses, according as their surfaces are plane, convex, or concave, and this in an infinity of different manners; nevertheless, with respect to the effect resulting from them in dioptrics, they may be reduced to the three following classes:—

The first comprehends glasses which are everywhere of an equal thickness; whether their two surfaces be plane and parallel to each other, (Plate VI. *Fig.* 3.) or the one convex and the other concave, but concentric, or described round the same centre (*Fig.* 4.), so that the thickness shall remain everywhere the same. It is to be remarked respecting

glasses of this class, that they produce no change in the appearance of the objects which we view through them; the objects appear exactly the same as if nothing interposed; accordingly, they are of no manner of use in dioptrics. This is not because the rays which enter into these glasses undergo no refraction, but because the refraction at the entrance is perfectly straightened on going off, so that the rays, after having passed through the glass, resume the same direction which they had pursued before they reached it. Glasses, therefore, of the other two classes, on account of the effect which they produce, constitute the principal object of dioptrics.

The second class of lenses contains those which are thicker at the middle than at the edge, (*Fig.* 5.) Their effect is the same, as long as the excess of the thickness of the middle over that of the edge has the same relation to the magnitude of the lens. All lenses of this class are commonly denominated *convex*, as convexity predominates, though otherways one of their surfaces may be plain, and even concave.

The third class contains all those lenses which are thicker at the edge than in the middle (*Fig.* 6.), which all produce a similar effect, depending on the excess of thickness toward the edge over that in the middle. As concavity prevails in all such lenses, they are simply denominated *concave*. They must be carefully distinguished from those of the second class, which are the convex.

Lenses of these two last classes are to be the subject of my following letters, in which I shall endeavour to explain their effects in dioptrics.

12th December 1761.

Letter LXXIV.—Effect of Convex Lenses.

In order to explain the effect produced by both convex and concave lenses, in the appearance of objects, two cases must be distinguished; the one when the object is very far distant from the lens, and the other when it is nearer.

But before I enter on the explanation of this, I must say a few words on what is called the axis of the lens. As the two surfaces are represented by segments of a circle, you have only to draw a straight line through the centres of the two circles; this line is named the axis of the lens. In *Fig.* 7. of Plate VI. the centre of the arch AEB being at C, and that of the arch AFB at D, the straight line CD is denominated the axis of the lens AB; and it is easy to see that this axis passes through the middle of it. The same thing would apply, if the surfaces of the lens were concave. But if one is plane, the axis will be perpendicular to it, passing through the centre of the other surface.

Hence it is obvious, that the axis passes through the two surfaces perpendicularly, and that accordingly, a ray of light coming in the direction of the axis, will suffer no refraction, because rays passing from one medium into another are not broken or refracted, except when they do not enter in a perpendicular direction.

It may likewise be proved, that all other rays passing through the middle of the lens O undergo no refraction, or rather that they again become parallel to themselves.

It must be considered, in order to comprehend the reason of this, that at the points E and F the two surfaces of the lens are parallel to each other, for the angle MEB which the ray ME makes with the arch of the circle EB, or its tangent at E, is perfectly equal to the angle PFA, which this same ray produced, or FP, makes with the arch of the circle AF, or its tangent at F: you recollect that two such angles are denominated alternate, and that it is demonstrated, when the alternate angles are equal, that the straight lines are parallel to each other; consequently, the two tangents at E and at F will be parallel, and it will be the same thing as if the ray MEFP passed through a lens whose two surfaces were parallel to each other. Now we have already seen that rays do not change their direction in passing through such a lens.

Having made these remarks, let us now consider a convex lens AB (Plate VI. *Fig.* 8.), whose axis is the straight line OEFP; and let us suppose that there is in this line, at a great distance from the lens, an object or luminous point O, which diffuses rays in all directions; some of these will pass through our lens AB, such as OM, OE, and ON; of which that in the middle, OE, will undergo no refraction, but will continue its direction through the lens in the same produced straight line FIP. The other two rays, OM and ON, in passing through the lens toward the edge, will be refracted both at entering and departing, so that they will somewhere meet the axis, as at I, and afterwards continue their progress in the direction IQ and IR. It might likewise be demonstrated that all the rays which fall between M and N will be refracted, so as to meet with the axis in the same point I. Therefore, the rays which had no lens interposed, would have pursued their rectilineal direction OM and ON, will, after the refraction, pursue other directions, as if they had taken their departure from the point I; and if there were an eye somewhere at P, it would be affected just as if the luminous point were actually at I, though there be no reality in this. You have only to suppose for a moment, that there is at I a real object, which diffusing its rays, would be equally seen by an eye placed at P, as it now sees the object at O by means of the rays refracted by the lens, because there is at I an image of the object O, and the lens AB there represents the object O, or transports it nearly to I. The point O is therefore no longer the object of vision, but rather its image, represented at I; for this is now its immediate object.

This lens, then, produces a very considerable change: an object very remote O is suddenly transported to I, from which the eye must undoubtedly receive a very different impression from what it would do, if withdrawing the lens, it were to view the object O immediately. Let O be considered as a star; the point O being supposed extremely distant, the lens will represent at I the image of that star, but an image which it is impossible to touch, and which has no reality, as nothing exists at I, unless it be that the rays proceeding from the point O are collected there by the refraction of the lens. Neither is it to be imagined, that the star would appear to us in the same manner as if it really existed at I. How could a body many thousands of times bigger than the earth exist at a point I? Our senses would be very differently struck by it: We must carefully remark, then, that an image only is represented at I, like that of a star represented in the bottom of the eye, or that which we see in a mirror, the effect of which has nothing to surprise us.

15*th December* 1761.

Letter LXXV.—The same Subject: Distance of the Focus of Convex Lenses.

I mean to employ this letter in explaining the effect produced by convex lenses, that is, such as are thicker at the middle than at the edge. The whole consists in determining the change which rays undergo in their progress, on passing through such a glass. In order to place this subject in its clearest light, two cases must be carefully distinguished; the

one when the object is very distant from the lens, and the other when it is at no great distance. I begin with considering the first case, that is, when the object is extremely remote from the lens.

In *Fig.* 9. of Plate VI. MN is the convex lens, and the straight line OAB is its axis, passing perpendicularly through the middle. I remark, by the way, that this property of the axis of every lens, that of passing perpendicularly through its middle, conveys the justest idea of it that we are capable of forming. Let us now conceive that on this axis there is somewhere at O an object OP, which I here represent as a straight line, whatever figure it may really have; and as every point of this object emits its rays in all directions, we confine our attention to those which fall on the lens.

My remarks shall be at present farther limited to the rays issuing from the point O, situated in the very axis of the lens. The figure represents three of these rays, OA, OM, and ON, the first of which, OA, passing through the middle of the lens, undergoes no change of direction, but proceeds, after having passed through the lens, in the same straight line BIS, that is in the axis of the lens; but the other two rays, OM and ON, undergo a refraction both on entering into the glass and leaving it, by which they are turned aside from their first direction, so as to meet somewhere at I with the axis, from which they will proceed in their new direction, in the straight lines MIQ and NIR; so that afterwards, when they shall meet an eye, they will produce in it the same effect as if the point O existed at I, as they preserve the same direction. For this reason, the convex lens is said to transport the object O to I; but in order to distinguish this point I from the real point O, the former is called the image of the latter, which in its turn is denominated the object.

This point I is very remarkable, and when the object O is extremely distant, the image of it is likewise denominated the focus of the lens, of which I shall explain the reason. If the sun be the object at O, the rays which fall on the lens are all collected at I; and being endowed with the quality of heating, it is natural that the concourse of so many rays at I should produce a degree of heat capable of setting on fire any combustible matter that may be placed there. Now, the place where so much heat is collected we call the *focus*; the reason of this denomination with respect to convex lenses is evident. Hence, too, a convex lens is denominated a *burning-glass*, the effects of which you are undoubtedly well acquainted with. I only remark, that this property of collecting the rays of the sun in a certain point, called their focus, is common to all convex lenses: they likewise collect the rays of the moon, of the stars, and of all very distant bodies; though their force is too small to produce any heat, we nevertheless employ the same term, focus: the focus of a glass, accordingly, is nothing else but the spot where the image of very distant objects is represented; to which this condition must still be added, that the object ought to be situated in the very axis of the lens; for if it be out of the axis, its image will likewise be represented out of the axis. I shall have occasion to speak of this afterwards.

It may be proper still farther to subjoin the following remarks respecting the focus:—

1. As the point O, or the object, is infinitely distant, the rays OM, OA, and ON, may be considered as parallel to each other; and, for the same reason, parallel to the axis of the lens.

2. The focus I, therefore, is the point behind the glass, where the rays parallel to the axis which fall on the lens are collected by the refraction of the lens.

3. The focus of a lens, and the spot where the image of an object, infinitely distant, and situated in the axis of the lens, is represented, are the same thing.

4. The distance of the point I behind the lens, that is the length of the line B I, is called the distance of the focus of the lens. Some authors call it the *focal distance*, or *focal length*.

5. Every convex lens has its particular distance of focus—one greater, another less—which is easily ascertained by exposing the lens to the sun, and observing where the rays meet.

6. Lenses formed by arches of small circles, have their focuses very near behind them; but those whose surfaces are arches of great circles, have more distant focuses.

7. It is of importance to know the focal distance of every convex lens employed in dioptrics; and it is sufficient to know the focus, in order to form a judgment of all the effects to be expected from it, whether in the construction of telescopes or microscopes.

8. If we employ lenses equally convex on both sides, so that each surface shall correspond to the same circle, then the radius of that circle gives nearly the focal distance of that lens; thus, to make a burning-glass which shall burn at the distance of a foot, you have only to form the two surfaces arches of a circle, whose radius is one foot.

9. But when the lens is plano-convex, its focal distance is nearly equal to the diameter of the circle, which corresponds to the convex surface.

Acquaintance with these terms will facilitate the knowledge of what I have farther to advance on this subject.

19th December 1761.

LETTER LXXVI.—DISTANCE OF THE IMAGE OF OBJECTS.

HAVING remarked that an object infinitely distant is represented by a convex lens in the very focus, provided the object be in the axis of the lens, I proceed to nearer objects, but always situated in the axis of the glass; and I observe, first, that the nearer the object approaches to the lens, the farther the image retires.

Let us accordingly suppose that F (PLATE VI. *Fig.* 10.) is the focus of the lens M M, so that when an object is infinitely distant before the glass, or at the top of the figure, the image shall be represented at F; on bringing the object nearer to the glass, and placing it successively at P, Q, R, the image will be represented at the points *p*, *q*, *r*, more distant from the lens than the focus: in other words, if A P is the distance of the object, B *p* will be the distance of the image; and if A Q is the distance of the object, B *q* will be that of the image; and the distance B *r* of the image will correspond to the distance A R of the object.

There is a rule by which it is easy to calculate the distance of the image behind the lens, for every distance of the object before it, but I will not tire you with a dry exposition of this rule; it will be sufficient to remark, in general, that the more the distance of the object before the glass is diminished, the more is the distance of the image behind it increased. I shall to this subjoin the instance of a convex lens, whose focal distance is six inches, or of a lens so formed, that if the distance of the object is infinitely great, the distance of the image behind the lens shall be precisely six inches; now, on bringing the object nearer to the lens, the image will retire, according to the gradations marked in the following table:

Distance of the Object.	*Distance of the Image.*
Infinity.	6
42	7
24	8
18	9
15	10
12	12
10	15
9	18
8	24
7	42
6	Infinity.

Thus the object being 42 inches distant from the lens, the image will fall at the distance of 7 inches, that is one inch beyond the focus. If the object is at the distance of 24 inches, the image will be removed to the distance of 8 inches from the lens, that is two inches beyond the focus; and so of the rest.

Though these numbers are applicable only to a lens whose focal distance is 6 inches, some general consequences may, however, be deduced from them.

1. If the distance of the object is infinitely great, the image falls exactly in the focus.

2. If the distance of the object is double the distance of the focus, the distance of the image will likewise be double the distance of the focus; in other words, the object and the image will be equally distant from the lens. In the example above exhibited, the distance of the object being 12 inches, that of the image is likewise 12 inches.

3. When the object is brought so near the lens, that the distance is precisely equal to that of the focus, say 6 inches, as in the preceding example,

then the image retires to an infinite distance behind the lens.

4. It is likewise observable in general, that the distance of the object and that of the image reciprocally correspond; or if you put the object in the place of the image, it will fall in the place of the object.

5. If, therefore, the lens MM (Plate VI. *Fig.* 11.) collects at I the rays which issue from the point O, the same lens will likewise collect at O rays issuing from the point I.

6. It is the consequence of a great principle in dioptrics, in virtue of which it may be maintained, that whatever are the refractions which rays have undergone in passing through several refracting media, they may always return in the same direction.

This truth is of much importance in the knowledge of lenses: thus, when I know, for example, that a lens has represented, at the distance of 8 inches, the image of an object 24 inches distant, I may confidently infer, that if the object were 8 inches distant, the same lens would represent its image at the distance of 24 inches.

It is farther essential to remark, that when the distance of the object is equal to that of the focus, the image will suddenly retire to an infinite distance; which perfectly harmonizes with the relation existing between the object and the image.

You will no doubt be curious to know in what place the image will be represented when the object is brought still nearer to the lens, so that its distance shall become less than that of the focus. This question is the more embarrassing, that the answer must be, the distance of the image will in this case be greater than infinity, since the nearer the object approaches the lens, the farther does the image retire. But the image being already infinitely distant, how

is it possible that distance should be increased? The question might undoubtedly puzzle philosophers, but is of easy solution to the mathematician. The image will pass from an infinite distance to the other side of the lens, and consequently will be on the same side with the object. However strange this answer may appear, it is confirmed, not only by reasoning, but by experience, so that it is impossible to doubt of its solidity; to increase beyond infinity is the same thing with passing to the other side: this is unquestionably a real paradox.

22d December 1761.

Letter LXXVII.—Magnitude of Images.

You can no longer doubt that every convex lens must represent somewhere the image of an object presented to it; and that in every case the place of the image varies as much according to the distance of the object as according to the focal distance of the lens: but a very important article remains yet to be explained, I mean the magnitude of the image.

When such a lens represents to us the image of the sun, of the moon, or of a star, at the distance of a foot, you are abundantly sensible that these images must be incomparably smaller than the objects themselves. A star being much greater than the whole earth, how is it possible that an image of such magnitude should be represented to us at the distance of a foot? But the star appearing to us only as a point, the image represented by the lens likewise resembles a point, and consequently is infinitely smaller than the object itself.

There are, then, in every representation made by lenses, two things to be considered; the one respects the place where the image is represented, and the other the real magnitude of the image, which may be very different from that of the object. The first being sufficiently elucidated, I proceed to furnish you with a very simple rule, by which you will be enabled in every case to determine what must be the magnitude of the image represented by the lens.

Let O P (Plate VI. *Fig.* 9.) be any object whatever situated on the axis of the convex lens M N; we must first look for the place of the image, which is at I, so that the point I shall be the representation of the extremity O of the object, as the rays issuing from the point O are there collected by the refraction of the lens. Let us now see in what place will be represented the other extremity P of the object; for this purpose let us consider the rays P M, P A, P N, which, issuing from the point P, fall on the lens. I observe that the ray P A, which passes through the middle of the lens, does not change its direction, but continues its progress in the straight line A K S; it will be therefore somewhere in this line at K, that the other rays P M and P N will meet: in other words, the point K will be the image of the other extremity P of the object, the point I being that of the extremity O: hence it is easy to conclude that I K will be the image of the object O P, represented by the lens.

In order then to determine the magnitude of this image, having found the place I, you have only to draw from the extremity P of the object, through A, the middle of the lens, the straight line P A K S, and to raise from I the line I K perpendicular to the axis, and this line I K will be the image in question; it is evident from this that the image is reversed, so that if the line O R were horizontal, and the object O P a man, the image would have the head K undermost, and the feet I uppermost.

On this I subjoin the following remarks:

1. The nearer the image is to the lens, the smaller it is; and the more remote it is, the greater its magnitude. Thus, O P (Plate VI. *Fig.* 13.) being the object placed on the axis before the lens M N, if the image fell at Q, it would be smaller than if it fell at R, S, or T. For, as the straight line P A *t*, drawn from the summit of the object P, through the middle of the lens, always terminates the image, at whatever distance it may be, it is evident that among the lines Q *q*, R *r*, S *s*, T *t*, the first Q *q* is the smallest, and that the others increase in proportion as they remove from the lens.

2. There is one case in which the image is precisely equal to the object: it is when the distance of the image is equal to that of the object; and this takes place, as I have already remarked, when the distance of the object A O is double that of the focus of the lens; the image will then be T *t*, so that the distance B *t* is equal to A O. You have only then to consider the two triangles O A P and T A *t*, which having the opposite angles at the point A, as well as the sides A O and A T, equal each to each, as likewise the angles at O and T, which are both right angles; these two triangles will be every way equal, and consequently the side T *t*, which is the image, will be equal to the side O P, which is the object.

3. If the image were twice farther from the lens than the object, it would be double the object; and in general, as many times as the image is farther from the lens than the object, so many times will it be greater than the object. For the nearer you bring the object to the glass, the farther the image retires, and consequently the greater it becomes.

4. The contrary takes place when the image is nearer the lens than the object; it is then as many times smaller than the object, as it is nearer the lens than the object is. If then the distance of the image were one thousand times less than that of the object, it would likewise be one thousand times smaller.

5. Let us apply this to burning-glasses, which being exposed to the sun, represent its image in the

focus, or rather represent the focus, that is, the luminous and brilliant circle, which burns, and which is nothing else but the image of the sun represented by the lens. You will no longer be surprised then at the smallness of the image, notwithstanding the prodigious magnitude of the sun, it being as many times smaller in the focus than the real sun, as the distance of the sun from the lens is greater than that of the image.

6. Hence likewise it is evident, that the greater is the distance of the focus of a burning-glass, the more brilliant also is the circle in the focus, that is, the greater will be the image of the sun; and the diameter of the focus is always about one hundred times smaller than the distance of the focus from the lens.

I shall afterwards explain the different uses which may be made of convex lenses; they are all sufficiently curious to merit attention.

26th December 1761.

Letter LXXVIII.—Burning-Glasses.

The first use of convex lenses, is their employment as burning-glasses, the effect of which must appear altogether astonishing, even to those who already have some acquaintance with natural philosophy. In fact, who could believe that the image of the sun simply should be capable of exciting such a prodigious degree of heat? But your surprise will cease, if you please to pay some attention to the following reflections:—

1. Let M N (Plate VI. *Fig.* 14.) be a burning-glass, which receives on its surface the rays of the sun R, R, R, refracted in such a manner as to present at F a small luminous circle, which is the image of the sun, and so much smaller as it is nearer to the glass.

2. All the rays of the sun, which fall on the surface of the glass, are collected in the small space of the focus F; their effect, accordingly, must in that space be as many times greater as the surface of the glass exceeds the magnitude of the focus, or of the sun's image. We say that the rays, which were dispersed over the whole surface of the glass, are concentrated in the small space F.

3. The rays of the sun having a certain degree of heat, they exert their power in a very sensible manner at the focus; it is possible even to calculate how many times the heat at the focus must exceed the natural heat of the sun's rays: we have only to observe how many times the surface of the glass is greater than the focus.

4. If the glass were not greater than the focus, the heat would not be stronger at the focus than any where else; hence we must conclude, that in order to the production of a strong heat by a burning-glass, it is not sufficient that it should be convex, or that it should represent the image of the sun; it must besides have a surface which several times exceeds the magnitude of the focus, which is smaller in proportion as it is nearer to the glass.

5. France is in possession of the most excellent burning-glass: it is three feet in diameter, and its surface is calculated to be nearly two thousand times greater than the focus, or the image of the sun which it represents.[*] It must produce, therefore, in the focus, a heat two thousand times greater than that which we feel from the sun. Its effects are accord-

[*] The lens here alluded to was, we believe, one of Tschirnhausen's, that the Duke of Orleans purchased for the Academy of Sciences. A more powerful burning lens, however, was afterwards made in England by Mr. Parker, which cost above L. 700. It had 2 feet $8\frac{1}{2}$ inches of clear diameter. Its thickness at the centre was $3\frac{1}{4}$ inches, and its focal length 6 feet 8 inches in diameter. It was made of flint-glass. This celebrated lens is now at Pekin. See *Edinburgh Encyclopædia*, article *Burning Instruments*, vol. v. p. 141.—Ed.

ingly prodigious: wood of every kind is in a moment set on fire; metals are melted in a few minutes; and, in general, the most ardent fire which we are capable of producing, is not once to be compared with the vehement heat of this focus.

6. The heat of boiling water is calculated to be about thrice greater than what we feel from the rays of the sun in summer; or, which amounts to the same thing, the heat of boiling water is thrice greater than the natural heat of the blood in the human body. But in order to melt lead, we must have a heat thrice greater than is requisite to make water boil; and to melt copper, a heat still thrice greater is necessary. To melt gold requires a much higher degree of heat. Heat, then, one hundred times greater than that of our blood is capable of melting gold; how far then must a heat two thousand times greater exceed the force of our ordinary fires?

7. But how are these prodigious effects produced by the rays of the sun, collected in the focus of a burning-glass? This is a very difficult question, with respect to which philosophers are very much divided. Those who maintain that the rays are an emanation from the sun, darted with the amazing velocity which I formerly described, are not greatly embarrassed for a solution; they have only to say that the matter of the rays, striking bodies with violence, must totally break and destroy their minute particles. But this opinion is no longer admitted in sound philosophy.

8. The other system, which makes the nature of light to consist in the agitation of the ether, appears little adapted to explain these surprising effects of burning-glasses. On carefully examining, however, all the circumstances, we shall soon be convinced of the possibility of this. The natural rays of the sun, as they fall on bodies, excite the minute particles of the surface to a concussion, or motion of vibration, which, in its turn, is capable of exciting new rays; and by these the body in question is rendered visible. And a body is illuminated only so far as these proper particles are put into a motion of vibration so rapid as to be capable of producing new rays in the ether.

9. It is clear, then, that if the natural rays of the sun have sufficient force to agitate the minute particles of bodies, those which are collected in the focus must put the particles which they meet there into an agitation so violent, that their mutual adhesion is entirely dissolved, and the body itself completely destroyed, which is the effect of fire. For if the body is combustible, as wood, the dissolution of these minute particles, joined to the most rapid agitation, makes a considerable part of it to fly off into air in the form of smoke, and the grosser particles remain in the form of ashes. Fusible bodies, as metals, become liquid by the dissolution of their particles, whence we may comprehend how fire acts on bodies; it is only the adhesion of their minutest particles which is attacked, and the particles themselves are thereby afterwards put into the most violent agitation. Here, then, is a very striking effect of burning-glasses, which derives its origin from the nature of convex lenses.* There are besides many wonderful effects to be described.

28th December 1761.

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* In the work already quoted, in p. 262, note, I have shown how Burning Lenses may be constructed of any size, by building them, as it were, of separate zones, each zone consisting of different segments, which are ground and polished separately. By this means the central parts of the Burning Lens are much less thick than when the lens is of one piece, and the error of the spherical aberration may be in a great measure corrected.—See the *Edinburgh Philosophical Journal*, vol. viii. p. 160.—Ed.

LETTER LXXIX.—THE CAMERA OBSCURA.

WE likewise employ convex lenses in the *camera obscura*, and by means of them all external objects are presented in the darkened room on a white surface, in their natural colours, in such a manner that landscapes and public buildings, or objects in general, are represented in much greater perfection than the power of the pencil is capable of producing. Painters accordingly avail themselves of this method, in order to draw with exactness landscapes and other objects which are viewed at a distance. The camera obscura, then, which is the subject of this letter, is represented at E F G H (PLATE V. *Fig.* 15,), closely shut up on all sides, except one little round aperture made in one of the window-shutters, in which is fixed a convex lens, of such a focus as to throw the image of external objects, say the tree O P, exactly on the opposite wall F G, at *o p*. A white and moveable table is likewise employed, which is put in the place of the images represented.

The rays of light, therefore, can be admitted into the chamber only through the aperture M N, in which the lens is fixed, without which total darkness would prevail.

Let us now consider the point P of any object, say the stem of our tree O P. Its rays P M, P A, P N, will fall on the lens M N, and be refracted by it, so as to meet again at the point *p* on the wall, or on a white table* placed there for the purpose. This point *p* will consequently receive no other rays but such as proceed from the point P; and in like manner every other point of the table will receive only the rays which proceed from the corresponding

point of the object; and reciprocally, to every point of the external object will correspond a point on the table, which receives those rays, and no other. If the lens were to be removed from the aperture M N, the table would be illuminated in quite a different manner; for in that case every point of the object would diffuse its rays over the whole table, so that every point of the table would be illuminated at once by all the external objects, whereas at present it is so by one only, that whose rays it receives: from this you will easily comprehend that the effect must be quite different from what it would be, if the rays entered simply by the aperture M N into the chamber.

Let us now examine somewhat more closely wherein this difference consists; and let us first suppose that the point P of the object is green; the point of the table *p* will therefore receive only those green rays of the object P, and these re-uniting on the wall or table, will make a certain impression, which here merits consideration. For this purpose you will please to recollect the following propositions, which I had formerly the honour of explaining to you:—

1. Colours differ from each other in the same manner as musical sounds: each colour is produced by a determinate number of vibrations, which in a given time are excited in the ether. The green colour of our point P is accordingly appropriated to a certain number of vibrations, and would no longer be green were these vibrations more or less rapid. Though we do not know the number of vibrations which produce such or such a colour, we may however be permitted to suppose here, that green requires twelve thousand vibrations in a second; and what we affirm of this number, twelve thousand, may likewise be easily understood of the real number, whatever it be.

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* The table should be made of Stucco, or Plaster of Paris, ground very smoothly, and ought to be concave, that every part of it may be equally distant from the lens.—ED.

2. This being laid down, the point *p* on the white table will be struck by a motion of vibration, of which twelve thousand will be completed in a second. Now, I have remarked, that the particles of a white surface are all of such a nature as to receive every sort of agitation, more or less rapid; whereas those of a coloured surface are adapted to receive only that degree of rapidity which corresponds to their colour. And as our table is white, the point *p* in it will be excited to a motion of vibration corresponding to the colour of green; in other words, it will be agitated twelve thousand times in a second.

3. As long as the point *p*, or the particle of the white surface which exists there, is agitated with a similar motion, this will be communicated to the particles of the ether which surround it; and this motion diffusing itself in all directions, will generate rays of the same nature, that is to say, green; just as, in music, the sound of a certain note, say C, agitates a string wound up to the same tone, and makes it emit a sound without being touched.

4. The point *p* of the white table will accordingly produce green rays, as if it were dyed or painted that colour; and what I affirm of the point *p*, will equally take place with respect to all the points of the illuminated table, which will produce all the rays, each of the same colour with that of the object whose image it represents. Every point of the table will therefore become visible, under a certain colour, as if it were actually painted that colour.

5. You will perceive, then, on the table, all the colours of the external objects, the rays of which will be admitted into the chamber through the lens; each point in particular will appear of the colour of that point of the object which corresponds to it, and you will see on the table a combination of various colours, disposed in the same order as you see them in the objects themselves; that is to say, a representation, or rather the perfect picture, of all the objects on the outside of the dark chamber which are before the lens N N.

6. All these objects will, however, appear reversed on the table, as you will conclude from what I have said in my foregoing letters. The under part of the tree O will be represented at *o*, and the summit P at *p*; for, in general, each object must be represented on the white table, in the place which is the termination of the straight line drawn from the object P through the middle of the lens A: that which is upward will consequently be represented downward, and that which is to the left will be to the right; in a word, every thing will be reversed in the picture; the representation will nevertheless be more exact and more perfect than the most accurate painter is capable of producing.

7. You will further remark, that this picture will be so much smaller than the objects themselves, in proportion as the focus of the lens is shorter. Lenses of a short focus will accordingly give the objects in miniature; and if you would wish to have them magnified, you must employ lenses of a longer focus, or which represent the images at a greater distance.

8. In order to contemplate these representations more at ease, the rays may be intercepted by a mirror, from which they are reflected, so as to represent the whole picture on a horizontal table; and this is of peculiar advantage when we wish to copy the images.*

2d January 1762.

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* The lens is sometimes ground on the anterior surface of a thick piece of glass, the posterior surface of which is ground flat, and inclined 45° to the axis of the lens. The picture is therefore reflected on a horizontal table, without the use of a mirror, and the image is much more perfect, as the light is totally reflected.—Ed.