it could not become visible to us till more than six years had elapsed, as its rays require that length of time to travel this distance. Had one been created at the beginning of the world a thousand times more distant than that which I have mentioned, it could not yet be visible to us, however brilliant, as 6000 years are not yet elapsed since the creation. The first preacher of the court of Brunswick, Mr. Jerusalem, has happily introduced this thought in one of his sermons. The passage runs thus:—

"Raise your thoughts from the earth which you inhabit, to all the bodies of the vast universe, which are so far above you; launch into the immensity of space which intervenes between the most remote which your eyes are able to discover, and those whose light, from the moment of creation till now, has not as yet, perhaps, come down to us. The immensity of the kingdom of God justifies this representation." (Sermon *on the Heavens, and Eternal Beatitude*).

I flatter myself that these reflections will excite a desire of further instruction respecting the system of light, from which is derived the theory of colours, and of vision.

17th June 1760.

Letter XXI.—Digression on the Distances of the Heavenly Bodies, and on the Nature of the Sun, and his Rays.

The observations which I have been making respecting the time which the light of the stars employs in making its progress down to us, convey a striking idea of the extent and greatness of the universe. The velocity of sound, which flies through

the space of 1000 feet in a second, furnishes us with nearly the first standard of measurement. It is about 2000 times more rapid than the pace of a man who is a good walker. Now the velocity of the rays of light is 900,000 times still more rapid than that of sound: these rays accordingly perform every second a course of 900 millions of feet, or 170,000 English miles.

What astonishing velocity! Yet the nearest fixed star is so remote, that its rays, notwithstanding this prodigious velocity, would take more than six years in descending to us. And were it possible for a great noise, such as that of the firing of a cannon, issuing from that star, to be conveyed to our ears, it would require a period of 5,400,000 years to reach us. And this is applicable only to those stars which are the most brilliant, and are probably nearest to us. Those which appear the smallest are very probably ten times still farther remote, and more. A whole century, then, at least, must elapse before the rays of these stars could possibly reach us. How prodigious must that distance be which cannot be passed through in less than 100 years, by a velocity which flies at the rate of 170,000 English miles every second!

Were, then, one of these stars to be just now annihilated, or eclipsed only, we should still continue to see it for 100 years to come, as the last rays which it emitted could not reach us in less time.

The generality of mankind is very far from having any thing like just ideas respecting the vast extent of the universe. Many consider it as a work of little importance, which chance alone might have produced. But what must be the astonishment of one who reflects, on observing, that all these immense bodies are arranged with the most consummate wisdom; and that the more knowledge we acquire on the subject, though it must ever be very imperfect, the more we must be disposed to admire their order and magnificence!

I return to the great luminous bodies, and particularly the sun, which is the principal source of the light and heat which we enjoy on the earth. It will be asked, in the first place, wherein consists the light which the sun is incessantly diffusing through the whole universe, without ever suffering the smallest diminution? The answer is obvious, according to the system which I have been endeavouring to establish. But that of emanation furnishes no satisfactory solution. The whole universe being filled with that extremely subtile and elastic fluid which is called ether, we must suppose, in all the parts of the sun, an incessant agitation, by which every particle is in a constant motion of vibration; and this, by communicating itself to the circumambient ether, excites in that fluid a similar agitation, and is thence transmitted to regions the most remote with the rapidity which I have been describing.

And to keep up the parallel between sound and light, the sun would be in a state similar to that of a bell which should be ringing continually. The particles of the sun must consequently be kept in this incessant agitation, to produce in the ether the undulations which we call rays of light. But it is still no easy matter to explain by what power this agitation in the particles of the sun is constantly kept up, as we observe that a match does not long continue burning, but presently goes out, unless it be supplied with combustible matter. But it must be remarked, that as the sun is a mass many thousand times greater than our whole globe, if it is once thoroughly inflamed, it may continue in that state for several ages without suffering any sensible diminution. Besides, the case is not the same with the sun and our

fires and candles, a considerable part of whose substance is dissipated in smoke and exhalations, from which a real waste results. Whereas, though perhaps some particles may be forced from the sun in form of smoke, they cannot remove to a great distance, but speedily fall back into its mass, so that there cannot be any real expenditure to occasion a diminution of his substance.

The only thing of which we are still ignorant respecting this subject, is the power which incessantly maintains all the particles of the sun in this agitation. But as it contains nothing inconsistent with good sense, and as we are under the necessity of acknowledging our ignorance of many other things much less remote than the sun, we ought to be satisfied if our ideas are not involved in contradiction.

21st June 1760.

Letter XXII.—Elucidations on the Nature of Luminous Bodies, and their Difference from Opaque Bodies Illumined.

The sun being a luminous body, whose rays are universally diffused in all directions, you can no longer be at a loss to account for this wonderful phenomenon, which consists in the shaking or vibration with which all the particles of the sun are agitated. The parallel of a bell lends considerable assistance toward the explanation of this fact. But it is obvious, that the vibrations produced by light must be much more vehement and rapid than those produced by sound, ether being incomparably more subtile than air. A feeble agitation not being capable of shaking the air so as to produce sound in it, that of a bell, and that of all other sonorous bodies, are too feeble relatively to ether to produce in it the vibration which constitutes light.

You will recollect, that in order to excite a perceptible sound, more than 30, and less than 7552 vibrations must be produced in a second; the air being too subtile to admit of a sensible effect from a sound consisting of less than 30 vibrations in a second, but not sufficiently so to receive one of more than 7552 vibrations in the second. A note higher than this could not be at all heard. It is the same with respect to ether: 7552 vibrations, produced in a second, could not possibly act upon it, because of its greater subtilty. It requires vibrations much more frequent. An agitation so rapid could not take place but in the minutest particles of bodies which elude our senses. The light of the sun, then, is produced by a very violent agitation, which affects all his infinitely minute particles, each of which must shake many thousands of times every second.

It is a similar agitation which likewise produces the light of the fixed stars, and of all fires, such as candles, tapers, torches, &c. which give us light, and supply the place of the sun during the night. On attentively observing the flame of a wax-light, you will easily perceive, that in the minutest particles, there is a constant and surprising agitation; and I do not apprehend that my system is liable on this side to any contradiction, while that of Newton requires a most enormous agitation, capable of launching the minutest particles with the velocity of 170,000 English miles in a second.

This, then, is the explanation of the nature of bodies luminous of themselves: for there are luminous bodies which are not so immediately, such as the moon and the planets, which are similar to our globe. We see the moon only when, and in as far as she is illuminated by the sun; and this is the

case of all terrestrial bodies, fires excepted, which have a light of their own. But other bodies, which are denominated opaque, become visible to us only when they are illuminated by some luminous body.

In a very dark night, or in an apartment, so closely shut on every side that no light can find admission, to no purpose will you turn your eyes toward the objects which surround you in the dark: you perceive nothing. But the moment a taper is introduced, you immediately see, not the taper only, but the other bodies which were before invisible. We have here, then, a very essential difference between luminous and opaque bodies. I have already employed the term *opaque* to denote bodies which are not transparent; but it comes to almost the same thing; and we must accommodate ourselves to the common modes of expression, though they are not perfectly accurate. Luminous bodies are visible by their own light, and never affect our organs of sight more than when the darkness is otherwise most profound. Those which I here denominate opaque, are rendered visible to us only by means of a light that is foreign to them. We perceive them not while they remain in darkness; but as soon as they are exposed to a luminous body, whose rays strike upon them, they become visible; and they disappear the moment that foreign light is withdrawn. It is not even necessary that the rays of a luminous body should fall upon them immediately; another opaque body, when well illuminated, produces nearly the same effect, but in a feebler manner.

The moon is an excellent instance. We know that the moon is an opaque body; but when she is illuminated by the sun, and we see her during the night, she diffuses a feeble light over all opaque bodies, and renders visible to us those which we could not have perceived without her assistance.

Placed in the day time in an apartment whose aspect is toward the north, and into which, of course, the rays of the sun cannot enter, it is, however, perfectly clear, and I am able to distinguish every object. What can be the cause of this clearness, but that the whole heaven is illuminated by the sun? What we call the azure sky, and, besides, the walls opposite to my apartment, and the other surrounding objects, are likewise illuminated, either immediately by the sun, or mediately by other opaque bodies, exposed to the action of that focus of light; and the light of all these opaque, but illuminated bodies, as far as it has admission into my apartment, renders it luminous, and that in proportion as the windows are high, wide, and well placed. The glass is little or no interruption, being, as I have already remarked, a transparent body, which freely transmits the rays of light.

When I completely exclude the light from the apartment by closing the window-shutters, I am reduced to a state of darkness, and discern no object, unless I call for a candle. Here then is an essential difference between luminous and opaque bodies; and likewise a very striking resemblance, namely, that opaque bodies, when illuminated, illuminate other opaque bodies, and produce in this respect nearly the same effect as bodies luminous of themselves. The explanation of this phenomenon has hitherto greatly perplexed philosophers; but I flatter myself that my solution of it has been clear and satisfactory.

24th June 1760.

LETTER XXIII.—HOW OPAQUE BODIES BECOME VISIBLE. NEWTON'S SYSTEM OF THE REFLECTION OF RAYS PROPOSED.

BEFORE I attempt an explanation of the phenomenon of opaque bodies becoming visible when they are illuminated, it must be remarked in general, that we see nothing but by means of the rays which enter into our eyes. When we look at any object whatever, rays issuing from every point of that object, and entering into the eye, paint upon it, if I may use the expression, the image of the object. This is not mere conjecture, but may be demonstrated by experiment. Take, for example, the eye of an ox, or of any animal recently killed, and, after having uncovered the bottom, you find all the objects which were before it painted there. As often then as we see an object, the image of it is painted on the bottom of our eyes; and this is produced by the rays which proceed from the object to us. I shall afterwards take occasion to go into a more minute detail on the subject of vision, and explain in what manner the images of objects are formed on the bottom of the eye: let this general remark suffice for the present.

As we see opaque bodies only when they are illuminated, this is a proof that there must proceed from every point of these bodies rays of light which subsist only during the illumination. The moment they are placed in the dark these rays disappear. They are not proper then to opaque bodies; their origin must be sought in the manner in which other bodies illuminate them. And this is the great question, how illumination alone is capable of producing rays on opaque bodies, or of putting them in nearly the same state as luminous bodies are, which, by an agitation in their minutest particles, produce rays of light?

The great *Newton*, and other philosophers who have examined the subject, assign *reflection* as the cause of this phenomenon: it is therefore of the highest importance that you should form a just idea of what is called reflection.

This name is given to the repulsion of one body struck against another, as may be seen in the game of billiards. When the ball is struck against the cushion or ledge of the billiard table, it recoils again; and this retrograde motion is termed reflection. It is necessary here to attend to a distinction between two cases. Let us suppose A B (PLATE I. *Fig.* 7.) to be the ledge of a billiard table. The first case is this: When you play the ball D perpendicularly against the ledge, in the direction of D C, perpendicular to A B, and consequently the adjacent angles A C D and B C D are right angles: in this case, the ball will be driven back or reflected in the same line D C. The other case is, when the ball is played obliquely against the ledge, suppose in the line E C, forming with A B an acute angle A C E, this is called the angle of incidence. The ball will in this case be repelled from the ledge in the direction of the line C F, so that this line shall make on the other side, with the ledge B C, an angle B C F, exactly equal to the angle of incidence A C E. This angle B C F, formed by the line in which the ball recoils, is called the angle of reflection. And this law always takes place when a body in motion meets with an obstacle.

A cannon ball shot against a wall sufficiently strong to resist it, is reflected conformably to this law. It extends, in like manner, to sounds which are frequently reflected from certain bodies; and you know that this reflection of sound is called echo.

It cannot be doubted, that the same thing frequently takes place with respect to the rays of light. The objects which we see in mirrors are represented to us by the reflection of rays, and every well polished surface reflects the rays of light which fall upon it. It is undoubtedly certain, therefore, that there are cases without number in which the rays that fall on certain bodies are reflected; and philosophers have thence taken occasion to maintain, that opaque bodies are rendered visible by means of reflected rays.

I see just now houses opposite to my windows which are illuminated by the sun. According, then, to the opinion of those philosophers, the rays of the sun falling on the surface of these houses, are reflected from them; they enter into my apartment, and render these houses visible to me. In the same manner, if we believe those philosophers, the moon and the planets become visible, and these are unquestionably opaque bodies. The rays of the sun which fall on these bodies, and illuminate the parts which are exposed to them, are reflected, and are thence transmitted to us, just as if the bodies were luminous of themselves. According to this opinion, we see the moon and the planets only by the rays of the sun which they reflect; and you must frequently have heard it affirmed, that the light of the moon is a reflection of the light of the sun. In the same manner, say they, the rays of the sun are reflected by the first opaque bodies which are exposed to them, on other bodies of the same nature, and undergo a series of similar reflections, till they are entirely weakened.

But however plausible this opinion may at first sight appear, it involves so many absurdities when closely examined, that it is absolutely untenable, which I hope to demonstrate, as a preparation for the true solution of this phenomenon.

28th June 1760.

Letter XXIV.—Examination and Refutation of Newton's System.

I affirm, then, that when we see an opaque body illuminated by the sun, it is impossible to maintain that it reflects luminous rays, and that by means of such rays it is rendered visible to us. The example of a mirror, which undoubtedly reflects the rays, and is employed to support this opinion, rather confutes it. The mirror, beyond contradiction, sends back the rays which fall upon it; but when these reflected rays enter into our eyes, what do they represent? You will readily answer, that it is not the mirror, but the objects from which they originally proceeded; and the reflection does nothing else but enable us to see these objects in another place. Besides, we see those objects not on the surface of the mirror, but rather within it; and it may be said with truth, that the mirror itself remains invisible to us.

But, on looking at an opaque body illuminated by the sun, we do not see in it the image of that glorious orb; we see only the surface of the bodies, with all the variations to be found on them. We perceive, then, a very essential difference between the rays which are reflected from a mirror, and those by means of which opaque bodies are rendered visible. But there is, besides, another difference equally palpable in the mirror; for on changing the place of the objects, or our own situation, the appearance will always change, and the rays, reflected from the mirror, will continually represent to our eyes other images, corresponding to the nature and position of the objects, and to the place where we are stationed; but, as I have already said, these reflected rays never represent to us the mirror itself.

Now, let a body be illuminated by the sun, or other bodies, whether luminous or opaque, already illuminated; in whatever manner this body may change its place, or we change ours relatively to it, its appearance is always the same; we see always the same object, and remark in it no change relative to the different circumstances above mentioned. This furnishes a new proof, that we do not see opaque bodies by means of the rays reflected from their surface.

An objection will perhaps be started, drawn from the dove's neck, and certain kinds of stuff, which present different objects, according as our point of view changes. But this in no respect weakens my conclusion with regard to ordinary opaque bodies, which are not subject to this change. The objection only proves, that these singular objects are endowed with certain qualities; as, for example, that their minuter particles are finely polished, and that a real reflection takes place, beside the usual and ordinary manner in which bodies are rendered visible to us.

Now, it is easy to comprehend, that this reflection must be clearly distinguished from the manner in which ordinary opaque bodies are illuminated.

Finally, the rays reflected from a mirror always represent to us, likewise, the colours of the bodies from which they originally proceed; and the mirror, which reflects, makes no change in this respect. One opaque body, illuminated by any other body, in whatever manner, always presents the same colours; and every body may be said to have its proper colour. This circumstance absolutely overturns the opinion of all those who maintain, that we see opaque bodies by means of the rays which their surface reflects.

Putting together all the reasons which I have now submitted to your consideration, there can be no 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.

15th 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.

22*d* *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.