hesitation in pronouncing, that this opinion is totally untenable in philosophy, or rather, in physics. I cannot, however, flatter myself with the hope, that philosophers, wedded to opinions once adopted, should yield to these reasons. But the naturalist, who is more nearly related to the mathematician, will have less difficulty in resigning an opinion, overthrown by reasons so convincing. You will again recollect what Cicero has said on this subject: That nothing so absurd can be conceived, as not to be supported by some philosopher. In fact, however strange the system which I have been refuting may appear to you, it has hitherto been propagated and defended with much warmth.

It is impossible to say, to what a degree the difficulties and contradictions which I have been endeavouring to expose, were unknown to, or overlooked by, the partisans of this system. The great *Newton* himself strongly felt their force; but as he rested in a very untenable idea respecting the propagation of light, it is not to be wondered at, that he should overlook these great difficulties; and, in general, depth of understanding does not always prevent a man from falling into absurdity in supporting an opinion once embraced.

But if this system, that opaque bodies are rendered visible by reflected rays, be false—say, its partisans, what then is the true one? They even think it impossible to imagine another explanation of this phenomenon. It is, besides, rather hard and humiliating for a philosopher to acknowledge ignorance of any subject whatever. He would rather maintain the grossest absurdities; especially if he possesses the secret of involving them in mysterious terms, which no one is capable of comprehending. For in this case, the vulgar are the more disposed to admire the learned; taking it for granted, that what is obscurity to others, is perfectly clear to them. We ought always to exercise a little mistrust, when very sublime knowledge is pretended to—knowledge too sublime to be rendered intelligible. I hope I shall be able to explain the phenomenon in question, in such a way as to remove every difficulty.

1*st July* 1760.

LETTER XXV.—A DIFFERENT EXPLANATION OF THE MANNER IN WHICH OPAQUE BODIES ILLUMINATED BECOME VISIBLE.

ALL the phenomena of opaque bodies, which I have unfolded in the preceding letter, incontestably demonstrate, that when we see an opaque body illuminated, it is not by rays reflected from its surface that it becomes visible, but because its minuter particles are in an agitation similar to that of the minuter particles of luminous bodies; with this difference, however, that the agitation in opaque bodies is far from being so strong as in bodies luminous of themselves; for an opaque body, however much illuminated, never makes on the eye an impression so lively as luminous bodies do.

As we see the opaque bodies themselves, but by no means the images of the luminous bodies which enlighten them, as must be the case if we saw them by the reflection of their surface, it must follow, that the rays emitted by opaque bodies are proper to them, just as the rays of a luminous body are peculiar to itself. As long as an opaque body is illuminated, the minuter particles of its surface are in a state of agitation proper to produce in the ether a motion of vibration, such as is necessary for forming rays, and for painting in our eyes the image of the body from which they proceed. For this effect, rays must be diffused from every point of the surface, in all directions—as experience evidently confirms. For, from whatever side we look at an opaque body, we see it equally in all its points; from which it follows, that every point emits rays in all directions. This circumstance essentially distinguishes these rays from such as are reflected, whose direction is always determined by that of the rays of incidence; so that if the incident rays proceed from one single quarter, say the sun, the reflected rays can follow only one single direction.

It must be admitted, then, that when an opaque body is illuminated, all the particles on its surface are put in a certain agitation, which produces rays, as is the case with bodies luminous of themselves. This agitation, likewise, is stronger, in proportion as the light of the illuminating body is more intense. Thus the same body, exposed to the sun, is agitated much more violently, than if, in a room, it were illuminated only by day-light; or in the night-time, by a taper, or by the moon. In the first case, its image is painted with much greater vivacity on the bottom of the eye than in the others, especially the last; the light of the moon being scarcely sufficient to enable us to distinguish, or to read, writing of a large size. And when the opaque body is conveyed into a close room, or into the dark, nothing is then to be seen—a certain proof, that the agitation in its parts has entirely ceased, and that they are now in a state of rest.

In this, therefore, consists the nature of opaque bodies; their particles are of themselves at rest, or at least destitute of the agitation necessary to produce light. But these same particles are so disposed, that when illuminated, or struck with rays of light, they are immediately put into a certain agitation, or motion of vibration, proper to produce rays;

and the more intense the light is which illuminates these bodies, the more violent also is this agitation. As long as an opaque body is illuminated, it is in the same state as luminous bodies; its particles are agitated in the same manner, and are capable of exciting, of themselves, rays in the ether; with this difference, that the agitation kept up in luminous bodies by an intrinsic force, subsists always of itself; whereas, in opaque bodies, this agitation is only momentary, and produced by the motion of the light which illuminates them.

This explanation is consistent with every phenomenon, and labours under none of the difficulties which determined us to abandon the other, namely, that founded on reflection. Whoever will take the trouble candidly to weigh all these reasons, must admit their force. But a very great difficulty still remains to be solved: How comes it that illumination simply, can put the particles of an opaque body into an agitation capable of producing rays; and that this agitation should always continue nearly the same, whatever difference there may be in the illumination?

I acknowledge, that were it impossible to answer this question, it would be a great defect in my theory, though it would not amount to a complete refutation; for it contains nothing contradictory. Supposing I were ignorant how illumination produces an agitation in the particles of opaque bodies, this would only prove that the theory is incomplete: and till it is demonstrated to be absolutely impossible that illumination should produce this effect, my system must subsist. But I shall endeavour to supply this defect, by showing you how illumination agitates the minutest particles of bodies.

5th July 1760.

LETTER XXVI.—CONTINUATION OF THE SAME SUBJECT.

I HAVE undertaken to show how the illumination of an opaque body must produce, in its minutest particles, an agitation proper to excite the rays of light, which render that same opaque body visible. The parallel between sound and light, which differ only in respect of less and more, light being the same thing relatively to ether that sound is relatively to air—this parallel, I say, will enable me to fulfil my engagement. Luminous bodies must be compared to musical instruments actually in a state of vibration. It is a matter of indifference whether this be the effect of an intrinsic or of a foreign power; it is sufficient for my purpose that sound is emitted. Opaque bodies, as long as they are not illuminated, must be compared to musical instruments not in use; or, if you will, to strings which emit no sound till they are touched.

The question, then, being transferred from light to sound, is resolved into this, Whether it be possible for the string of an instrument in a state of rest, when brought within the sphere of activity of the sound of instruments in a state of vibration, to receive, in certain circumstances, some agitation, and emit sound, without being touched? Now this is confirmed by daily experience. If you take the trouble, during a concert, to attend to a particular string in proper tune, you will observe that string sometimes to tremble without having been touched, and it will emit the same sound as if it had been immediately put into vibration. This experiment will succeed still better, if the instruments strike the same note with the string. Consider attentively the strings of a harpsichord not played upon, while a violin strikes the note *a*, for example, and you will observe on the harpsichord the string of the same note begin sensibly to tremble, and even to emit sound, without having been touched; some other chords will likewise be agitated, particularly those which are distant an octave, a fifth, and even a third, provided the instrument be perfectly in tune.

This phenomenon is well known to musicians; and Mr. Rameau, one of the most celebrated French composers, established his principles of harmony upon it. He maintains, that octaves, fifths, and thirds, must be considered as consonances, because one chord is agitated by the sound only of another chord, which is in unison, or an octave, a fifth, or a third, from the first. But it must be admitted, that the principles of harmony are so well established by the simplicity of the relations which sounds have to each other, that they have no need of a new confirmation. In truth, the phenomenon observed by Mr. Rameau is a very natural consequence from the principles of harmony.

To render this more sensible, let us attend to two chords wound up to unison; on striking the one, the other will begin of itself to tremble, and will emit its sound. The reason is abundantly clear: for as a chord communicates to the air by its trembling a motion of vibration similar to its own, the air, agitated by this motion of vibration, must reciprocally make the chord tremble, provided that by its degree of tension it be susceptible of this motion. The air being put into vibration, strikes the chord ever so little at every reverberation, and the repetition of strokes soon impresses on the chord a sensible motion; because the vibrations to which it is disposed by its tension accord with those of the air. If the number of vibrations in the air is the half, or the third, or any other whose relation is sufficiently simple, the chord does not receive a new impulse at every vibration, as in the preceding case, but only at the second, or the third, or the fourth, which will continue to increase its tremulous motion, but less than in the first case.

But if the vibrations of the air have not any simple relation with that which corresponds to the chord, the agitation of that fluid will produce no effect whatever upon it; the vibrations of the chord, if there be any, not corresponding to those of the fluid, the following impulsions of the air destroy for the most part the effect which the first might have produced; and this is completely confirmed by experience. Thus, when a chord is shaken by a sound, that sound must, in order to its being perceptible, be precisely the same with that of the chord. Other sounds which have a consonance with that of the chord, will produce, it is true, a similar but less sensible effect, and dissonances will produce none at all. This phenomenon takes place not only in musical strings, but in all sonorous bodies whatever. One bell will resound by the noise only of another bell which is in unison with it, or at the distance of an octave, a fifth, or a third.

The instance of a person who could break glasses by his voice, farther confirms what I have advanced. When a glass was presented to him, by striking it he found out the note; he then began to squall in unison, and the glass immediately caught the vibration; proceeding to give to his voice all the force he was able, always preserving the unison, the vibration of the glass became at length so violent, that it broke. It is confirmed, then, by experience, that a chord and every other sonorous body is put into vibration by its kindred sound. The same phenomenon must take place with regard to opaque bodies, of which the minuter particles may be put into a state of agitation by illumination only—which is the question I proposed to solve. The following letter will contain a more ample discussion of it.

8th July 1760.

Letter XXVII.—Conclusion: Clearness and Colour of Opaque Bodies Illuminated.

After what has been just submitted to your consideration, you will no longer be surprised that an opaque body is capable of receiving, from illumination alone, an agitation in its particles similar to that of the particles of luminous bodies, and which gives them the property of producing rays that render them visible. Thus the great objection to my explanation of the visibility of opaque bodies is happily removed; while the other theory, founded on the reflection of rays, has to encounter difficulties which grow in proportion as you attempt to make a more direct application of them to known phenomena.

It is then an established truth, that the particles of the surfaces of all bodies which we see, undergo an agitation similar to that of a chord in vibration, but their vibrations are much more rapid; whether it be that this agitation is the effect of an intrinsic force, as in bodies luminous of themselves, or whether it be produced by the rays of light which fall upon the bodies, that is to say, by illumination, as is the case in opaque bodies. It is false, then, that the moon being an opaque body, reflects the rays of the sun, and that, by means of this reflected light, she is rendered visible to us, as is commonly understood. But the rays of the sun falling on the surface of the moon, excite in its particles a concussion, from which result the rays of the moon; and these, entering into our eyes, paint its image there; it is the same with the other planets, and with all opaque bodies. This agitation of opaque bodies, when illumined, lasts only during the illumination which is the cause of it; and as soon as an opaque body ceases to be illumined, it ceases to be visible.

But is it not possible that this agitation, once impressed on the particles of an opaque body, may be for some time kept up, as we see that a string once struck, frequently continues to vibrate, though no new impression be made upon it? I do not pretend to deny the fact: I even believe that we have examples of it in those substances which Mr. Margraff presented to you, and which, once illumined, preserve their light for some time, though conveyed into a dark room. This, however, is an extraordinary case, the vibration of the minuter particles disappearing in all other bodies with the illumination which occasioned it. But this explanation, which thus far is perfectly self-consistent, leads me forward to researches of still greater importance.

It is undoubtedly certain, that we find an infinite difference between the particles of opaque bodies, according to the variety of the bodies themselves. Some will be more susceptible of vibrations, and others less, and others finally not at all so. This difference in bodies occurs but too evidently. One, whose particles easily receive the impression of the rays which strike it, appears to us brilliant; another, on the contrary, in which the rays scarcely produce any agitation, cannot appear luminous. Among several bodies, equally illumined, you will always remark a great difference, some being more brilliant than others. But there is besides another and a very remarkable difference between the particles of opaque bodies, respecting the number of vibrations which each of them, being agitated, will make in a certain time.

I have already observed, that this number must always be very great, and that the subtilty of ether is such as to require many thousands in a second. But the difference here may be endless, if some particles, for example, should make 10,000 vibrations in a second, and others 11,000, 12,000, 13,000, according to the smallness, the tension, and the elasticity of each, as in the case of musical chords, in which the number of vibrations given in a second may be varied without end; and thence it is I have deduced the difference of high and low notes. As this difference is essential in sounds, and as the ear is affected by it in a manner so particular as to render it the foundation of the whole theory of music, it cannot be called in question, that a similar difference in the frequency of the vibrations of rays of light must produce a variation as particular in vision. If, for example, a particle makes 10,000 vibrations in a second, and produces rays of the same species, the rays which enter into the eye will strike the nerves of that organ 10,000 times in a second; and this effect, as well as the sensation, must be totally different from those produced by a different particle which should make more or less vibrations in a second. There will be in vision a difference similar to that which the ear perceives on hearing sharp or flat notes.

You will no doubt be desirous to know into what this difference in vision is to be resolved; and what different sensations correspond to the number, greater or less, of the vibrations produced in every body during a second. I have the honour of informing you, that diversity of colours is occasioned by this difference; and that difference of colour is to the organ of vision what sharp or flat sounds are to the ear. We have resolved, therefore, without going after it, the important inquiry respecting the nature of colours, which has long employed the attention of the greatest philosophers. Some of them have called it a modification of light absolutely unknown to us. *Descartes* maintains, that colours are only a certain mixture of light and shade. *Newton* accounts for difference of colour by tracing it up to the rays of the sun; which, according to him, are a real emanation, whose matter may be more or less subtile; and thence settles the rays of all the colours, as red, yellow, green, blue, violet, &c.

But as this system falls to pieces of itself, all that has been said respecting colours conveys no information; and you are now clearly sensible, that the nature of each colour consists in the number of vibrations produced in a certain time, by the particles which present them to the eye.

12*th July* 1760.

LETTER XXVIII.—NATURE OF COLOURS IN PARTICULAR.

THE ignorance which prevailed respecting the true nature of colours, has occasioned frequent and violent disputes among philosophers; each of whom made an attempt to shine, by maintaining a peculiar opinion on the subject. The system which made colours to reside in the bodies themselves, appeared to them too vulgar and too little worthy of a philosopher, who ought always to soar above the multitude. Because the clown imagines that one body is red, another blue, and another green, the philosopher could not distinguish himself better than by maintaining the contrary; and he accordingly affirms that there is nothing real in colours, and that there is nothing in bodies relative to them.

The Newtonians make colours to consist in rays only, which they distinguish into *red, yellow, green, blue, indigo,* and *violet;* and they tell us that a body appears of such and such a colour when it reflects rays of that species. Others, to whom this opinion seemed absurd, pretend that colours exist only in ourselves. This is an admirable way to conceal ignorance; the vulgar might otherwise believe, that the scholar was not better acquainted with the nature of colours than themselves. But you will readily perceive that these affected refinements are mere cavil. Every simple colour (in order to distinguish from compound colours) depends on a certain number of vibrations, which are performed in a certain time; so that this number of vibrations, made in a second, determines the red colour, another the yellow, another the green, another the blue, and another the violet, which are the simple colours represented to us in the rainbow.

If, then, the particles of the surface of certain bodies are disposed in such a manner, that being agitated, they make in a second as many vibrations as are necessary to produce, for example, the red colour, I call such a body red, just as the clown does; and I see nothing like a reason for deviating from the common mode of expression. And rays which make such a number of vibrations in a second, may with equal propriety be denominated red rays; and finally, when the optic nerve is affected by these same rays, and receives from them a number of impulsions, sensibly equal, in a second, we receive the sensation of the red colour. Here every thing is clear; and I see no necessity for introducing dark and mysterious phrases, which really mean nothing.

The parallel between sound and light is so perfect, that it holds even in the minutest circumstances. When I produced the phenomenon of a musical chord, which may be excited into vibration, by the resonance only of certain sounds, you will please to recollect, that the one which gives the unison of the chord in question is the most proper to shake it, and that other sounds affect it only in proportion as they are in consonance with it. It is exactly the same as to light and colours; for the different colours correspond to the different musical sounds.

In order to display this phenomenon, which completely confirms my assertion, let a dark room be provided; make a small aperture in one of the shutters; before which, at some distance, place a body of a certain colour, say a piece of red cloth, so that, when it is illumined, its rays may enter by the aperture into the darkened room. The rays thus transmitted into the room will be red, all other light being excluded; and if you hold on the inside of the room, opposite to the aperture, a piece of cloth of the same colour, it will be perfectly illumined, and its red colour appear very brilliant; but if you substitute in its place a piece of green cloth, it will remain obscure, and you will hardly see any thing of its colour. If you place on the outside, before the aperture, a piece of green cloth, that within the chamber will be perfectly illumined by the rays of the first, and its green colour appear very lively. The same holds good as to all other colours: and I do not imagine that a more convincing demonstration of the truth of my system can be demanded.

We learn from it, that in order to illuminate a body of a certain colour, it is necessary that the rays which fall upon it should have the same colour; those of a different colour not being capable of agitating the particles of that body. This is farther confirmed by a well known experiment. When the spirit of wine is set on fire in a room, you know that the flame of spirit of wine is blue, that it produces only blue rays, and that every person in the room appears very pale—their faces, though painted ever so deep, have the aspect of death. The reason is evident; the blue rays not being capable of exciting or putting in motion the red colour of the face, you see on it only a feeble and bluish colour; but if one of the company is dressed in blue, such dress will appear uncommonly brilliant. Now the rays of the sun, those of a wax taper, or of a common candle, illuminate all bodies almost equally; from whence it is concluded, that the rays of the sun contain all colours at once, though he himself appears yellowish.

In truth, when you admit into a dark room the rays of all the simple colours, red, yellow, green, blue, and violet, in nearly equal quantities, and blend them, they represent a whitish colour. The same experiment is made with various powders, coloured in like manner; on being mixed together, a whitish colour is the result. Hence it is concluded, that white is not a simple colour, but that it is rather a compound of all the simple colours; accordingly we see that white is adapted to the reception of all colours. As to black, it is not properly a colour. Every body is black, when its particles are such that they can receive no motion of vibration, or when it cannot produce rays. The want of rays, therefore, produces the sensation of that colour; and the more particles there are found in any body not susceptible of any motion of vibration on its surface, the more blackish and obscure it appears.

15*th July* 1760.

LETTER XXIX.—TRANSPARENCY OF BODIES RELATIVE TO THE TRANSMISSION OF RAYS.

I HAVE already remarked, that there are bodies, such as glass, water, and especially air, which transmit the rays of light, and, on account of this property, are denominated pellucid or diaphanous. The ether, however, is the medium in which the rays of light are formed, to which this property most intimately appertains; and other transparent bodies are endowed with it only by means of the ether which they contain, and with which they are so blended, that the agitations excited by the light may be communicated farther, without being interrupted in their progress. But this transmission is never performed so freely as in the pure ether, though it always loses something; and this in proportion as the transparent body is more or less gross. The grossness may even become so considerable, that the light shall be wholly lost in it; and then the body is no. longer transparent. Thus, though glass be a transparent body, a great lump of glass several feet thick is not so. In like manner, however pure the water of a river may be, you cannot see the bottom where it is very deep, though you can very easily see it where it is shallow.

Transparency, then, is a property of bodies relative only to their thickness; and when this property is ascribed to glass, to water, &c. it must always be understood with this restriction, that these bodies are not too gross; and that to every species there is a certain measure of thickness, beyond which the body ceases to be transparent. There is not one opaque body, on the contrary, which may not itself become transparent, if reduced to a plate extremely fine. Thus, though gold is not transparent, gold leaf is so; and on examining the minuter particles of all bodies with a microscope, they are found to be transparent. It may then be with truth affirmed, that all bodies are transparent when reduced to a certain degree of fineness; and that no one is so when too gross.

In common language we denominate transparent the bodies which preserve this quality to a certain degree of thickness, though they lose it when they go beyond that bound. But with respect to ether, it is of its own nature perfectly transparent, and its extent diminishes not this quality in the smallest degree. The prodigious distance of the fixed stars prevents not their rays from being transmitted to us. But though our air appears to be of a perfect transparency, if it extended as far as the moon, that transparency would be entirely lost, and would prevent every ray of the sun, and of the other heavenly bodies, from penetrating to us. We should then be involved in Egyptian darkness.

The reason of it is evident, and we remark the same thing in sound, whose resemblance to light is confirmed in every respect. Air is the most proper medium for the propagation of sound; but the agitations excited in the air are capable of shaking also the particles of all bodies; and these again putting in motion the interior particles, finally transmit the vibration through the substance of all bodies, unless they be too thick. There are bodies, then, which, relatively to sound, are the same thing which transparent bodies are relatively to light; and all bodies have this property with relation to sound, provided they are not too thick. When you are in your apartment, you can hear almost every thing that passes in the anti-chamber, though the doors are closely shut, because the agitation of the air in the anti-chamber communicates itself to the partitions, and penetrates through them into the inner apartment, with some loss, however. Were the partition removed, you would undoubtedly hear more distinctly. Now, the thicker the walls are, the more of its force does the sound lose in piercing through them; and the walls may be made so thick, that nothing could be heard from without, unless it were some terrible noise, such as a discharge of cannon.

This leads me forward to a new remark, that very powerful sounds may be heard through walls which are impenetrable to sounds more feeble; and, consequently, in order to form a judgment whether a wall is capable of transmitting sounds, it is necessary to take into the account, not only the thickness of the wall, but likewise the strength of the sound. If the sound is very feeble, a very thin wall is sufficient to stop it; though a louder could find an easy transmission. The same thing holds as to bodies which are permeable only to a very strong light. Objects not very brilliant are invisible through a glass blackened with smoke, but the rays of the sun force themselves through it, and it transmits perfectly well the image of that luminary. Astronomers employ this method to observe him; for without such precaution he would dazzle the eye. And when you happen to be in a dark room, with an aperture in the shutter exposed to the sun, in vain will you attempt to exclude the light, by opposing your hand to the aperture; the rays of the sun will force themselves through.

It is perceivable, at the same time, that the light of the sun loses much of its lustre in passing through a body which, relatively to other objects, is not itself transparent. But a very strong light may lose much of its lustre before it is entirely extinguished, while a feebler light is lost at once. A piece of very thick glass, then, will not be transparent with respect to objects less brilliant, though the sun may be visible through it.

These remarks on transparent bodies lead me to the theory of refraction, of which you have frequently heard, and which I shall endeavour to place in its proper light.

18*th July* 1760.

LETTER XXX.—OF THE TRANSMISSION OF RAYS OF LIGHT, THOUGH TRANSPARENT MEDIUMS, AND THEIR REFRACTION.

As long as light moves in the same medium, whether it be ether, air, or any other transparent body, the propagation proceeds in straight lines, denominated rays, as they diverge from the luminous point, in all directions, like the radii of a circle or a globe issuing from the centre. In the system of emanation, the particles darted from luminous bodies move in straight lines; the same thing holds in that which I have had the honour of proposing, in which the agitations are communicated in straight lines, as the sound of a bell is transmitted in a straight line, by which also we judge from what quarter the sound comes; the rays in both systems, then, are represented by straight lines, as long as they pass through the same transparent medium; but they may undergo some bending, in passing from one to another; and this bending is called the *refraction* of the rays of light, the knowledge of which is necessary to account for many phenomena. I proceed, therefore, to lay down the principles, in conformity to which refraction takes place.

It is an invariable law, that when a ray, such as E C (PLATE I. *Fig.* 8.) falls perpendicularly on the surface A B of another medium, it continues its progress in the same straight line extended, as C F; it will, in this case, undergo no bending or refraction. If, then, E C is a ray of the sun, falling perpendicularly on the surface A B of water, or of glass, it will enter it in the same direction, and continues its progress in the line C F, which is likewise perpendicular to the surface A B, so that E F shall be in one and the same straight line. This is the only case in which there is no refraction. But as often as the ray does not fall perpendicularly on the surface of another transparent body, it does not pursue its progress in the same straight line; it recedes less or more from it, and undergoes a refraction.

Let P C (Plate I. *Fig.* 9.) be a ray, falling obliquely on the surface A B, of another transparent medium. On entering into this medium, it will not continue its progress in the direction of the line C Q, which is the line P C produced; but will recede from it, in the direction of the line C R, or C S. It will undergo, then, at the point C, a bending, which we call refraction, which depends partly on the difference of the two mediums, and partly on the obliquity of the direction of the ray P C.

In order to comprehend the laws of this bending, it is necessary to explain certain terms employed in treating this subject.

1st, The surface A B, which separates the two mediums, that from which the ray comes, and that into which it enters, is called the *refracting surface.* 2dly, The ray P C, which falls upon it, is called the *incident ray;* and, 3dly, the ray C R, or C S, which pursues, in the other medium, a course different from C Q, is called the *broken* or *refracted ray.* And, having drawn through the surface A B, the perpendicular line E C F, we call, 4thly, the angle P C E, formed by the incident ray P C, with the perpendicular E C, *the angle of incidence;* and, 5thly, the angle R C F, or S C F, formed by the refracted ray C R or C S, with the perpendicular C F, is called the *angle of refraction.*

Therefore, because of the bending which the ray of light undergoes, the angle of refraction is not equal to the angle of incidence P C E; for producing the line P C to Q, the angles P C E and F C Q being vertical, are equal to each other (Euclid's Elements, Book I. Prop. 15.), as you will easily recollect. The angle Q C F, then, is equal to the angle of incidence P C E; therefore, the angle of refraction R C F or S C F, is greater or less. There are, then, only two cases which can exist; the one, in which the refracted ray being C R, the angle of refraction R C F, is less than the angle of incidence P C E; and the other, in which the refracted ray being C S, the angle of refraction is greater than the angle of incidence P C E. In the former case, we say, that the ray C R approaches the perpendicular C F; and in the other, that the refracted ray C S, recedes or deviates from the perpendicular.

It is necessary, then, to inquire, In what cases the one or the other of these changes will take place? And we shall find, that this phenomenon depends on the difference of the density of the two mediums, or because the rays are transmitted with more or less difficulty through each of them. To prove this, it must be recollected, that ether is of all mediums the most rare, and that through which rays are transmitted without the slightest resistance. After it, the other common transparent mediums are thus arranged: air, water, glass; thus glass is a medium more dense than water; water than air; and air than ether.

This being laid down, we have only to attend to these two general rules: 1st, When rays pass from a medium less dense into one which is more so, the refracted ray approaches the more to the perpendicular. This is the case, in which the incident ray being P C, the refracted ray is C R. 2dly, When the rays pass from a medium more dense, to one less so, the refracted ray recedes from the perpendicular. This is the case, in which the incident ray being P C, the refracted ray is C S. Now, this bending is greater or less, according as the two mediums differ in respect of density. Thus, rays, in passing from air into glass, undergo a greater refraction, than when they pass from air into water; in both cases, however, the refracted rays approach the perpendicular. In like manner, rays passing from glass into air, undergo a greater refraction than when they pass from water into air; but in these cases, the refracted ray recedes from the perpendicular.

Finally, it must likewise be remarked, that the difference between the angle of incidence and the angle of refraction is so much greater, as the angle of incidence is greater; or, as the incident ray recedes farther from the perpendicular, the greater will be the bending or refraction of the ray. A relation between all these angles exists, and is determinable by geometry; but it is not now necessary to enter into the detail. What has been already said, is sufficient for understanding what I have farther to propose on the subject.

22d July 1760.

LETTER XXXI.—REFRACTION OF RAYS OF DIFFERENT COLOURS.

YOU have seen, that when a ray of light passes obliquely from one transparent medium to another, it undergoes a bending, which is called refraction, and that the refraction depends on the obliquity of the incidence, and the density of the mediums. I must now call upon you to remark, that diversity of colours occasions, likewise, a small variety in the refraction. This arises, undoubtedly, from the circumstance, that the rays which excite in us the sensations of different colours, perform unequal numbers of vibrations in the same times, and that they

differ among themselves, in the same manner as sharper or flatter sounds do. Thus, it is observable, that rays of *red* undergo the least bending or refraction; after them come the *orange*, the *yellow*, the *green*, the *blue*, and the *violet*, follow in order; so that violet-coloured rays undergo the greatest refraction; it being always understood, that the obliquity of the incidence, and the density of the mediums, are the same. Hence, it is concluded, that rays of different colours have not the same refrangibility; that the *red* are the least, and the *violet* the most refrangible.

If then, P C (PLATE I. *Fig.* 10.) is a ray passing, for example, from *air* into *glass*; the angle of incidence being P C E, the refracted ray will approach the perpendicular C F; and if the ray be *red*, the refracted ray will be in the direction C—*red*; if it be *orange*, the refracted ray will be C—*orange*; and so of the rest, as may be seen in the figure. All these rays deviate from the line C Q, which is P C produced, toward the perpendicular C F; but the red ray deviates the least from C Q, or undergoes the least refraction, and the violet recedes the farthest from C Q, and undergoes the greatest refraction.

Now if P C is a ray of the sun, it produces at once all the coloured rays indicated in the figure; and if a piece of white paper is placed to receive them, you will in effect see all these colours; hence it is affirmed, that every ray of the sun contains at once all the simple colours. The same thing happens if P C is a ray of white, or if it proceeds from a white body. We see all the colours produced from it by refraction, whence it is concluded that white is an assemblage of all the simple colours, as we formerly showed. In truth, we have only to collect all these coloured rays into a single point, and the colour of white will be the result.

It is thus we discover what are the simple colours. Refraction determines them incontestibly. In following the order which it presents, they are these: 1. red, 2. orange, 3. yellow, 4. green, 5. blue, 6. violet.* But it must not be imagined that there are but six; for as difference of colours arises from the number of vibrations which rays perform in one and the same time, or rather the undulations which produce them, it is clear that the intermediate numbers equally give simple colours. But we want names by which to design these colours; for between *yellow* and *green*, we evidently perceive intermediate colours, for which we have no separate names.

In conformity to the same laws, are produced the colours visible in the *Rainbow.* The rays of the sun, in passing through the drops of water which float through the air, are by them reflected and refracted, and the refraction decompounds them into the simple colours. You must undoubtedly have remarked, that these colours follow each other in the same order in the rainbow, the *red, orange, yellow, green, blue,* and *violet;* but we discover in it also all the intermediate colours, as shades of one colour to another; and had we more names to distinguish these degrees, we might find more of them from the one extremity to the other. A more copious language may perhaps enable another nation actually to reckon a greater number of different colours; and another, it may be, cannot reckon so many; if, for

example, it wants a term to express what we call orange. Some to these add *purple,* which we perceive at the extremity of the red, but which others comprehend under the same name with red.

C.	D.	E.	F.	G.	A.	B.
Purple.	Red.	Orange.	Yellow.	Green.	Blue.	Violet.

These colours may be compared to the notes of an octave, as I have done here, because the relations of colours, as well as those of sounds, may be expressed by numbers. There is even an appearance, that by straining the violet a little more, you may come round to a new purple, just as in rising from sound to sound, on going beyond B you come round to *c*, which is the octave above C. And as in music we give to these two notes the same name, because of their resemblance, the same thing takes place in colours, which, after having risen through the intervals of an octave, resume the same names; or, if you will, two colours, like two sounds, in which the number of vibrations in the one is precisely the double of the other, pass for the same, and bear the same name.

On this principle it was that Father *Castel,* in France, contrived a species of music of colours. He constructed a harpsichord, of which every key displayed a substance of a certain colour; and he pretended that this harpsichord, if skilfully touched, would present a most agreeable spectacle to the eye. He gave it the name of the *Ocular Harpsichord,** and you must undoubtedly have heard it talked of.

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* When the beam of light is very small, Dr. Wollaston found that there were only *four* colours, viz. *red, yellowish-green, blue,* and *violet,* in the proportions 16, 23, 36, and 25. These proportions, however, vary with the inclination of the incident ray, and also with the nature of the refracting body, of which the prism is formed. The power of any body to produce colour by a separation of the coloured rays, is called its *dispersive power,* which does not depend upon its *refractive power.* See the *Edinburgh Encyclopædia,* Art. Optics, vol. xv. p. 485. 541.—Ed.

* An account of Father Castel's Ocular Harpsichord will be found in Dr. Brewster's *Treatise on the Kaleidoscope,* p. 131.—Ed.

For my part, painting rather seems to be that to the eye which music is to the ear; and I greatly doubt whether the representation of several shreds of cloth of different colours could be very agreeable.

27th July 1760.

LETTER XXXII.—OF THE AZURE COLOUR OF THE HEAVENS.

YOU have just seen, that the cause of the visibility of objects is a motion of vibration extremely rapid, by which the minuter particles of their surfaces are agitated, and that the frequency of these vibrations determines the colour.

It is the same thing whether these particles be agitated by an intrinsic force, as in luminous bodies, or whether they receive their agitation from illumination, or from foreign rays, by which they are illumined, as in opaque bodies. The frequency or rapidity of the vibrations depends on the grossness of these particles, and on their elasticity, as that of the vibrations of a musical string depends on its thickness and degree of tension; thus, as long as the particles of a body preserve the same elasticity, they represent the same colour, as the leaves of a plant preserve a green colour as long as they are fresh; but when they begin to dry, the difference of elasticity, which then takes place, produces likewise a different colour. This subject I have already discussed. I now proceed to explain why the heavens appear to us of a blue colour in the day-time.

On observing this phenomenon with a vulgar eye, it would appear that we are surrounded by a prodigious vault of azure, as painters represent the sky on a ceiling. I have no occasion to undeceive you respecting this prejudice: a small degree of reflection is sufficient to make you comprehend that the heavens are not an azure vault, to which the stars are affixed like so many luminous studs. You are perfectly convinced that the stars are immense bodies, at inconceivable distances from us, and which move freely through a space almost void, or which is filled only by that subtile matter called ether. And I will show you that this phenomenon is to be ascribed to our atmosphere, which is not perfectly transparent.

Were it possible to rise higher and higher above the surface of the earth, the air would become gradually more and more rare, till it ceased to assist respiration, and would at length entirely cease; we should then have reached the region of pure ether. Accordingly, in proportion as we ascend on mountains, the mercury in the barometer continues to fall, because the atmosphere becomes lighter and lighter; and then likewise it is remarked, that the azure colour of the heavens becomes fainter; and were it possible to mount into pure ether, it would entirely disappear: on looking upward, we should see nothing at all, and the heavens would appear black as night; for where no ray of light can reach us, every thing wears the appearance of black.

There is good reason, then, for asking, Why the heavens appear to be blue? This phenomenon could not exist, were air a perfectly transparent medium, as ether is: in that case, we should receive from above no other rays but those of the stars: but the lustre of day-light is so great, that the feeble light of the stars is absorbed by it. You could not perceive the flame of a taper in the day-time, at any considerable distance; but that same flame, in the night, would appear very brilliant at much greater distances. This clearly proves, that we must look for the cause of the azure colour of the heavens, in the want of transparency in the air. The air is loaded with a great quantity of small particles, which are not perfectly transparent, but which, being illuminated by the rays of the sun, receive from them a motion of vibration, which produces new rays proper to these particles; or else they are opaque, and become visible to us from being illumined.

Now, the colour of these particles is blue; and this explains the phenomenon: the air contains a great quantity of small blue particles: or it may be said, that its minuter particles are bluish, but of a colour extremely delicate, and which becomes sensible to us only in an enormous mass of air. Thus, in a room, we perceive nothing of this blue; but when the bluish rays of the whole atmosphere penetrate our eyes at once, however delicate the colour of each singly, their totality may produce a very deep colour.

This is confirmed by another phenomenon, with which you must be well acquainted. If you look at a forest, from a moderate distance, it appears quite green; but in proportion as your distance increases, it acquires a bluish cast, and this gradually becomes deeper and deeper. The forests on the mountains of Hartz, which may be seen from Magdeburg, appear thence to be blue, but viewed from Halberstadt, they are green. The great extent of air between Magdeburg and these mountains, is the reason of it. However delicate or rare the bluish particles of the air may be, there is such a prodigious quantity of them in that interval, the rays of which enter into the eye at once, that they represent a tolerable deep blue *.

We remark a similar phenomenon in a fog, when the air is loaded with a great quantity of opaque particles of a whitish colour. On looking only to a small distance, you scarcely perceive the fog; but when the distance is considerable, the whitish colour becomes very perceptible; to such a degree, that it is impossible to see through it. The water of the sea appears green at a certain depth; but when you take up a small quantity, as much, for instance, as a glass will contain, it is sufficiently diaphanous, and has no sensible colour: but in a great extent, when you look toward the bottom, so many greenish rays collected produce a deep colour.

27th July 1760.

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* When the purest spring water is placed in a large reservoir lined with something white, its tint is invariably of a blue colour. Hence arises the blue colour of masses of transparent ice, in the glaciers of Switzerland, and the fine blue colour of the Rhone, in issuing out of the Lake of Geneva.—ED.

LETTER XXXIII.—OF RAYS ISSUING FROM A DISTANT LUMINOUS POINT, AND OF THE VISUAL ANGLE.

As long as the rays produced by the rapid vibration of the minuter particles of a body, move in the same transparent medium, they preserve the same direction, or diffuse themselves in all directions, in straight lines. These rays may be represented by the radii of a circle, or rather of a sphere, which, issuing from a centre, proceed in straight lines to the circumference; and it is on account of this resemblance that we employ the same term *radius*, or ray, to express them, though, properly speaking, the light does not consist of lines, but of very rapid vibrations, going continually forward, in the direction of straight lines; and, for this reason, light may be considered as straight lines, issuing from a luminous point, in all directions.

Let C (PLATE I. *Fig.* 11.) be a luminous point, from which rays issue in all directions. Let two spheres be described round C, as a centre, of the one of which, let the great circle be *a b d e*, and of the other A B D E. The light diffused over the surface of the smaller sphere *a b d e*, will likewise occupy that of the greater sphere A B D E. The light, then, must be more faint and weak at the surface of this last, than at that of the smaller sphere *a b d e*. Hence it may be concluded, that the effect of light must be smaller, in proportion to the distance from the luminous point. If we suppose, that the radius of the greater sphere is double that of the smaller, the surface of the greater sphere will be four times as great. Since, therefore, the same quantity of light is diffused over the surface of the greater sphere, and over that of the smaller, it must follow, that light, at double the distance, is four times more faint; at thrice the distance, nine times; at a quadruple distance, sixteen times; and so on.

On applying this rule to the light of the sun, it will appear, that if the earth were removed to double the distance from the sun, the light derived from him would be rendered four times more faint; and if the sun were an hundred times further from us, his brightness would be a hundred times a hundred, that is, ten thousand times less. Supposing, then, a fixed star to be as great and as luminous as the sun, but that it was 400,000 times farther from us, its light will be 400,000 times 400,000, that is, 160,000,000,000 times more faint than that of the sun. Hence we see, that the light of a fixed star is nothing compared to that of the sun; and this is the reason that we do not see the stars in the day time; as a feebler light always disappears in presence of one much more bright. The same thing holds good with respect to candles, and all other luminous bodies, which administer less light, in proportion to their distance from us; and you must have frequently remarked, that however strong a light may be, it is insufficient to assist us in reading a printed book, if you remove from it to any considerable distance.

There is still another circumstance, closely connected with what I have just observed, namely, that the same object appears smaller to us, in proportion to its distance. A giant, at a great distance, does not appear taller than a dwarf near us. To form a clearer judgment of this, it is necessary to attend to the angles at which these objects are seen by us.

Let us suppose, then, A B (PLATE I. *Fig.* 12.) to be an object, for example, a man, and that the eye looks at it from the point C. Draw from that point the straight lines A C and B C, which represent the extreme rays proceeding from the object to the eye; we call the angle formed at C, the visual angle of that object for the point C. If we look at the same object from a smaller distance, at D, the visual angle D will be undoubtedly greater: hence it is clear, that the more distant the same object is, the smaller is its visual angle; and the nearer it approaches, its visual angle becomes greater.

Astronomers measure very accurately the angles under which we see the heavenly bodies; and they have found, that the visual angle of the sun is somewhat more than half a degree. If the sun were twice as far from us, this angle would be reduced to the half; and then it will not seem surprising that it should furnish us four times less light. And if the sun were 400 times farther off, his visual angle would become so many miles less, and then that luminary would appear no greater than a star. We must, therefore, carefully distinguish the apparent greatness of any object from its real greatness. The first is always an angle greater or less, according as the object is nearer or more distant. Thus the apparent greatness of the sun, is an angle of about half a degree, whereas his real magnitude far surpasses that of the earth; for the sun being a globe, his diameter is estimated to be about 790,000 English miles, while the diameter of the earth is only 7912 English miles.

29th July 1760.

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

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

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

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

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