## Letter LXXX.—Reflections on the Representation in the Camera Obscura.

Though you can no longer entertain any doubt respecting the representations made in a dark chamber, by means of a convex lens, I hope the following reflections will not appear superfluous, as they serve to place this subject in a clearer light:—

1. The chamber must be completely darkened, for were the light admitted, the white table would be visible, and the particles of its surface, already agitated, would be incapable of receiving the impression of the rays which unite to form the images of external objects. Though, however, the chamber were a little illuminated, still something of the representation would appear on the table, but by no means so vivid as if the chamber were entirely dark.

2. We must carefully distinguish the picture represented on the white table, from the image which the lens in virtue of its own nature represents, as I have formerly explained. It is very true, that placing the table in the very place where the image of the objects is formed by the lens, this image will be confounded by the picture we perceive on the table; these two things are nevertheless of a nature entirely different: the image is only a spectre or shadow floating in the air, which is visible but in certain places; whereas the representation is a real picture, which every one in the chamber may see, and to which duration alone is wanting.

3. In order the more clearly to elucidate this difference, you have only to consider carefully the nature of the image *o* (Plate VI. *Fig.* 16.), represented by the convex lens M N, the object being at O. This image is nothing else but the place in which the rays O M, O C, O N, of the object, after having passed through the lens, meet by refraction, and thence continue their direction as if they proceeded from the point *o*, though they really originated from O, and by no means from *o*.

4. Hence the image is visible only to eyes situated somewhere within the angle R *o* Q, as at S, where an eye will actually receive the rays which come to it from the point *o*. But an eye situated out of this angle, as at F or V, will see nothing at all of it, because no one of the rays collected at *o* is directed toward it: the image at *o*, therefore, differs very essentially from a real object, and is visible only in certain places.

5. But if a white table is placed at *o*, and its surface at this point *o* is really excited to an agitation similar to that which takes place in the object O, this spot *o* of the surface itself generates rays which render it visible every where. Here, then, is the difference between the image of an object, and its representation made in a camera obscura: the image is visible only in certain places, namely, those through which are transmitted the rays that originally proceed from the object; whereas the picture, or representation formed on the white table, is seen by its own rays, excited by the agitation of the particles of its surface, and consequently visible in every place of the camera obscura.

6. It is likewise evident, that the white table must absolutely be placed exactly in the place of the image formed by the lens, in order that every point of the table may receive no other rays except such as proceed from a single point of the object; for if other rays were likewise to fall upon it, they would disturb the effect of the former, or render the representation confused.

7. Were the lens to be entirely removed, and free admission given to the rays into the dark chamber, the white table would be illuminated by it, but no

picture would be visible. The rays of the different objects would fall on every point of the table, without expressing any one determinate image. The picture, accordingly, which we see in a camera obscura, on a white surface, is the effect of the convex lens fixed in the shutter: this it is which collects anew, in a single point, all the rays that proceed from one point of the object.

3. A very singular phenomenon is here however observable, when the aperture made in the window-shutter of the dark chamber is very small; for though no lens be applied, you may nevertheless perceive, on the opposite partition, the images of external objects, and even with their natural colours; but the representation is very faint and confused, and if the aperture is enlarged, this representation entirely disappears. I shall explain this phenomenon.

In *Fig.* 17. Plate VI. MN is the small aperture through which the rays of external objects are admitted into the dark chamber EFGH. The wall FG opposite to the aperture is white, the better to receive the impression of rays of all sorts.

Let the point O be an object, of which the rays OM, ON alone, with those which fall between them, can enter into the chamber. These rays will be confined to the small space *o o* of the wall, and will illuminate it. This space *o o* will be so much smaller, or approach the nearer to a point, in proportion as the aperture MN is small: if then this aperture were very small, we should have the effect already described, according to which every point of the white table receives only the rays proceeding from a single point of the object: there would be produced, of consequence, a representation similar to that which is produced by the application of a convex lens to an aperture in the window-shutter. But in the present case, the aperture being of a certain extent, every point O of the object will illuminate a certain small space *o o* on the wall, and agitate it by its rays. The same thing then, nearly, would take place, as if a painter, instead of making points with a fine pencil, should with a coarse one make spots of a certain magnitude, attending, however, to design and colouring: the representation made on the wall will have a resemblance to this sort of daubing; but it will be clearer in proportion to the smallness of the aperture by which the rays are admitted.

*5th January* 1762.

## LETTER LXXXI.—OF THE MAGIC LANTERN, AND SOLAR MICROSCOPE.

THE camera obscura has properly no effect except on very distant objects, but you will easily comprehend, that its application may be equally extended to nearer objects. For this purpose, the white table must be removed farther from the lens, conformably to this general rule, that the nearer the object is brought to the convex lens, the farther does the image, where the white table ought to be placed, retire from it; and if the chamber is not of sufficient depth, a different lens, of a shorter focus, must be employed.

You may place, then, out of the chamber, before the aperture to which the convex lens is fitted, any object or picture whatever, and you will see a copy of it on the white table within the dark chamber, greater or smaller than the original, according as the distance of the image is greater or smaller; but it would be more commodious, undoubtedly, if the object could be exposed within the dark chamber, in order to its being moved and changed at pleasure. But here a great difficulty occurs,—the object itself would in this case be darkened, and consequently rendered incapable of producing the effect we wish.

The thing wanted, then, is, to illuminate the object as much as possible within the dark chamber, and at the same time to exclude the light. I have found out the means of doing this. You will recollect that I constructed a machine to the effect I am mentioning, which I had the honour of presenting to you six years ago; and now you will easily comprehend the structure, and the principles on which it is founded.

This machine consists of a box very close on all sides, nearly of a figure similar to *Fig.* 27. PLATE VI. The farther side of which EG has an opening IK, in which are to be fitted the objects, portraits or other pictures, OP, which you mean to represent; on the other side, directly opposite, is a tube MNQR, containing a convex lens MN; this tube is moveable, for the purpose of bringing the lens nearer to the object, or of removing it, at pleasure. Then, provided the object OP be well illuminated, the lens will throw somewhere the image of it *o p*, and if you there place a white tablet, you will see upon it a perfect copy of the object, so much the clearer as the object itself is more illuminated.

For this purpose I have contrived in this box two side wings, for the reception of lamps with large wicks, and in each wing is placed a mirror to reflect the light of the lamps on the objects OP; above, at EF, is a chimney, by which the smoke of the lamps passes off. Such is the construction of this machine, within which the object OP may be very strongly illuminated, while the darkness of the chamber suffers no diminution. In order to the proper use of this machine, attention must be paid to the following remarks.

1. On sliding inward the tube MNQR, that is, bringing the lens MN nearer to the object OP, the image *o p* will retire; the white tablet must therefore be removed backward, to receive the image at the just distance; the image will thereby be likewise magnified, and you may go on to enlarge it at pleasure, by pressing the lens MN nearer and nearer to the object OP.

2. On removing the lens from the object, the distance of the image will be diminished: the white tablet must in this case be moved nearer to the lens, in order to have a clear and distinct representation; but the image will be reduced.

3. It is obvious that the image will be always reversed; but this inconvenience is easily remedied; you have only to reverse the object OP itself, turning it upside down, and the image will be represented upright on the white tablet.

4. It is a farther general remark, that the more the image is magnified on the white tablet, the less luminous and distinct it will be; but on reducing the image, it is rendered more distinct and brilliant. The reason is plain—the light proceeds wholly from the illumination of the object; the greater that the space is over which it is diffused, the more it must be weakened, and the more contracted it is, the more brilliant.

5. Accordingly, the more you wish to magnify the representation, the more you must strengthen the illumination of the object, by increasing the light of the lamps in the wings of the machine; but for small representations a moderate illumination is sufficient.

The machine which I have been describing is called the *Magic Lantern*, to distinguish it from the common camera obscura, employed for representing distant objects; its figure, undoubtedly, has procured it the name of lantern, especially as it is designed to contain light; but the epithet *magic* must have been an invention of its first proprietors, who wished to impress the vulgar with the idea of magic or witchcraft. The ordinary magic-lanterns, however, are not constructed in this manner, and serve to represent no other objects but figures painted on glass, whereas this machine may be applied to objects of all sorts.

It may even be employed for representing the smallest objects, and for magnifying the representation to a prodigious size, so that the smallest fly shall appear as large as an elephant; but, for this purpose, the strongest light that lamps can give is far from being sufficient; the machine must be disposed in such a manner that the objects may be illuminated by the rays of the sun, strengthened by a burning glass; the machine, in this case, changes its name, and is called the *Solar Microscope*. I shall have occasion to speak of it more at large in the sequel.

*8th January* 1762.

## Letter LXXXII.—Use and Effect of a simple Convex Lens.

We likewise employ convex lenses for immediately looking through; but in order to explain their different uses, we must go into a closer investigation of their nature.

Having observed the focal distance of such a glass, I have already remarked, that when the object is very remote, its image is represented in the focus itself; but on bringing the object nearer to the lens, the image retires farther and farther from it: so that if the distance of the object be equal to that of the focus of the lens, the image is removed to an infinite distance, and consequently becomes infinitely great.

The reason is, that the rays OM, OM, (Plate VI. *Fig.* 18.) which come from the point O, are refracted by the lens, so as to become parallel to each other, as NF, NF; and as parallel lines are supposed to proceed forward to infinity, and as the image is always in the place where the rays, issuing from one point of the object, are collected again after the refraction; in the case when the object OA is equal to that of the focus of the lens, the place of the image removes to an infinite distance; and as it is indifferent whether we conceive the parallel lines NF and NF to meet at an infinite distance to the left or to the right, it may be said indifferently, that the image is to the right or to the left infinitely distant, the effect being always the same.

Having made this remark, you will easily judge what must be the place of the image, when the object is brought still nearer to the lens.

Let OP (Plate VI. *Fig.* 19.) be the object, and as its distance OA from the convex lens is less than the distance of the focus, the rays OM, OM, which fall upon it from the point O, are too divergent to admit of the possibility of their being rendered parallel to each other by the refractive power of the lens: they will therefore be still divergent after the refraction, as marked by the lines NF, NF, though much less so than before; therefore, if these lines are produced backward, they will meet somewhere at *o*, as you may see in the dotted lines N *o*, N *o*. The rays NF, NF, will, of consequence, after having passed through the lens, preserve the same direction as if they had proceeded from the point *o*, though they have not actually passed through that point, as it is only in the lens that they have taken this new direction. An eye which receives these refracted rays NF, NF, will be therefore affected as if they really came from the point *o*, and will imagine that the object of its vision exists at *o*. There will, however, be no image at that point, as in the preceding case. To no purpose would you put a white tablet at *o*, it would present no picture there for want of rays: for this reason we say that there is an imaginary image at *o*, and not a real one—the term *imaginary* being opposed to that of *real*.

Nevertheless, an eye placed at E receives the same impression as if the object OP, from which the rays originally proceed, existed at *o*. It is of great importance, then, to know, as in the preceding cases, the place and the magnitude of this imaginary image *o p*. As to the place, it is sufficient to remark, that if the distance of the object AO be equal to the distance of the focus of the lens, the image will be at an infinite distance from it; and this is what the present case has in common with the preceding: but the nearer the object is brought to the lens, or the less that the distance AO becomes than that of the focus of the lens, the nearer does the imaginary image approach to the lens; though, at the same time, it remains always at a greater distance from the lens than the object itself.

To elucidate this by an example, let us suppose that the focal distance of the lens is 6 inches; and for the different distances of the object, the annexed table indicates the distance of the imaginary image *o p*.

| *If the distance of the Object A O is* | *The Distance of the Imaginary Image A O will be* |
|---:|:---|
| 6 | Infinity |
| 5 | 30 |
| 4 | 12 |
| 3 | 6 |
| 2 | 3 |
| 1 | 1 and a fifth. |

The rule for ascertaining the magnitude of this imaginary image *o p* is easy and general; you have only to draw through the middle of the lens, marked C, and through the extremity of the object P, the straight line C P *p*; and where it meets with the line *o p* drawn from *o* at right angles with the axis of the lens, you will have found the magnitude of the imaginary image *o p*: from which it is evident, that this image is always greater than the object O P itself, as many times as it is farther from the lens than the object O P. It is likewise evident, that this image is not reversed, as in the preceding case, but upright as the object.

You will easily comprehend, from what I have said, the benefit that may be derived from lenses of this sort, by persons whose sight is not adapted to the view of near objects, but who can see them to more advantage at a considerable distance. They have only to look at objects through a convex lens, in order to see them as if they were very distant. The defect of sight with respect to near objects occurs usually in aged people, who consequently make use of spectacles with convex glasses, which, exposed to the sun, produce the effect of a burning-glass, and this ascertains the focal distance of every glass. Some persons have occasion for spectacles of a very near focus, others of one more distant, according to the state of their sight; but it is sufficient for my present purpose, to have given a general idea of the use of such spectacles.

*12th January* 1762.

## Letter LXXXIII.—Use and Effect of a Concave Lens.

You have seen how convex glasses assist the sight of old people, by representing to them objects as at a greater distance than they really are; there are eyes, on the contrary, which, in order to distinct vision, require the objects to be represented as nearer; and concave glasses procure them this advantage; which leads me to the explanation of the effect of concave lenses, which is directly the contrary of that of convex ones.

When the object O P (PLATE VI. *Fig.* 20.), is very distant, and its rays OM, OM, fall almost parallel on the concave lens TT; in this case, instead of becoming convergent by the refraction of the lens, they, on the contrary, become more divergent, pursuing the direction NF, NF, which, produced backward, meet at the point *o*; so that an eye placed, for example, at E, receives these refracted rays in the same manner as if they proceeded from the point *o*, though they really proceed from the point O; for this reason, I have in the figure dotted the straight lines N *o*, N *o*.

As the object is supposed to be infinitely distant, were the lens convex the point *o* would be what we call the focus; but as, in the present case, there is no real concurrence of rays, we call this point the imaginary focus of the concave lens; some authors likewise denominate it *the point of dispersion*, because the rays, refracted by the glass, appear to be dispersed from this point.

Concave lenses, then, have no real focus, like the convex, but only an imaginary focus, the distance of which from the lens A *o* is, however, denominated the focal distance of this lens, and serves, by means of a rule similar to that which is laid down for convex lenses, to determine the place of the image, when the object is not infinitely distant. Now, this image is always imaginary, whereas in the case of convex lenses, it becomes so only when the object is nearer than the distance of the focus. Without entering into the explanation of this rule, which respects calculation merely, it is sufficient to remark:—

1. When the object OP is infinitely distant, the imaginary image *o p* is represented at the focal distance of the concave lens, and this, too, on the same side with the object. Nevertheless, though this image be imaginary, the eye placed at E is quite as much affected by it as if it were real, conformably to the explanation given on the subject of convex lenses, when the object is nearer the lens than its focal distance.

2. On bringing the object O P nearer to the lens, its image *o p* will likewise approach nearer, but in such a manner, that the image will always be nearer to the lens than the object is; whereas, in the case of convex lenses, the image is more distant from the lens than the object. In order to elucidate this more clearly, let us suppose the focal distance of the concave lens to be 6 inches.

| *If the Distance of the Object* O A *is* | *The Distance of the Image o* A *will be* |
|---:|:---|
| Infinite. | 6 |
| 30 | 5 |
| 12 | 4 |
| 6 | 3 |
| 3 | 2 |
| 2 | 1 and a half. |

3. By the same rule you may always determine the magnitude of the imaginary image *o p*. You draw from the middle of the lens a straight line, to the extremity of the object P, which will pass through the extremity *p* of the image. For, since the line PA represents a ray coming from the extremity of the object, this same ray must, after the refraction,

pass through the extremity of the image; but, as this ray PA passes through the middle of the lens, it undergoes no refraction; therefore it must itself pass through the extremity of the image, at the point *p*.

4. This image is not reversed, but in the same position with the object; and it may be laid down as a general rule, that whenever the image falls on the same side of the lens that the object is, it is always represented upright, whether the lens be convex or concave; but when represented on the other side of the lens, it is always reversed; and this can take place only in convex lenses.

5. It is evident, therefore, that the images represented by concave lenses are always smaller than the objects; the reason is obvious—the image is always nearer than the object; you have only to look at the figure to be satisfied of this truth. These are the principal properties to be remarked respecting the nature of concave lenses, and the manner in which objects are represented by them.

It is now easy to comprehend how concave glasses may be rendered essentially serviceable to persons whose sight is short. You are acquainted with some who can neither read nor write without bringing the paper almost close to their nose. In order, therefore, to their seeing distinctly, the object must be brought very near to the organ of vision: I think I have formerly remarked that such persons are denominated *Myopes*. Concave lenses, then, may be made of great use to them, for they represent the most distant objects as very near; the image not being farther from such glasses than their focal distance, which, for the most part, is only a few inches.

These images, it is true, are much smaller than the objects themselves; but this by no means prevents distinctness of vision. A small object near, may appear greater than a very large body at a distance.

In fact, the head of a pin appears to the eye greater than a star in the heavens, though that star far exceeds the earth in magnitude.

Persons whose sight is short, or *Myopes*, have occasion, then, for glasses which represent objects as nearer; such are concave lenses. And those whose sight is long, or *Presbytes*, need convex glasses, which represent to them objects at a greater distance.

16*th January* 1762.

## LETTER LXXXIV.—OF APPARENT MAGNITUDE, OF THE VISUAL ANGLE, AND OF MICROSCOPES IN GENERAL.

I HAVE been remarking, that *Myopes* are obliged to make use of concave glasses to assist their vision of distant objects, and that *Presbytes* employ convex glasses in order to a more distinct vision of such as are near; each sight has a certain extent, and each requires a glass which shall represent objects perfectly. This distance in the *Myopes* is very small, and in the *Presbytes* very great; but there are eyes so happily conformed, as to see nearer and more distant objects equally well.

Nevertheless, of whatever nature any person's sight may be, this distance is never very small: there is no *Myope* capable of seeing distinctly at the distance of less than an inch; you must have observed, that when the object is brought too close to the eye, it has a very confused appearance; this depends on the structure of the organ, which is such in the human species, as not to admit of their seeing objects very near. To insects, on the contrary, very distant objects are invisible, while they easily see such as are nearer. I do not believe that a fly is capable of seeing the stars because it can see extremely well at the distance of the tenth part of an inch, a distance at which the human eye can distinguish absolutely nothing. This leads me to an explanation of the microscope, which represents to us the smallest object as if it were very great.

In order to convey a just idea of it, I must entreat you carefully to distinguish between the apparent and the real magnitude of every object. Real magnitude constitutes the object of geometry, and is invariable as long as the body remains in the same state. But apparent magnitude admits of infinite variety, though the body may remain always the same. The stars, accordingly, appear to us extremely small, though their real magnitude is prodigious, because we are at an immense distance from them. Were it possible to approach them, they would appear greater; from which you will conclude, that the apparent magnitude depends on the angle formed in our eyes, by the rays which proceed from the extremities of the object.

Let P O Q (Plate VI. *Fig.* 21.) be the object of vision, which, if the eye were placed at A, would appear under the angle P A Q, called the visual angle, and which indicates to us the apparent magnitude of the object; it is evident, on inspecting the figure, that the farther the eye withdraws from the object, the smaller this angle becomes, and that it is possible for the greatest bodies to appear to us under a very small visual angle, provided our distance from them be very great, as is the case with the stars. But when the eye approaches nearer to the object, and looks at it from B, it will appear under the visual angle P B Q, which is evidently greater than P A Q. Let the eye advance still forward to C, and the visual angle P C Q is still greater. Farther, the eye being placed at D, the visual angle will be P D Q; and on advancing forward to E, the visual angle will be P E Q, always greater and greater. The nearer, therefore, the eye approaches to the object, the more the visual angle increases, and consequently likewise the apparent magnitude. However small the object may be, it is possible, therefore, to increase its apparent magnitude at pleasure; you have only to bring it so near the eye as is necessary to form such a visual angle. A fly near enough to the eye may, of consequence, appear under an angle as great as an elephant at the distance of ten feet. In a comparison of this sort, we must take into the account the distance at which we suppose the elephant to be viewed; unless this is done, we affirm absolutely nothing; for an elephant appears great only when we are not very far from it; at the distance of a mile, it would be impossible, perhaps, to distinguish an elephant from a pig; and, transported to the moon, he would become absolutely invisible; and I might affirm with truth, that a fly appeared to me greater than an elephant, if the latter was removed to a very considerable distance. Accordingly, if we would express ourselves with precision, we must not speak of the apparent magnitude of a body, without taking distance likewise into the account, as the same body may appear very great or very small, according as its distance is greater or less. It is very easy, then, to see the smallest bodies under very great visual angles; they need only to be placed very close to the eye.

This expedient may be well enough adapted to a fly, but the human eye could see nothing at too small a distance, however short its sight may be; besides, persons of the best sight would wish to see likewise the smallest objects extremely magnified. The thing required, then, is to find the means of enabling us to view an object distinctly, notwithstanding its great proximity to the eye. Convex lenses render us this service, by removing the image of objects which are too near.

Let a very small convex lens M N be employed (Plate VI. *Fig.* 22.), the focal distance of which shall be half an inch; if you place before it a small object O P, at a distance somewhat less than half an inch, the lens will represent the image of it $o\,p$, as far off as could be wished. On placing the eye, then, behind the lens, the object will be seen as if it were at $o$, and at a sufficient distance, as if its magnitude were $o\,p$: as the eye is supposed very near the lens, the visual angle will be $p\,t\,o$, that is the the same as $P\,t\,O$, under which the naked eye would see the object O P in that proximity; but the vision is become distinct by means of the lens: such is the principle on which microscopes are constructed.

19*th January* 1762.

## Letter LXXXV.—Estimation of the Magnitude of objects viewed through the Microscope.

When several persons view the same object through a microscope, the foot of a fly, for example, they all agree that they see it greatly magnified, but their judgment respecting the real magnitude will vary; one will say, it appears to him as large as that of a horse; another, as that of a goat; a third, as that of a cat. No one then advances any thing positive on the subject, unless he adds at what distance he views the feet of the horse, the goat, or the cat. They all mean, therefore, without expressing it, a certain distance, which is undoubtedly different; consequently, there is no reason to be surprised at the variety of the judgments which they pronounce, as the foot of a horse viewed at a distance, may very

well, appear no bigger than that of a cat viewed near to the eye. Accordingly, when the question is to be decided, How much does the microscope magnify an object? we must accustom ourselves to a more accurate mode of expression, and particularly to specify the distance, in the comparison which we mean to institute.

It is improper, therefore, to compare the appearances presented to us by the microscope with objects of another nature, which we are accustomed to view sometimes near, and sometimes at a distance. The most certain method of regulating this estimation seems to be that which is actually employed by authors who treat of the microscope. They compare a small object viewed through the microscope with the appearance which it would present to the naked eye, on being removed to a certain distance; and they have determined, that in order to contemplate such a small object to advantage by the naked eye, it ought to be placed at the distance of eight inches, which is the standard for good eyes, for a short-sighted person would bring it closer to the eye, and one far-sighted would remove it. But this difference does not affect the reasoning, provided the regulating distance be settled; and no reason can be assigned for fixing on any other distance than that of eight inches, the distance received by all authors who have treated of the subject. Thus, when it is said that a microscope magnifies the object a hundred times, you are to understand that, with the assistance of such a microscope, objects appear a hundred times greater than if you viewed them at the distance of eight inches; and thus you will form a just idea of the effect of a microscope.

In general, a microscope magnifies as many times as an object appears larger than if it were viewed without the aid of the glass, at the distance of eight inches. You will readily admit that the effect is surprising, if an object is made to appear even a hundred times greater than it would to the naked eye, at the distance of eight inches: but it has been carried much farther; and microscopes have been constructed, which magnify five hundred times—a thing almost incredible. In such a case it might be with truth affirmed, that the leg of a fly appears greater than that of an elephant. Nay, I have full conviction, that it is possible to construct microscopes capable of magnifying one thousand, or even two thousand times, which would undoubtedly lead to the discovery of many things hitherto unknown.

But when it is affirmed, that an object appears through the microscope a hundred times greater than when viewed at the distance of eight inches, it is to be understood that the object is magnified as much in length as in breadth and depth, so that each of these dimensions appears a hundred times greater. You have only, then, to conceive, at the distance of eight inches, another object similar to the first, but whose length is a hundred times greater, as well as its breadth and depth, and such will be the image viewed through the microscope. Now, if the length, the breadth, and depth, of an object be a hundred times greater than those of another, you will easily perceive that the whole extent will be much more than a hundred times greater. In order to put this in the clearest light, let us conceive two parallelograms ABCD, and EFGH, (Plate VI. *Fig.* 23.) of the same breadth, but that the length of the first, AB, shall be five times greater than the length of the other, EF; it is evident that the area, or space contained in the first, is five times greater than that contained in the other, as in fact this last is contained five times in the first. To render, then, the parallelogram AD, five times greater than the parallelogram EH, it is sufficient that its length AB be five times greater, the breadth being the same; and if, besides, the breadth were likewise five times greater, it would become five times greater still, that is five times five times, or twenty-five times greater. Thus, of two surfaces, if the one be five times longer and five times broader than the other, it is in fact twenty-five times greater.

If we take, farther, the height or depth into the account, the increase will be still greater. Conceive two apartments, the one of which is five times longer, five times broader, and five times higher than the other; its contents will be five times 25 times, that is, 125 times greater. When, therefore, it is said that a microscope magnifies 100 times, as this is to be understood not only of length, but of breadth and depth, or thickness, that is of three dimensions, the whole extent of the object will be increased 100 times 100 times 100 times; now 100 times 100 make 10,000, which taken again 100 times make 1,000,000; thus, when a microscope magnifies 100 times, the whole extent of the object is represented 1,000,000 times greater. We satisfy ourselves, however, with saying that the microscope magnifies 100 times; but it is to be understood that all the three dimensions, namely, length, breadth, and depth, are represented 100 times greater. If then a microscope should magnify a 1000 times, the whole extent of the object would become 1000 times 1000 times 1000 times greater, which makes 1000,000,000, or a thousand millions: a most astonishing effect! This remark is necessary to the formation of a just idea of what is said respecting the power of microscopes.

23*d January* 1762.

## LETTER LXXXVI.—FUNDAMENTAL PROPOSITION FOR THE CONSTRUCTION OF SIMPLE MICROSCOPES. PLAN OF SOME SIMPLE MICROSCOPES.

HAVING explained in what manner we are enabled to judge of the power of microscopes, it will be easy to unfold the fundamental principle for the construction of simple microscopes. And here it may be necessary to remark, that there are two kinds of microscopes; some consisting of a single lens, others of two or more, named, accordingly, simple or compound microscopes, and which require particular elucidations. I shall confine myself at present to the simple microscope, which consists of a single convex lens, the effect of which is determined by the following proposition: *A simple microscope magnifies as many times as its focal distance is nearer than eight inches.* The demonstration follows.

Let MN, (PLATE VI. *Fig.* 24.) be a convex lens, whose focal distance, at which the object OP must be placed nearly, in order that the eye may see it distinctly, shall be C O; this object will be perceived under the angle O C P. But if it be viewed at the distance of eight inches, it would appear under an angle as many times smaller as the distance of eight inches surpasses the distance C O: the object will appear, therefore, as many times greater than if it were viewed at the distance of eight inches. Now, in conformity to the rule already established, a microscope magnifies as many times as it presents the object greater than if we viewed it at the distance of eight inches. Consequently, a microscope magnifies as many times as its focal distance is less than eight inches. A lens, therefore, whose focal distance is an inch, will magnify precisely eight times; and a lens whose focal distance is only half an inch, will magnify sixteen times. The inch is divided into twelve parts, called *lines*; half an inch, accordingly, contains six lines: hence it would be easy to determine how many times every lens, whose focal distance is given in lines, must magnify; according to the following table:—

| | Focal distance of the lens in lines. | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 12. | 8. | 6. | 4. | 3. | 2. | 1. | ½ lines |
| magnifies | 8. | 12. | 16. | 24. | 32. | 48. | 96. | 192 times. |

Thus a convex lens, whose focal distance is one line, magnifies *ninety-six times*; and if the distance be half a line, the microscope will magnify *one hundred and ninety-two*, that is near two hundred times. Were greater effect still to be desired, lenses must be constructed of a still smaller focus.* Now, it has been already remarked, that in order to construct a lens of any certain given focus, it is only necessary to make the radius of each face equal to that focal distance, so that the lens may become equally convex on both sides. I now proceed, then, to place before you (PLATE VI. *Fig.* 25.) the form of some of these lenses or microscopes:—

No. I. The focal distance of this lens A O is one inch or twelve lines. This microscope, therefore, magnifies eight times.

No. II. The focal distance of the lens M N is eight lines. This microscope magnifies twelve times.

No. III. The focal distance of the lens M N is six lines. This microscope magnifies sixteen times.

No. IV. The focal distance of this lens is four lines; and such a microscope magnifies twenty-four times.

No. V. The focal distance here is three lines. This microscope magnifies thirty-two times.

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* Lenses have been ground and polished having only a focal length of one-fiftieth of an inch, consequently their magnifying power is 400 times.—ED.

No. VI. The focal distance here is two lines. This microscope magnifies forty-eight times.

No. VII. The focal distance of this lens is only one line; and such a microscope magnifies ninety-six times.

It is possible to construct microscopes still much smaller. They are actually executed, and much more considerable effects are produced; whence it must be carefully remarked, that the distance of the object from the glass becomes smaller and smaller, as it must be nearly equal to the focal distance of the lens. I say *nearly*, as every eye brings the glass closer to it, somewhat more or less, according to its formation; the short-sighted apply it closer, the far-sighted less so. You perceive, then, that the effect is greater as the microscope or lens becomes smaller, and the closer likewise the object must be applied: this is a very great inconvenience, for, on the one hand, it is troublesome to look through a glass so very small; and, on the other, because the object must be placed so near the eye. Attempts have been made to remedy this inconvenience by a proper mounting, which may facilitate the use of it; but the vision of the object is considerably disturbed as soon as the distance of it undergoes the slightest change: and as in the case of a very small lens, the object must almost touch it, whenever the surface of the object is in the least degree unequal, it is seen but confusedly. For, while the eminences are viewed at the just distance, the cavities, being too far removed, must be seen very confusedly. This renders it necessary to lay aside simple microscopes when we wish to magnify very considerably, and to have recourse to the compound microscope.

*26th January* 1762.

## LETTER LXXXVII.—LIMITS AND DEFECTS OF THE SIMPLE MICROSCOPE.

You have now seen how simple microscopes may be constructed, which shall magnify as many times as may be desired; you have only to measure off a straight line of eight inches, like that which I have marked A B* (PLATE VI. *Fig.* 26.), which contains precisely eight inches of the Rhenish foot, which is the standard all over Germany. This line A B must then be subdivided into as many equal parts as correspond to the number of times you wish to magnify the object proposed, and one of these parts will give the focal distance of the lens that is requisite. Thus, if you wish to magnify a hundred times, you must take the hundredth part of the line A B, consequently you must construct a lens, whose focal distance shall be precisely equal to that part A I, which will give, at the same time, the radius of the surfaces of the lens represented in No. VII. of the preceding figure. Hence it is evident, that the greater the effect we mean to produce, the smaller must be the lens, as well as the focal distance at which the object O P must be placed before the lens, while the eye is applied behind it: and if the lens were to be made twice smaller than what I have now described, in order to magnify two hundred times, it would become so minute, as almost to require a microscope to see the lens itself; besides, it would be necessary to approach so close, as almost to touch the lens, which, as I have already observed, would be very inconvenient. The effect of the microscope, therefore, could hardly be carried beyond two hundred times; which is by no means sufficient

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* It being impossible here to insert a straight line of eight inches, one of half that length is employed, for the purpose of illustration.

for the investigation of many of the minuter productions of nature. The purest water contains small animalcules, which, though magnified two hundred times, still appear no bigger than fleas; and a microscope which should magnify 20,000 times, would be necessary to magnify their appearance to the size of a rat; and we are far from reaching this degree, even with the assistance of the compound microscope.

But besides the inconveniences attending the use of simple microscopes, which have been already pointed out, all those who employ them with a view to very great effect, complain of another considerable defect; it is this—the more that objects are magnified, the more obscure they appear; they seem as if viewed in a very faint light, or by moonlight, so that you can hardly distinguish any thing clearly. You will not be surprised at this, when you recollect, that the light of the full moon is more than two hundred thousand times fainter than that of the sun.

It is of much importance, therefore, to explain whence this diminution of light proceeds. We can easily comprehend, that if the rays which proceed from a very small object must represent it to us as if it were much larger, this small quantity of light would not be sufficient. But however well founded this reasoning may appear, it wants solidity, and throws only a false light on the question. For if the lens, as it proceeded in magnifying, necessarily produced a diminution of clearness, this must likewise be perceptible in the smallest effects, even supposing it were not to so high a degree; but you may magnify up to fifty times, without perceiving the least apparent diminution of light, which, however, ought to be fifty times fainter, if the reasons adduced were just. We must look elsewhere, then, for the cause of this phenomenon, and even resort to the first principles of vision.

I must entreat you, then, to recollect what I have already suggested respecting the use of the pupil, or that black aperture which we see in the eye at the middle of the iris. It is through this aperture that the rays of light are admitted into the eye; accordingly, the larger this aperture is, the more rays are admitted. We must here consider two cases in which objects are very luminous and brilliant, and in which they are illuminated by only a very faint light. In the first, the pupil contracts of itself, without any act of the will; and the Creator has bestowed on it this faculty, in order to preserve the interior of the eye from the too dazzling effect of light, which would infallibly injure the nerves. Whenever, therefore, we are exposed to a very powerful light, we observe that the pupil of every eye contracts, to prevent the admission of any more rays into the eye than are necessary to paint in it an image sufficiently luminous. But the contrary takes place when we are in the dark; the pupil in that case expands, to admit the light in a greater quantity. This change is easily perceptible every time we pass from a dark to a luminous situation. With respect to the subject before us, I confine myself to this circumstance, that the more rays of light are admitted into the eye, the more luminous will be the image transmitted to the retina; and reciprocally, the smaller the quantity of rays which enter the eye, the fainter does the image become, and, consequently, the more obscure does it appear. It may happen, that though the pupil is abundantly expanded, a few rays only shall be admitted into the eye. You have only to prick a little hole in a card with a pin, and look at an object through it; and then, however strongly illuminated by the sun, the object will appear dark in proportion as the aperture is small; nay, it is possible to look at the sun itself, employing this precaution. The reason is obvious, a few rays only are admitted into the eye: however expanded the pupil may be, the pin-hole in the card determines the quantity of light which enters the eye, and not the pupil, which usually performs that function.

The same thing takes place in the microscopes which magnify very much; for when the lens is extremely small, a very few rays only are transmitted, as $m\ n$ (PLATE VI. *Fig.* 28.), which being smaller than the aperture of the pupil, make the object appear so much more obscure; hence it is evident that this diminution of light takes place only when the lens M N, or rather its open part, is smaller than the pupil. If it were possible to produce a great magnifying effect, by means of a greater lens, this obscurity would not take place; and this is the true solution of the question. In order to remedy this inconvenience in the great effects of the microscope, care is taken to illuminate the object as strongly as possible, to give greater force to the few rays which are conveyed into the eye. To this effect objects are illuminated by the sun itself; mirrors likewise are employed, which reflect on them the light of the sun. These are nearly all the circumstances to be considered respecting the simple microscope, and by these you will easily form a judgment of the effect of all those which you may have occasion to inspect.*

*30th January* 1762.

## LETTER LXXXVIII.—ON TELESCOPES, AND THEIR EFFECT.

BEFORE I proceed to explain the construction of compound microscopes, a digression respecting the telescope may perhaps be acceptable. These two instruments have a very intimate connexion; the one greatly assists the elucidation of the other. As microscopes serve to aid us in contemplating nearer objects, by representing them under a much greater angle than when viewed at a certain distance, say *eight* inches; so the telescope is employed to assist our observation of very distant objects, by representing them under a greater angle than that which they present to the naked eye. Instruments of this sort are known by several names, according to their size and use; but they must be carefully distinguished from the glasses used by aged persons to relieve the decay of sight.

A telescope magnifies as many times as it represents objects under an angle greater than is presented to the naked eye. The moon, for example, appears to the naked eye under an angle of half a degree, consequently a telescope magnifies 100 times when it represents the moon under an angle of fifty degrees, which is 100 times greater than half a degree. If it magnified 200 times, it would represent the moon under an angle of one hundred degrees; and the moon would, in that case, appear to fill more than half of the visible heavens, whose whole extent is only 180 degrees.

In common language, we say that the telescope brings the object nearer to us. This is a very equivocal mode of expression, and admits of two different significations. The one, that on looking through a telescope, we consider the object as many times nearer as it is magnified. But I have already remarked, that it is impossible to know the distance of objects but by actual measurement, and that such measurement can be applied only to objects not greatly remote; when, therefore, they are so remote as is here supposed, the estimation of distance might

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* For an account of various improvements on the Single Microscope, the reader is referred to the article *Optics*, in the *Edinburgh Encyclopædia*, vol. xv. p. 681., and *Ferguson's Lectures*, vol. ii. p. 294.—ED.

greatly mislead us. The other signification, which conveys the idea, that telescopes represent objects as great as they would appear if we approached nearer to them, is more conformable to truth. You know, that the nearer we come to any object, the greater becomes the angle under which it appears; this explanation, accordingly, reverts to that with which I set out. When, however, we look at well-known objects, say men, at a great distance, and view them through a telescope under a much greater angle, we are led to imagine such men to be a great deal nearer, as in that case we would, in effect, see them under an angle so much greater. But in examining objects less approachable, such as the sun and moon, no measurement of distance can take place. This case is entirely different from that which I have formerly submitted to you, that of a concave lens, employed by near-sighted persons, which represents the images of objects at a very small distance. The concave lens which I use, for example, represents to me the images of all remote objects at the distance of four inches; it is impossible for me, however, to imagine, that the sun, moon, and stars, are so near: accordingly, we do not conclude that objects are where their images are found represented by glasses; we believe this as little as we do the existence of objects in our eyes, though their images are painted there. You will please to recollect, that the estimation of the real distance and real magnitude of objects depends on particular circumstances.

The principal purpose of telescopes, then, is to increase, or multiply, the angle under which objects appear to the naked eye; and the principal division of telescopes is estimated by the effect which they procure. Accordingly, we say such a telescope magnifies five, another ten, another twenty, another thirty times, and so on. And here I remark, that pocket-glasses

rarely magnify beyond *ten* times; but the usual telescopes employed for examining very distant terrestrial objects magnify from *twenty* to *thirty* times, and their length amounts to *six* feet or more. A similar effect, though very considerable with regard to terrestrial objects, is a mere nothing with respect to the heavenly bodies, which require an effect inconceivably greater. We have, accordingly, astronomical telescopes, which magnify from 50 to 200 times; and it would be difficult to go farther, as according to the usual mode of constructing them, the greater the effect is, the longer they become. A telescope that shall magnify 100 times must be at least 30 feet long; and one of 100 feet in length could scarcely magnify 200 times. You must be sensible, therefore, that the difficulty of pointing and managing such an unwieldy machine, must oppose insurmountable obstacles to pushing the experiment farther. The famous Hevelius, the astronomer at Dantzic, employed telescopes 200 feet long; but such instruments must undoubtedly have been very defective, as the same things are now discovered by instruments much shorter.

This is a brief general description of telescopes, and of the different kinds of them, which it is of importance carefully to remark, before we enter into a detail of their construction, and of the manner in which two or more lenses are united, in order to produce all the different effects.

*2d February* 1762.

## Letter LXXXIX.—Of Pocket-glasses.

We have no certain information respecting the person to whom we are indebted for the discovery of the telescope; whether he were a Dutch artist, or an Italian of the name of Porta.* Whoever he was, it is almost one hundred and fifty years since small pocket-glasses were first constructed, composed of two lenses, of which the one was convex, and the other concave. To pure chance, perhaps, a discovery of so much utility is to be ascribed. It was possible, without design, to place two lenses nearer to, or farther from each other, till the object appeared distinctly.

The convex lens PAP (Plate VI. *Fig.* 29.) is directed toward the object, and the eye is applied to the concave lens QBQ; for which reason, the lens PAP is named the *object-glass*, and QBQ the *eye-glass.* These two lenses are disposed on the same axis AB, perpendicular to both, and passing through their centres. The focal distance of the convex lens PAP must be greater than that of the concave; and the lenses must be disposed in such a manner, that if AF be the focal distance of the objective PAP, the focus of the eye-glass QBQ must fall at the same point F; accordingly, the interval between the lenses A and B, is the difference between the focal distances of the two lenses, AF being the focal distance of the object-glass, and BF that of the eye-glass. When the lenses are arranged, a person with good eyes will clearly see distant objects, which will appear as many times greater as the line AF is greater than BF. Thus, supposing the focal distance of the object-glass to be six inches, and that of the eye-glass one inch, the object will be magnified six times, or will appear under an angle six times greater than when viewed with the naked eye; and, in this case, the interval between the lenses A, B will be five inches, which is, at the same time, the length of the instrument. There is no need to inform you that these two lenses are cased in a tube of the same length, though not thus represented in the figure.

Having shown in what manner the two lenses are to be joined together in order to produce a good instrument, two things must be explained to you: the one, How these lenses come to represent objects distinctly; and the other, Why they appear magnified as many times as the line AF exceeds the line BF. With respect to the first, it must be remarked, that a good eye sees objects best, when they are so distant that the rays which fall on the eye may be considered as parallel to each other.

Let us consider, then, a point V (Plate VI. *Fig.* 30.) in the object toward which the instrument is directed, and on the supposition of its being very distant, the rays which fall on the object-glass PQ, QA, PQ, will be almost parallel to each other; accordingly, the object-glass QAQ, being a convex lens, will collect them in its focus F, so that these rays, being convergent, will not suit a good eye. But the concave lens at B having the power of rendering the rays more divergent, or of diminishing their convergency, will refract the rays QR, QR, so that they shall become parallel to each other; that is, instead of meeting in the point F, they will assume the direction RS, RS, parallel to the axis BF. Thus a good eye, according to which the construction of these is always regulated, on receiving these parallel rays RS, BF, RS, will see the object distinctly. The rays RS, RS, become exactly parallel to each other, because the concave lens has its focus, or rather its point of dispersion, at F.

You have only to recollect, that when parallel rays fall on a concave lens, they become divergent by refraction, so that being produced backward, they meet in the focus. This being laid down, we have only to reverse the case, and to consider the rays SR,

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* If the telescope was not actually invented by Roger Bacon, or Leonard Digges, they at least constructed combinations of lenses and mirrors, which produced the same effect.—Ed.

SR, as falling on the concave lens: in this case it is certain they would assume the directions RQ, RQ, which, produced backward, would meet in the point F, which is the common focus of the convex and concave lenses. Now it is a general law, that in whatever manner rays are refracted in their passage from one place to another, they must always undergo the same refractions in returning from the last to the first. If, therefore, the refracted rays RQ, RQ, correspond to the incident rays SR, SR; then, reciprocally, the rays QR, QR, being the incident ones, the refracted rays will be RS and RS.

The matter will perhaps appear in a clearer light still, when I say that concave lenses have the power of rendering parallel those rays which, without the refraction, would proceed to their focus. You will please carefully to attend to the following laws of refraction, which apply to both convex and concave lenses.

1. By a convex lens (Plate VI. *Fig.* 31.) parallel rays are rendered convergent.

Convergent rays become still more so (Plate VII. *Fig.* 1.), and divergent less divergent.

2. By a concave lens parallel rays are rendered divergent. (Plate VII. *Fig.* 2.)

Divergent rays become still more divergent, *Fig.* 3, and convergent rays less convergent.

All this is founded on the nature of refraction and the figure of the lenses, the discussion of which would require a very long detail; but the two rules which I have now laid down contain all that is essential. It is abundantly evident, then, that when the convex and the concave lenses are so combined that they acquire a common focus at F, they will distinctly represent distant objects, because the parallelism of the rays is restored by the concave lens after the convex lens had rendered them convergent. In other words, the rays of very distant objects, being nearly

parallel to each other, become convergent by a convex lens; and afterwards, the concave lens destroys this convergency, and again renders the rays parallel to each other.

*6th February* 1762.

## Letter XC.—On the magnifying power of Pocket-glasses.

The principal article respecting telescopical instruments remains still to be explained, namely, their effect in magnifying objects. I hope to place this in so clear a light, as to remove every difficulty in which the subject may be involved; and for this purpose I shall comprise what I have to say in the following propositions.

1. Let E*e* (Plate VII. *Fig.* 4.) be the object, situated on the axis of the instrument which passes perpendicularly through both lenses in their centres. This object E *e* must be considered as at an infinite distance.

2. If, then, the eye, placed at A, looks at this object, it will appear under the angle E A *e*, called its visual angle. It will, accordingly, be necessary to prove, that on looking at the same object through the glass, it will appear under a greater angle, and exactly as many times greater as the focal distance of the object-glass PAP exceeds that of the eye-glass QBQ.

3. As the effect of all lenses consists in representing the objects in another place, and with a certain magnitude, we have only to examine the images which shall be successively represented by the two lenses, the last of which is the immediate object of the sight of the person who looks through the instrument.

4. Now, the object E *e* being infinitely distant from the convex lens PAP, its image will be repre-