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OBSERVATIONS ON LIGHT AND COLOURS

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INTRODUCTION

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" Had the ingenious author of this paper (who died December, 1753, at the age of 27) lived to put the finishing hand to it, he would, probably, have added many things, and perhaps retrenched some others, by which it would have been rendered still more deserving of the approbation of the public. Mr. Melvill used to observe, that as, of all Sir Isaac Newton's discoveries, those relating to light and colours were, perhaps, the most curious ; it was somewhat remarkable, that few, if any, of his followers had gone one step beyond him on these subjects, or attempted to complete what he had left unfinished. Our Author, therefore, proposed to have applied himself particularly to the further illustration of the theory of light and colours. The following essay is a specimen of what might have been expected from him, and sufficiently shews the uncommon genius of its Author."

SECTION 1

ON THE MUTUAL PENETRATION OF LIGHT

One of the first and greatest difficulties that occurs in reflecting on this subject, is, to conceive how it is possible that light can move through light in all imaginable directions, without occasioning the least perceivable confusion or deviation from its rectilinear course. Many have been induced, from this consideration, to believe it incorporeal ; and all who have thoroughly weighed the difficulty, have seen the necessity of ascribing a subtility to it incomparably greater than we are led, by any phenomena, to ascribe to any other species of bodies in Nature. There is no physical point in the visible horizon which does not send rays to every other point; no star in the heaven which does not send rays to every other star: the whole horizon is filled with a sphere of rays from every point in it; and the whole visible universe, with a sphere of rays from every star. In short, for any thing we know, there are rays of light joining every two physical points in the universe, and that in contrary directions; except where opaque bodies intervene.

Those who suppose that light is nothing else than vibrations or pulses propagated through a subtile elastic medium from the visible object to the eye, may perhaps remove the difficulty by ascribing a sufficient minuteness to the particles of that medium; since we see, by experience, that sound in the air, and waves in the water, are conveyed in different directions, without sensibly interfering; but, as that hypothesis seems insupportable on other accounts, we must endeavour to accomodate our solution to the only other conception we can frame of it; namely, that of particles actually projected from the luminous body.

It is manifest, that, though the mere subtility of the particles of light may tend to account for its easy passage, in all directions, through dense transparent bodies, it will not serve to explain its easy passage through other light equally subtile: but, for this purpose, it seems necessary to suppose light incomparably rare when at the densest; that is, that the semi-diameters of two of the nearest particles in the same or in different rays, soon after their emission, are incomparably less than their distance.

Let us consider a little the course of a particle of light from any of the remoter fixed stars to the human eye; for instance, from the small one called the Rider in the tail of the Great Bear: The particles by which we see that star, have, in the first place, passed through the space surrounding it, in which there are probably several planets revolving, and which must be therefore so filled with a sphere of rays from each of them that they may be visible to an eye anywhere situated in those spaces;

after that, they have passed laterally through the whole torrent of light flowing from the star of the second magnitude which we see beside it ; and lastly, they have passed likeways across the whole ocean of the solar light, and all that light with which the space surrounding the sun is filled from all the comets, planets, and satellites ; and besides, in every physical point of their numerous journey from the Rider to our eye, they have passed through rays of light flowing in all directions from every fixed star in the visible universe ; and yet, during the whole, they have never justled against one particle of light ; otherways they could not have arrived in their true direction to our eye. This reflection cannot fail to suggest a general notion of the rarity and tenuity of light, far surpassing all the suppositions which are usually made about it.

The chance which any one body has to justle with others of like magnitude, is lessened in proportion to the bulk of the bodies with respect to the space in which they move. It must be, therefore, supposed, as we mentioned above, that the distance of the nearest particles, flowing in the same and in different lines, must exceed their diameter, not indeed, infinitely, but a number of times utterly incomparable with all our ordinary numbers, in order that a particle may escape in one physical point of its progress ; but, that it may pass freely on through the whole distance of the remotest fixed stars, it is evident, that this proportion of excess must be multiplied by a number again incomparable. But this excess, so increased, must be raised to a power whose exponent is a number equal to the number of all the fixed stars, planets and comets. And lastly, if there is an elastic medium diffused through the mundane space, as the propagation of heat and many other phenomena seem to insinuate ; this last number must be at least doubled, if we would express the proportion in which the distance of the nearest rays exceed the diameters of their particles : and yet this distance of the nearest rays, flowing from the same center, is so incomparably below our smallest measures, that there is no possibility of defining it.

Had Euler considered this extreme rarity, as well as tenuity of light, which must be acknowledged by all who suppose that its particles are actually projected from the lucid body, he would not have alleged, that this opinion is inconsistent with the freedom and perpetuity of the celestial motions.

Some have thought, that, if the particles of light repel one another, their mutual perturbation may be prevented ; but the contrary is manifest upon the least reflection ; for though, by that means, the particles might be prevented from striking, they must instantly turn one another from their rectilinear courses, as soon as they come, in different directions, within the reach of their mutual powers. Thus, we find by experience, it is impossible to make one stream of air penetrate another without confusion ; for the two streams either unite into a common one with an intermediate direction, or produce irregular eddies.

Here, by the bye, we may see that the ingenious system of Boscovich, the Roman Professor, concerning the elements of matter, whatever may be said for it from other considerations, gives us no assistance in comprehending the mutual penetration of light ; for indivisible points, endued with an insuperable repulsive power, reaching to a finite distance, are as subject to interfere, as solid particles of a finite magnitude.

SECTION 2

ON THE HEATING OF BODIES BY LIGHT

It appears, by Sir Isaac Newton's experiments on the inflection of light, that bodies act upon it at some distance ; and that the same power, variously exercised in various circumstances, is the cause, likeways, of refraction and reflection. We know no instance of any kind of attraction or repulsion in Nature which is not mutual; we observe likeways that bodies are heated by the influence of the sun's rays : it is therefore natural to look upon this as the effect of the reaction of light upon bodies, and that, at a distance from them ; for, there is no reason to think that light produces heat by actually striking the solid parts of bodies, after we are satisfied that bodies produce the reflection and refraction of light, without suffering it to come into contact with them.

From these principles it follows, that light, in passing out of one medium into another of different density, must always produce some degree of heat ; because it is partly refracted and reflected at the common surface ; secondly, that, in passing forwards through the same homogeneous or perfectly transparent medium, it can produce no heat ; because there is no reflection or refraction, no influence of the body upon the light, but every ray pursues its own right-lined course, as if it moved in a perfect void.[*]

Hence it appears, that, in water, glass and other transparent mediums, which are warmed by the sun's rays the heat must be propagated from their surfaces towards their central parts.[†]

Hence likeways we understand why opaque bodies are sooner heated by the sunbeams than transparent ones ; since, there are innumerable reflections and refractions within their substances, besides what happen in common with transparent bodies at their superficial parts. As each colorific particle of an opaque body, by the reaction of the particles of light, must be somewhat moved when the light is reflected backward and forward between the same particles, it is manifest that they likeways must be driven backward and forward with a vibratory motion ; and the time of a vibration will be equal to that which light takes in moving through a particle, or from one particle of a body to another adjoining. This distance in most solid opaque bodies cannot be supposed greater than $\frac{1}{12500}$th of an inch, which space a particle of light describes in $\frac{1}{125000000000000}$th of a second. With so rapid a motion therefore may the internal part of bodies be agitated by the influence of light, as to perform 125,000,000,-

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[*] Sir Isaac Newton, in the third book of his *Principia*, where he disputes concerning the tails of comets, lays it down as an obvious principle, Quod radii folis non agitant media quæ permanent, nisi in reflectione et refractione.

[†] I have found, by repeated trials, that the heat of water in deep lakes decreases regularly from the surface downward.

000,000 vibrations or more in a second of time! The arrival of different particles of light at the surface of the same colorific particle in the same or different rays, may disturb the regularity of their vibrations, but will evidently increase their frequency, or raise still minuter vibrations among the parts which compose these particles; by which means the intestine motion becomes more subtile and thoroughly diffused. If the quantity of light admitted into the body be increased, the vibrations of the particles must likeways increase in magnitude and velocity; till, at last, they may be so violent as to make all the component particle dash one another to pieces by their mutual collisions: in which case, the colour and texture of the body must be destroyed. Thus may we form from known principles, some imperfect conception of the manner in which bodies are heated and burned by the action of light: More than an imperfect notion of these secret operations of Nature is not to be expected; for they certainly depend, in great measure, upon laws and principles utterly unknown to us.

If one beam or ray of light, by passing straight onwards through the same pellucid substance, can communicate no heat to its internal parts; neither will the greatest quantity of rays, though crowded into the narrowest space, by crossing one another. From hence it follows, that the portion of air which lies in the focus of the most potent speculum is not at all affected by the passage of light through it, but continues of the same temperature with the ambient air; although any opaque body, or even any transparent body denser than air, when put in the same place, would be intensely heated in an instant.

This consequence, evidently flowing from the plainest and most certain principles, seems not to have been rightly understood by many philosophers:* for which reason, I thought

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*See Boerhaave element, chem. tom. 1, on fire, coroll. 5, after exper. 14. and coroll. 1, and 7, after exper. 17. See also Rutherforth's system of natural philosophy, prop. 366, of the astronomical part; and Nolet lecons de physique, tom. 4. The silence of most physical writers, concerning this paradoxical truth, makes it probable that they were unaquainted with it.

it might be worth while to say something in explication of it. The easiest way to be satisfied of the matter experimentally, is, to hold a hair or down immediately above the focus of a lens or speculum, or, to blow a stream of smoke from a pipe horizontally over it ; for, if the air in the focus were hotter than the surrounding fluid, it would continually ascend upon account of its rarefaction, and thereby sensibly agitate these slender bodies. Or a lens may be so placed as to form its focus within a body of water or some other transparent substance, the heat of which can be examined from time to time with a thermometer : but care must be taken in this experiment to hold the lens as near as possible to the transparent body , lest the rays, by falling closer than ordinary on its surface, should warm it more than the common sunbeams.

It is well known that the rays of light, by passing obliquely through our atmosphere, are inflected into a curve by the continued infraction arising from the continual increase of its density ; therefore they must produce some degree of heat in every part of their progress through it (No. 10.). But as the whole successive refraction is just equal to the single refraction that would be made in passing at once from the celestial spaces into a medium as dense as the lowest part of our atmosphere, and all the successive reflections that can be made from every different stratum, are but equal to what would be made at once from the surface of a medium of the same density ; it easily appears, by comparing the densities of air and water, and their respective signs of refraction, that all the refraction and reflection which the whole depth of our atmosphere produces is much less than what happens at one surface of water ; and consequently, the heat produced in our atmosphere, by the immediate action of light upon it, must likeways be much less than what is raised in water. The air seems to have the greatest part of its heat communicated to it from the opaque vapours which float in it and the general surface of sea and land to which it is contiguous.

SECTION 3

ON THE SILVER-LIKE APPEARANCE OF DROPS OF WATER ON THE LEAVES OF COLEWORT

It is common to admire the volubility and lustre of drops of rain that lie on the leaves of colewort and some other vegetables; but no philosopher, as far as I know, has put himself to the trouble of explaining this curious phenomenon. Upon inspecting them narrowly, I find, that the lustre of the drop arises from a copious reflection of light from the flattened part of its surface contiguous to the plant: I observe further, that, when the drop rolls along a part which has been wetted, it immediately loses all its lustre; the green plant being then seen clearly through it; whereas, in the other case, it is hardly to be discerned.

From these two observations laid together, we may certainly conclude, that the drop does not really touch the plant when it has the mercurial appearance, but hangs in the air at some distance from it, by the force of a repulsive power; for, there could not be any copious reflection of white light from its under surface, unless there were a real interval between it and the surface of the plant.*

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*Newt. Optics, query 29.

Let AB, Tab. III., Fig. 4, represent the extremity of any repulsive body immersed in water, for instance a slice of colewort leaf, CL and DM, the convex surfaces of water immediately surrounding it, and CD perpendicular to AB, the common tangent of these curves, which will be the continuation of the general surface of the water. The forces with which any two particles, E and F, are pressed by the water in the directions EG, FH perpendicular to KB, are known to be as KG and KH, and the repulsive powers which balance them must be in the same proportion. If therefore the relation between the ordinate and abscissa in the curve DM could be any way found by experiment, the law of the repulsive power might be determined, upon supposition that the particles are influenced by no force bnt the repulsive power of the line KB and the gravity of the superincumbent fluid; but their mutual attraction, which tends to lessen their lateral tendency must be likeways taken into the account in order to an exact determination.

Before I leave this subject of attraction and repulsion, I beg leave to pro-

If that surface were perfectly smooth, the under surface of the drop would be so likeways; and would therefore show an image of the illuminating body by reflection, like a piece of polished silver; but, as it is considerably rough and unequal,

pose to the Society, the spontaneous motions of light bodies on the surfaces of fluids, as a thing worthy of being inquired into; for, though it be manifest in general that they depend upon the different figures of the surface, it is far from being an easy matter to explain the particular cases by mechanical or hydrostatical laws. The following account of the phenomena may be useful towards such as enquiry. Case 1. Suppose a fluid which is attracted to the side of its containing vessel, and consequently is elevated, at the sides, into a concave surface: If a body be immersed which attracts the fluid, and is therefore surrounded likeways with a concave elevation of the fluid; as soon as the two elevations begin to join, the body will move towards the side of the vessel with an accelerated motion. Case 2. Suppose a fluid which is formed into a convex surface either by the repulsive power of the containing vessel or cohesive force of its own particles: If a light body be immersed which attracts the fluid; as soon as its surrounding elevation begins to join with the lateral depression of the fluid, it will begin to move towards the middle of the vessel; and if it be brought by force towards the side, it will recede from it again with an accelerated motion.

In both the first and second cases, if the attracting body be held fast, and the whole fluid made easily moveable with its containing vessel, it will remove to or from the attracting body in the same manner as the attracting body did with respect to it; *i.e.*, in the first case, the whole fluid will move so that the attracting body may come to its edge; and in the second, so that it may recede from it. Case 3. If, in a fluid which is attracted by the sides of its vessel, a body be immersed which repels the fluid, and is therefore surrounded with a ditch or convex depression of the fluid; as soon as that depression begins to join the elevation of the fluid at the sides, it will recede towards the middle; and, if forcibly brought to the side of the vessel, will fly from it with an accelerated motion. Case 4. If, in a fluid which is formed into a convex surface at the sides, a repelling body be immersed; as soon as its depression begins to unite with the lateral depression of the fluid, it will move towards the side with an accelerated motion. In these two last cases, the same observation holds as with respect to the first and second, *viz.*, that the whole fluid will move with correspondent motions by the force of reaction, if the repelling body be held fast. Case 5. If two bodies be immersed in a fluid, which each of them attracts: as soon as their elevations begin to join, they will rush towards one another with equal forces and accelerated motions, and continue to adhere together. Case 6. If two bodies be immersed in a fluid which they repel; as soon as the two depressions that surround them begin to interfere, they will likeways rush together with an accelerated motion. Case 7. If two the under surface becomes rough likeways ; and so, by reflecting the light copiously in different directions, assumes the resplendent white colour of unpolished silver.

After it is thus proved by an optical argument that the drop is really not in contact with the plant which supports it, we easily conceive whence its wonderful volubility arises, and why it leaves no tract of moisture where it rolls.

From the like reasoning, we may conclude, that, when a smooth needle is made to swim, it does not any where touch the water, but forms around it, by its repulsive power, a ditch or bed, whose concavity is much larger than the bulk of the needle. (See Tab. 111., Fig. 3.). And hence it is easy to understand how the needle swims upon a fluid lighter than itself ; since the

bodies be immersed in a fluid, the one of which attracts and the other repels it ; as soon as the depression surrounding the one begins to join with the elevation of the other, they will mutually fly from each other. Lastly, if a body be immersed in a fluid which it attracts in one part and repels in another, it will approach to or recede from other bodies and parts of the fluid, differently according to its situation, by the rules above laid down.

The different figures ascribed to the surface of the water in these several cases are plainly discernible by the sight ; if the experiments are made with candle-light, they are distinguished by the shadowy or luminous rings which they project on the bottom of the vessel, according as they are convex or concave.

Some writers have been so inattentive as to ascribe the motions in the first case to an immediate attraction between the swimming body and the side of the vessel. See Helsham's Lectures. Before I had observed the fourth and sixth cases, I thought the phenomena might be all explained from this principle, that the light bodies always tend to the highest parts of the water. It has been suggested to me by some, that this tendency, combined with the greater or lesser immersion of the bodies, upon account of the ring of water which they elevate or depress, may produce all the different cases : and by others, that the whole is explicable from the single principle of attraction between the parts of water which causes two drops to run into one. I believe it will be found, on due consideration that none of these accounts is satisfactory ; but there is no reason to despair of coming to the bottom of these phenomena ; since other motions of a like kind have been successfully explained. Thus the running of a drop of oil towards the concourse of two glass-planes and the motion of a bubble on the surface of liquors, when the glass is held obliquely towards that point, where the glass is inclined to the liquor in the smallest angle, are easily understood from the direction of the compound force with which the drop and bubble are acted.

quantity of water, displaced by it, may be equal to the weight of the needle. Phenomena of this kind, instead of being reduced to hydrostatical principles, are commonly attributed to the mere tenacity of water, and even used for measuring its cohesive power. See Musschenbrœck, "Elementa Physices."

This instance furnishes us with a just and necessary correction of the common hydrostatical law, that "the whole swimming body is equal in weight to a quantity of the fluid whose bulk is equal to that of the part immersed:" for, to comprehend this, as well as all ordinary cases, it should be said more generally, that "the whole weight of the swimming body is equal to the weight of the quantity of the fluid displaced by it."

These Phenomena appeared to me worthy of observation here: both because they shew the fertility of optical principles in leading to the knowledge of things otherways inaccessible; and because they exhibit a clear specimen of a repulsive power, similar to that which we suppose necessary for the reflection of light from the anterior surface of a denser medium. Nor do I see how it is possible to account for the suspension of the drop in the air by comparative attractions; into which some other appearances of repulsion have been, perhaps, not unsuccessfully resolved.*

SECTION 4

ON THE CHANGE WHICH COLOURED BODIES UNDERGO IN DIFFERENT LIGHTS

Sir Isaac Newton has abundantly proved, by a variety of arguments, that the ordinary colours of natural bodies arise solely from the compounded colour of those rays which they reflect; their colour being denominated by the species of those primitive rays which they reflect in greatest plenty: but this part of the Newtonian doctrine will receive further confirmation by examining the different colours which the same body assumes

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*See the article on Capillary Attraction, at the end of Cotes's Hydrostatical Lectures.

when illuminated by different lights; and which may be called, in distinction from the former, their extraordinary colours.

Bodies of all the principal colours, *viz.*, red, yellow, green and blue, are very little altered when seen by the light of burning spirits: but, if salts be continually mixed with them during the burning, different changes ensue.

When sal ammon., potash or alum are infused, the colour of red bodies appears somewhat faded and dirty: green and blue appear much the same as in candle-light; both being faint and hardly distinguishable: white and yellow are scarcely at all affected.

When nitre or sea-salt are plentifully mixed with the burning spirits, and the whole is stirred about briskly; the brightest red bodies, seen by the light then emitted, are reduced to a dirty tawny brown, that seems to have nothing of redness in it: green is transformed into another sort of brown, only distinguishable from the former by a certain inclination to a livid olive-colour; when nitre is mixed with the spirits, one may still see some remains of a greenish colour, unless it be poured in very plentifully: dark blue is hardly to be known from black, except that it appears the deeper black of the two: light blue is changed into a very light brown of a peculiar kind: white assumes a livid yellowish cast: and yellow alone appears unaltered and extremely luminous. These experiments I made with different sorts of rich-coloured bodies, as silks, cloths and paints. Polished copper, which has contracted from the air a high-flaming colour, is reduced by the same light into the appearance of yellow brass; the faces and hands of spectators appear like those of a dead corpse; and other mixed colours, which have red or green in their composition, undergo like changes.

Having placed a paste-board with a circular hole in it between my eye and the flame of the spirits, in order to diminish and circumscribe my object, I examined the constitution of these different lights with a prism, (holding the refracting angle upwards) and found, that, in the first case (No. 25), when sal ammon., alum or potash fell into the spirits, all sorts of rays were

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emitted, but not in equal quantities; the yellow being vastly more copious than all the rest put together, and red more faint than the green and blue.

In the light of spirits mixed with nitre or sea-salt, I could still observe some blue, though excessively weak and diluted: with the latter, the green was equally faint; but, with the former, pretty copious. But, when either of these salts were used, I could hardly see any vestige of the red at all, at least when they were poured in plentifully, and the spirits constantly agitated. At every little intermission indeed the red rays would show themselves very manifestly below the hole, and red bodies seen by that light resumed somewhat of their ordinary colour: and it was very entertaining to observe how both would evanish again at once, as soon as the salting and stirring were renewed.

The proportion in which the bright yellow exceeds the other colours in this light, is still more extraordinary than in the former; insomuch that the hole seen through the prism appears uniformly of this yellow, and as distinctly terminated as through a plain glass; except that there is adjoining to it on the upper side a very faint stream of green and blue. White bodies illuminated with it appear also through the prism perfectly well defined; both which are very surprising phenomena to those who have been accustomed to the use of the prism in other heterogeneous lights, where it never fails to throw confusion on the extremities of all visible objects.

Because the hole appears through the prism quite circular and uniform in colour; the bright yellow which prevails so much over the other colours, must be of one determined degree of refrangibility; and the transition from it to the fainter colour adjoining, not gradual, but immediate.

Upon examining soap-water-films in the same light, I could only observe luminous bands separated by dark ones; the green and blue being too weak to affect my eye in this view. It would be needless labour to enter here into a particular detail of the reasons of the different transformations of coloured bodies, above related (No. 24, 25 and 26); since, in general, it is evident enough, that they are owing to the different compositions of the lights with which they were illuminated: the experiments with the prism (No. 27, 28,) are of themselves sufficient commentary upon the rest.

SECTION 5

A REMARK ON EULER'S NOVA THEORIA LUCIS ET COLORUM

Euler, in that treatise, (published lately along with some other tracts, under the title of Opuscula Mathematica) endeavours to amend the Huygenian hypothesis of vibrations, and support it against the objections which made Newton and his followers reject it : we shall not enter here upon the discussion of that question ; as it would require a discourse of considerable length ; and the rather, that the Newtonian theory of light and colours depends not on any particular hypothesis with respect to the intimate nature of light (in like manner as his system of universal gravitation is independent of all hypothesis concerning the cause of gravity). In his optics, he lays down his discoveries at full length, without ever inquiring whether light consists in vibrations propagated through a fluid or of particles projected in straight lines from the luminous body: and, in his queries, where he touches this matter, he seems to be more positive in rejecting the hypothesis of vibrations, than in establishing any other.

But Euler likeways advances a new notion with respect to the origin of colours in opaque bodies, which is entirely inconsistent with the principal part of Sir Isaac Newton's doctrine. He supposes, that coloured bodies reflect the sun's incident white light from their anterior surface ; but, that the particular species of light, by which they appear coloured, is properly emitted by the parts of the body: for instance, he imagines that vermilion does not appear red by a more copious reflection of red than of other incident rays, but by the new emission of red rays from the particular velocity of vibration which its elastic parts are capable of conceiving by the impulse of the incident light.

It is a sufficient refutation of this system, that no phenomena prove or require its existence: whereas Newton's theory not only solves the phenomena, but is directly drawn from a multitude of experiments. According to Euler's hypothesis, a body of one colour, placed in homogeneous light of another, ought not to appear of the colour of the light, but of a middle one between that and its own natural colour; which is contrary to experience.

If it should be said, that none of the incident light is capable of qualifying the body for emitting its proper colour, but rays of the same colour; that which he calls new light emitted will be, in his scheme, more properly incident light reflected.

The chief or only fact which seems to have led him into that opinion, is, that there are many coloured bodies, such as metals, which are capable of receiving a fine polish; and, therefore, of reflecting regularly the images of other objects, and at the same time retain their proper colour by which they are seen in all positions. That light by which we see in them the images of other objects, he acknowledges to be incident light properly reflected; but the other, he supposes, is properly emitted from the colorfic parts of the body. But what necessity is there of recurring to this supposition, when we know, previously that the component parts of all opaque bodies are transparent; that, from every transparent body, there is a double reflection; part of the incident light being reflected at the first surface, and a part of what passes through the first, reflected at the second, and when we know, further, that very thin bodies, (soap-bubbles, Muscovy-glass, and air in a fracture of glass or ice, or between two lenses) while they reflect some rays of all colours from the first surface, reflect only particular colours at the second?. Do not these facts lead us naturally to suppose the first sort of light to be only a part of the incident light reflected from the first surface of the body; and the second, a part of what had passed on, reflected from the posterior surfaces of the superficial particles?

SECTION 6

CONCERNING THE CAUSE OF THE DIFFERENT REFRANGIBILITY OF THE RAYS OF LIGHT*

In order to account for the different refrangibility of the differently-coloured rays, Sir Isaac Newton and several of his followers have supposed, that their particles are of different magnitudes or densities : but, if there be any analogy between gravity and the refractive power, it will produce equal perpendicular velocities in all particles, whatever their magnitude or density be ; and so all sorts of rays would be still equally refrangible.

It seems, therefore, a more probable opinion, which others have advanced, that the differently-coloured rays are projected with different velocities from the luminous body : the red, with the greatest ; violet, with the least ; and the intermediate colours, with intermediate degrees of velocity : for, upon this hypothesis, it is manifest, that they will be differently refracted in the prismatic order ; according to observation. Since, according to Sir Isaac Newton's doctrine of refraction now generally received, the velocity of a ray, after entering any new medium, is, to its former velocity, as the sine of incidence to the sine of refraction ; if all the colours move with equal swiftness in any one medium, their velocity will necessarily become unequal, upon entering a denser medium, in the inverse proportion of their several sines of refrangibility : though we suppose, therefore, the sun's rays to be emitted with one common velocity, it will follow that their velocities are unequal in air, glass, water, or any transparent body, whose refractive density differs from that of the solar atmosphere. This consideration is sufficient to take off the appearance of improbability from our hypothesis.

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*Although the doctrine contained in this section has been already published in the *Philosophical Transactions* for 1753, (vid. Vol. XIVIII. part 1, p. 262, etc.) having been communicated to the Royal Society, by the Author, in a letter to the Rev. Dr. James Bradley, D.D., F.R.S.; yet it could not be omitted here, on account of its connection with some of the queries that follow; besides that it contains several illustrations not to be found in the *Transactions*.

On supposition that the different refrangibility of the rays of light arises solely from their different velocities before incidence ; these velocities must be, to one another, nearly as their sines of refraction.

Sir Isaac found their sines of refraction from glass into air, beginning from the extreme violet, to be as,* 78, $77\frac{7}{9}$, $77\frac{2}{3}$, $77\frac{1}{2}$, $77\frac{1}{3}$, $77\frac{1}{5}$, $77\frac{1}{8}$, 77 ; the sine of incidence being 50 : from whence their sines of refraction out of air into glass, beginning from the extreme red, and ending with the extreme violet, are found to be † as 78000, 77873, 77797, 77663, 77496, 77330, 77220, 77000 ; the sine of incidence being 120120. These numbers, therefore, nearly express the velocities in air, of the several rays, before their incidence.‡

Hence their velocities in any other medium, may be found ;

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* Newt. Opt. book 1, parts 2, prop. 3.

† The extreme sines are plainly reciprocal to the former ; and those of intermediate colours are fourth proportionals to the sine in Sir Isaac's experiment, 77 and 78.

‡ The quantities which give the accurate proportion of the velocities, before incidence, must be in a constant ratio : the sines of refraction, by which the above calculations are made, have this condition : but, it is otherways manifest, that they give only a gross approximation to the truth. From what follows, perhaps, an exacter computation might be made, if a proper mean angle of incidence were made use of, although the quantities in the canon are really not in a constant ratio.

Tab. III., fig. 1. Let two rays, falling in the same line of incidence IC, with different velocities, upon AB the surface of a denser medium, be refracted into different lines CR, CV. Taking any lines CD in the perpendicular to represent the total action of the refracting power on the less refrangible ray, and CE on the more refrangible : If, through D and E, parallels to IC be drawn, meeting the refracted rays in V, R and G ; it is plain, that CR, CV will be, as their respective velocities after refraction ; and DR, EV, as their velocities before incidence. Since the whole acceleration which a given power produces in a body, is cæteris paribus, as the time in which it operates ; CD must be to CE nearly as the time which the swifter ray takes to pass through the refracting space, to that which the slower ray takes in passing through the same, inversely, as their velocities before incidence ; that is, as EV to DR : but CD is likeways to CE as DG to EV : therefore DR, EV and DG are continued proportionals ; therefore DR is to EV in the for, they are, to these, as the sine of incidence to the sine of refraction, when a ray passes from air into the given medium.

While the differently-coloured rays are supposed to move with one common velocity, any pulses, excited in the ethereal medium, must overtake them at equal distances ; and, therefore, the intervals of reflection and transmission, if they arise in this manner, as Sir Isaac Newton conjectures, would be all equal : but, if the red move swiftest, the violet slowest, and the intermediate colours with intermediate velocities ; it is plain, that the same pulses must overtake the violet soonest, the other colours in their order, and, last of all, the red ; that is, the intervals of the fits must be least in violet, and gradually greater in the prismatic order ; according to observation.

As the proportion between these intervals in red and violet can be assigned by experiment, and the proportion of their velocities in any medium likeways, by No. 40.: the velocity of the ethereal pulses in any medium, and their distance from one another, may be thence computed by the following rule : "Multiply the product under the velocities of the red and violet rays by the difference of the intervals of their fits ; then divide by the difference of the two products which are formed by multiplying the interval of the fits in red by the velocity of the violet, and the interval of the fits in violet by the velocity of red :" the quotient shall express the velocity of the ethereal pulses.*

subduplicate ratio of DR to DG; but DR is to DG in a ratio compounded of DR to DC, and DC to DG, that is, in the compounded ratio of S, DCR to S, DRC and of S, DGC to S, DCG ; wherefore DR is to EV in the subduplicate ratio of S, DCR × S, DGC to S, DCG × S, DRC ; that is, "The velocities before incidence are nearly in the direct subduplicate ratio of these sines and the reciprocal subduplicate ratio of the sines of the excesses of the common angle of incidence above the several angles of refraction."

*Let C denote the celerity of the ethereal pulses, V the velocity of red light, and v that of violet, I and i the intervals of their fits, and D the perpendicular distance of two succeeding pulses : it is plain, from the nature of the hypothesis that I is to D as V to C − V, and again, D to i as C − v to v ; therefore, ex æquo, I is to i as CV − Vv to Cv − Vv : from which arises the equation.

$$C = \frac{(I - i)\,Vv}{Iv - iV}.$$

The velocities of the red and violet in air, are, by the above estimation, as 78 and 77*; and the intervals of their fits are, by experiments†, as 100 and 63: from whence by the canon now laid down, the velocity of the ethereal pulses is found to be, to that of red light, as 79763 to 78000. As light moves from the sun to us, by Dr. Bradley's latest computation‡, in 8^m, 12^s, the pulses of the ethereal fluid will be propagated through the same space in 8^m, 1^s.

The distance between the ethereal pulses, is, to§ the intervals of the fits in red, as the difference between the velocity of the ethereal pulses and that of red light is to the velocity of red light; that interval, therefore, is not much more than $\frac{1}{44}$th of the interval of the fits in red, and, therefore, does not much exceed $\frac{1}{2457931}$ of an inch.||

The velocity of the ethereal pulses being determined, as above, from the intervals of the fits in the two extreme colours, as found by experiment, the intervals of the fits in the six intermediate rays may be calculated from theory; for the interval in any one colour must be, to that in red, as a product under the velocity of the given colour and the excess of the velocity of the ethereal pulses above that of red, is to a product under the velocity of red and the excess of the velocity of the ethereal pulses above that of the given colour: but, even upon the supposition of the truth of our theory, an exact coincidence between calculation and experiment is not to be expected till the velocities of the rays be more accurately determined.

Upon the hypothesis of the different velocities of different colours, we may understand, at least in general, whence it is, that the intervals of the fits may bear a proportion some way

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* In the celestial medium they are less, (No. 40) but very nearly in the same proportion.

† Newt. Opt. book 2, p. 1, observat. 14.

‡ See Eames Abridg. transact. Vol. VI., p. 157.

§ See note to foregoing page.

|| See the table of the thickness of coloured plates in, Newt. Opt. part 2, book 2.

related to the spaces occupied* by the several colours in the spectrum; an analogy otherways very unaccountable! Since, from the velocities of the several rays upon which the intervals of the several fits depend, arise likeways their several degrees of refrangibility, which determine the space occupied by each in the spectrum.

And thus likeways we may conceive, how the different rays are qualified to produce different sensations in the mind: for, having different degrees of impulsive force, they may cause vibrations of different magnitude or velocity in the optic nerve; by which, according to the laws of our constitution, the ideas of different colours may be excited;† in like manner as the ideas of different tones arise from different vibrations of the air communicated to the auditory organ. It has been said, that the different sensations excited in the mind cannot arise from the different force of the particles of light; since the colour of homogeneal rays is not altered by passing through different media, though their velocity be thereby always increased or diminished.‡ But it ought to be considered, that every ray, as it must pass at last through the humours of the eye in order to vision, falls upon the retina with one given velocity, whatever number of refractions it has previously undergone: for the velocity of any ray in any one medium being, to its velocity in any other medium, in a constant proportion, *viz.* the inverse of the sines of incidence and refraction, when a ray passes from the one into the other; it is manifest, that each ray must have a certain determined velocity in any given medium, which cannot be either increased or diminished by making the ray pass previously through any number of transparent bodies any how disposed.§

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* Compare Newt. Opt. b. i., part 2, prop. 3, with b. ii., part 3, prop. 16th.

† Newton's Optics, query 13.

‡ Musschenbrœck, Elementa Physices, 1161.

§ Here it is proper to observe, that the hypothesis which supposes the intervals of the fits to be determined by the velocity of the ray, agrees well with a remarkable observation of Sir Isaac Newton (Optics, b. ii., part i., observ. 21): *viz.* That these intervals in any medium, at a given angle of incidence, are of a given magnitude, without regard to the density of the surrounding medium.

It is impossible, therefore, to know, whether an alteration of the swiftness, with which a homogeneal ray strikes the retina, would alter its colour ; I mean the sensation of colour produced by it in the mind : since it is impossible to alter, at pleasure, the density of that fluid which determines its final velocity.

One may distinguish two different effects of the refractive power on the rays of light, *viz.*, the change of direction and change of velocity. Sir Isaac Newton has proved with respect to the first, that it is different in the differently coloured rays, and of a determined degree in each ; he has further proved, that refraction, considered in its first effect, does not change the colour of any simple ray. But, it appears, from what we have now said, that none of his experiments prove the immutability of simple rays by the second effects of refraction.

As it is of great consequence in philosophy to distinguish between facts and hypotheses, however plausible ; it ought to be observed, that the various refrangibility, reflexibility, and inflexibility, of the several colours, and their alternate dispositions at equal intervals to be reflected and transmitted, which are the whole ground-work of the Newtonian system, are to be considered as certain facts deduced from experiment : but whether the velocities of the different rays are exactly equal, or different in the manner now described, is no more than probable conjecture ; and, though this point should be decided by a method proposed afterwards, it would still continue uncertain, whether the fits of reflection and transmission are occasioned by an alternate acceleration and retardation of the motion of light, or in some other manner,* and, after all, it is no more than probable conjecture, that such an alternate acceleration and retar-

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* For instance it might be supposed, that every particle of light has two contrary poles, like a load-stone ; the one of which is attracted by the parts of bodies, and the other repelled ; and that, besides their uniform rectilineal motion, the particles of differently-coloured rays revolve in different periods round their centre: for thus, their friendly and unfriendly poles being alternately turned towards the surface of bodies, they might be alternately disposed to reflection and transmission ; and that at different intervals, in proportion to the periods of their rotation.

dation is brought about by the influence of pulses excited in the ethereal medium: nay there are some circumstances in these phenomena that seem hardly intelligible by that hypothesis alone; as, why the intervals of the fits are less* in denser mediums; and why they increase so fast and in so intricate a proportion, according to the obliquity of incidence.

According to Dr. Bradley's beautiful theory of the aberration of light, the stars appear to be removed from their true places to a certain distance, by the proportion which the velocity of the earth bears to the velocity of light. It is plain therefore, that, on our hypothesis, a star must have a different apparent place for every different colour; that is, its apparent disk must be extended by the aberration into a longitudinal form resembling the prismatic spectrum, having its red extremity nearest to its true place. In the stars situated near the pole of the ecliptic, its length should continue always the same, though directed along all the different secondaries of the ecliptic in the course of a year: but, in those which lie in or near the plane of the ecliptic, it should be greatest at the limits of the eastern and western aberrations; the star recovering its colour and figure when the true and mean places coincide. But, there is no hope of discovering, whether our hypothesis be true or false, by this consequence of it; for the greatest length of the dilated disk, being, to the whole aberration, as the difference of the velocity of red and violet to the mean velocity of light, *i. e.*, as 1 to 77 nearly, (No. 39) cannot much exceed one-fourth part of a second; for the greatest aberration is but about twenty seconds.

The time which the extreme violet takes to move through any space must be, to that which the red takes, as 78 to 77. If Jupiter be supposed in a quadrate aspect with the sun, in which case the eclipses of his satellites are most commodiously observed, his distance from the earth being nearly equal to his distance from the sun; light takes about forty-one minutes of time in passing from him to the earth: therefore, the last violet colour which a satellite reflects, before its total immersion into the

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* Newt. Optics, b. 2, part 3, prop. 17.

shadow of Jupiter, ought to continue to affect the eye for a 77th part of 41^m, or 32^s, after the red reflected at the same time is gone: that is, a satellite seen from the earth, ought to change its colour above half a minute before its total immersion from white to a livid greenish colour, thence into blue, and at last evanish in violet. I need scarcely observe, that the same phenomenon should take place in the time of emersion, by a contrary succession of colours, beginning with red and ending in white.

If this phenomenon should be actually perceived by astronomers, we shall have a sufficient direct proof of the different velocities of the coloured rays; for I see not to what other cause the phenomenon could be rationally ascribed. If it be not, we may conclude that rays of all colours are emitted and reflected with one common velocity.*

SECTION 7

ON THE IMPERFECTION OF OUR KNOWLEDGE CONCERNING THE INFLECTIONS OF LIGHT

Sir Isaac Newton went a very considerable length in examining the inflections of light, as well as its reflections and refractions; but did not bring his enquiry on this head to a conclusion. He tells us, that he intended once, if other business had not called him off, to have made more experiments; not for confirming himself in preconceived opinions, as many do; but for discovering the true manner in which light is inflected, for producing the coloured fringes with black lines between them. He adds, however, some queries which contain hints of what he had gathered on this subject from his own observations, *viz.* that the rays of light differ according to their colour in their degrees of flexibility, and that they are bent several times backwards and forwards with a serpentine motion in passing by the sharp edges of bodies: these thoughts he threw out "in order to incite others to a further search," but, so far have his intentions been disappointed hitherto, that few physical writers seem to comprehend distinctly the hints which he has left concerning the man-

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* Newt. Optics, b. 2, part 3, prop. 15,

ner of inflections;* and none, as far as I know, has advanced

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* When any opaque body is held at the distance of three or four inches from the eye, so that a part of some more distant luminous object, such as the window or the flame of a candle, may be seen by rays passing near its edge: if another opaque body, nearer to the eye, be brought across from the opposite side, the edge of the first body will seem to swell outwards and meet the latter, and in doing so, will intercept a portion of the luminous object that was seen before.

This phenomenon has been rashly ascribed to the inflection of light, by such as understood not thoroughly the nature of inflection, nor observed accurately the circumstances of the fact.

Let AB represent the luminous object (Tab. iii., Fig. 5) to which the sight is directed, CD the more distant opaque body, GH the nearer, and EF the diameter of the pupil; join ED, FD, EG, FG, and produce them till they meet AB in K, N, M, and L: It is plain, that the parts of AN, MB of the luminous object cannot be seen. But, taking any point a between N and K, and drawing aDd; since the portion dF of the pupil is filled with light flowing from that point, it must be visible: any point b between a and K must fill fF a greater portion of the pupil, and, therefore, must appear brighter. Again, any point c between b and K must appear brighter than b, because it fills a greater portion gF with light. The point K itself, and every other point in the space KL, must appear with complete lustre; since they send entire pencils of rays EKF, ELF to the eye: and the visible brightness of every point from L towards M must decrease gradually as from K to N: *i. e.*, the spaces KN, LM will appear as dim shadowy borders of fringes adjacent to the edges of the opaque bodies. When the edge G is brought to touch the right line KF, the penumbras unite; and as soon as it reaches NDF, the above phenomenon begins: for it cannot pass that right line without meeting some line aDd drawn from a point between N and K, and by intercepting all its rays that fell upon the pupil render it invisible. In advancing gradually to the line KDE, it will meet other lines bDf, cDg, etc., and, therefore, render the points b, c, etc., from N to K successively invisible; and, therefore, the edge of the fixed opaque body CD must seem to swell outwards, and cover the whole space NK, while GH by its motion covers MK. When GH is put to a greater distance from the eye, CD continuing fixed; the space OP to be passed over for intercepting NK is less; and, therefore, with an equal motion of GH, the apparent swelling of CD must be quicker; which is found true by experience. If ML represents a luminous object, and REFQ any plane exposed to its light; the space FQ will be entirely shaded from the rays, and the space FE will be occupied by a penumbra gradually darker from E to F. Let now GH continue fixed, and CD move parallel to the plane EF; and, as soon as it passes the line LF, it is evident, that the shadow QF will seem to swell outwards, and when CD reaches ME so as to cover with its shadow the space RE, QF by its extension will cover FE. This is found to hold true likeways by experiment.

one step beyond them. It is surprising, that, before Sir Isaac Newton, the world continued so long entirely ignorant of the true theory of light and colours; and it is no less so, that, since he quitted the subject, no further discovery of any moment has yet been made amongst all the philosophical societies in Europe.

Many ingenious men have bestowed infinite thought and labour on the more complex and astonishing phenomena of Nature, without arriving at any certain or definite discoveries; such as earthquakes, thunder and other meteors, magnetism, electricity, vegetation, fermentation and other chemical operations: and the subtility of those matters will probably continue to elude the search of latest posterity. But, in the simpler, steadier, and more regular subjects, such as light and colours, which are capable of accurate mensuration and mathematical reasoning, a sagacious and industrious observer can hardly fail of making some progress; especially in a branch of the inquiry which is already pushed to a considerable length. Discoveries of this kind are capable of a particular sort of proof which is very beautiful and convincing, from the exact coincidence of the computed effects with the real ones, as to quantity. Many instances of this, occur in Sir Isaac's Newton's writings, and in all mathematical philosophy: such as the calculation of the moon's irregularities; of the tides; of the precession of the equinoxes; of the resistance of fluids; and, in optics, his computation of the dimensions of the rainbow; of the aberration of colours; of the intervals of the fits of reflection and transmission; and of the coloured rings reflected by thick transparent speculums.

What further I have to offer concerning light and colours, consisting chiefly of doubts, difficulties or loose conjectures, shall be proposed under the form of queries.

SECTION 8

QUERIES, CONSISTING OF DOUBTS, DIFFICULTIES, AND CONJECTURES, CONCERNING LIGHT, COLOURS AND COLOURED BODIES

Are not the rays, emitted by all sorts of luminous bodies, similar to those of the sun, both as to colour and degrees of refrangibility? And, do not luminous bodies differ from one another only according to the colours which they emit most plentifully, in like manner as opaque bodies are distinguished by the colours of incident light which they reflect in greatest abundance? (See Nos. 24, 25, 26, 27, 28 and 29). But, to make our induction sufficiently strong, ought not experiments to be made with the lights of a greater variety of bodies? And would it not further conduce to the illustration of this question to form, by Sir Isaac's method,* a beam of solar light, consisting of such colours and in such proportions as were seen in the lights of salts and burning spirits; and then to observe in it the appearance of coloured bodies? Further, are not the intervals of the fits, in rays of any one colour, the same in the same medium, from whatever luminous body they are emitted? For, if these intervals were different, would there not be changes in the colours of bodies not to be accounted for by the compositions of the lights with which they are illuminated?†

Do not all luminous bodies, the most languid as well as most bright, emit their lights of any one colour with one determinate velocity; since it is found by experience, that they are all equally refracted by the same medium? And, therefore, does not the different splendour of luminous bodies proceed wholly from the different density of their light at equal distances? And is not this confirmed by equality of Bradley's aberration of light in fixed stars of all magnitudes?‡ If this be so, the comparative strength of different lights, such as of the

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* Newt. Opt., book 1, part 2, prop. 11.

† See Art.

‡ Eame's Abridg. of *Transactions*, vol. 6, p. 158.

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sun, moon, a candle, etc., may be easily estimated by finding the greatest distances to which the same opaque body is visible when illuminated by each of them, or the limits beyond which it is invisible to a given eye; for the densities of the incident lights are nearly as the squares of the distances of these limits from the object.[*] Does not all light move with the same velocity after reflection as before; since the angle of reflection is always equal to the angle of incidence? The exception, made by some, of electrical light is founded on no less a mistake than confounding the luminous body with its light.[†] But, the best proof of this proposition is from the coincidence of the computations of the velocity of light, from the equation of the eclipses of Jupiter's satellites and the aberration of fixed stars.[‡]

Is light emitted with the same velocity, in whatever medium the luminous body be placed? Or, is it not rather emitted with greater velocity in denser mediums, and that in proportion to their refractive powers? The same argument from whence we gather in general the equal velocity of light emitted by all sorts of luminous bodies, seems to prove the truth of the latter supposition. For, since rays of any one colour, from the sun and a candle, for instance, are equally refracted by a surface of glass or water, we may conclude, that their velocities in air are equal. Wherefore, if the density of the sun's atmosphere, contigious to his surface, be different from the density of our lower air, as may be safely presumed, his rays must have been emitted with

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[*] Let A and a (Tab. 11, fig. 6) denote the same or two equal bodies of the same colour illuminated with different lights, and B, b, the limits. As we suppose the light received by the eye, at these points, is just sufficient to affect it sensibly and no more, the two lights at these different distances must be nearly of the same density: taking, therefore, in AB a line Ab equal to ab, the density of the light at b must be, to the density of the light at b, nearly as AB^2 to Ab^2: and, it is evident, that these densities, at equal distances, must be as the whole quantities of light reflected; and these again very nearly as the whole quantities of light incident.

[*] Musschenbrœk's Elementa Physices, late edition, in his chapter on electricity.

[†] Eame's *Transactions*, vol. vi., etc.

more or less velocity than that of the candle ; otherways, they could not have the same velocity afterwards in any common medium : for, the velocity with which any ray is emitted, is, by the laws of refraction, to its velocity in any given medium, as the sine of refraction to the sine of incidence, when a ray passes from the medium of emission into the given medium,

If the atmosphere is not much warmed by the passage of the sun's light through it, but chiefly by its contact with the heated surface of the globe, as we showed above (No. 15,) ; may we not hence give one very simple and plausible reason, why it is coldest in all climates on the tops of very high mountains ; namely, because they are removed to the greatest distance from the general surface of the earth? For it is well-known, that a fluid heated by its contact with a solid body decreases in heat, in some inverse proportion to the distance from the body. But, to have this question fully determined, the temperature of the air in the valley and on the mountain-top must be observed every hour both night and day, and carefully compared together.

From what has been laid down in Section 2. concerning the manner of the action of light in heating bodies, is it not reasonable to suppose that the heat produced by a given number of rays, in an opaque body of a given magnitude, must be greater when the rays are more inclined to one another than when they are less so? For the direction of the vibrations, raised by the action of the light, whether in the colorific particles or those of an inferior order, will more interfere with one another ; from whence the intestine shocks and collisions must increase ; besides this, the colorific particles of opaque bodies being disposed in various situations perhaps, upon the whole, the rays will fall more directly on each, the more they are inclined to one another. Is not this the reason of what has been remarked by philosophers,* that the heat of the sun's light, collected into a cone, increases in approaching the focus in a much higher proportion than according to its density? That the difference of the angle,

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* Bœrhaave, Element. Chemic. de igne ; Musschenbr. Elementa Physices, 1040.

in which the rays fall on any particle of a given magnitude placed at different distances from the focus, is but small, is no proof that the phenomenon cannot be ascribed to it; since we know not in what high proportion one or both the circumstances now mentioned may operate. However, that it proceeds not from any unknown action of the rays upon one another, as has been insinuated,* is evident from this, that each particular ray, after passing through the focus, preserves its own colour and its own direction, in the same manner as if it were alone.

May it not be inferred, that the component parts of opaque bodies are greater than those of transparent ones, as theory requires,† from this simple observation, that the former, such as metals, stones, woods, etc., when broken transversely, show a visible roughness and inequality at the fracture; whereas the latter, such as glass, crystal, gems, ice, etc., appear as smooth, almost, as when they are polished?

Do not Newton's experiments with the Iceland and rock crystal sufficiently prove, that the rays of light have different permanent properties in their different sides, relative to these two bodies? Must we not therefore conceive each particle of light to preserve its position invariably while it moves forward, at least so as not to revolve round its centre perpendicularly to the direction of its motion? Would it not be proper to try how light is inflected in passing closely by the several angles and sides of these fossils?

Is it not possible to prove by experiment what Sir Isaac Newton takes for granted as a reasonable supposition that thin transparent plates, of any uniform colour, divided into similar fragments, would compose a powder of like colour?‡ And would not this tend to strengthen the analogy between the colours of such plates and those of natural bodies? For this purpose, I have tried to freeze soap-bubbles; but could never

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* Musschenbrœk's Elementa Physices, 1040.

† Newton's Opt., book 2, part 3, prop. 4.

‡ Newton's Opt., book 2, part 3, prop. 5.

make any stand till they were turned to ice, except such as were too thick to have lively colours: however, I doubt not, but, with due care, the thing might be done; especially, if the soap-water, instead of being blown with a pipe into bubbles, were drawn out into a plain plate upon any wooden or metalline frame: for, the sides of a plain surface bearing a greater proportion to its area, than a base of a spherical segment to its surface, the frost would be sooner communicated to the whole water in the former case than in the latter. There is this advantage too in using a plain surface of soap-water that, before it freezes, the observer may draw out any particular colours, which he chooses, to a greater breadth, by stroking it along with a wet finger. For this reason, amongst others, I have found it a more convenient subject for examining the various orders of colours, than spherical bubbles adhering to a plane. Perhaps, melted rosin might be drawn out into a thin coloured plate before it hardens; for I have often blown it into bubbles with a tobacco-pipe till it became coloured. I know no other ways in which the various orders of colours can be preserved for deliberate inspection, but either in a frozen plate of water or rosin, or in the permanent scoria that appear on heated metals. I have counted, on the side of a clean-polished copper tea-kettle, the six first orders of colours distinctly and regularly ranged in the same succession in which they appear in the soap-bubbles; the first order being formed on that part of the kettle that had been least heated.

What else is the inflection of light towards the fine edges of bodies than a particular case of refraction, in which the rays, after being bent by the attractive power, are carried beyond the refracting surface, and miss entering it, because of its small extent? For, if the surface of the edge be produced it will meet the inflected rays; and thus the inflection will become properly refraction. And, in like manner, we may consider the inflection of light off from the edges of bodies, as a species of reflection.

Is it not impossible that an animal can see, if the diameter of its eye be much less than the interval between the fits of transmission and reflection in water, that is, than $\frac{1}{375000}$th of an inch?

There are many experiments which show that a yellow and blue ray mixed, make a green one; a yellow and blue powder, a green powder; and a mixture of rays or paints of all the prismatic colours, a white ray or paint. Now, do not the same experiments equally demonstrate, that the idea of green is a confusion or mixture of the ideas of yellow and blue; the idea of white, a mixture of the ideas of all the colours; and, in general, the ideas of all compound colours, a mixture of the ideas of their constituents? In the experiments which Sir Isaac Newton performed with the toothed instrument, the component colours are not, indeed, presented to the eye all at once; yet they follow one another in so rapid a succession that their respective impressions remain in the eye till they are renewed, and therefore they must affect the mind all at once.* If a piece of paper be daubed all over with small dots of blue and yellow, it will appear green to an eye which is placed

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*It is in this manner that philosophers explain (Newt. Opt. Quer. 16.) the appearance of a fiery circle, which is made by a burning body whirled about swiftly. We shall here give an account of some other phenomena that flow from the same principle.

If a white rod be moved rapidly backwards and forwards with an angular motion, the whole circular space which it runs over will appear whitish; but not equally so, being faintest and most dilute in the middle, and brighter towards the two sides, which seem to be distinctly terminated with two white rods intersecting each other in the center of rotation. (See Tab. III. Fig. 7.).

The total impression made upon the eye by equal small parts of the sector must be, as the quantity of light emitted from it and the frequency of the returns of the rods to it: *i. e.*, inversely as the time between the returns of the rod. Let ABC represent the circular sector, and DC a line bisecting it; the rod always returns to DC after the time of one vibration; and to any other line EC between DC and AC or AB, the mean time of its return is the same; for it alternately returns in twice the time of describing AE, and twice the time of describing EB, so that two succeeding intervals of its returns are equal to the time of two vibrations; but the intervals of the returns to the lines, AC or CB are manifestly equal to the time of two entire vibrations. The brightness of the sector therefore in DC, or any line between DC, AB and BC, must be simply as the quantity of light emitted from equal small portions of the sector; that is, in the inverse proportion of the velocities of the rod when in these lines. It is plain from this, that the sector must be incomparably brighter in AC and BC, where it rests, than any where else, notwithstanding at too great a distance to distinguish the seperate points. In whatever manner sensation be performed, it is certain that the

that the intervals of return thither are double; that is, it will appear to be bounded distinctly with a white rod on each side.

If the rod be agitated with small and quick vibrations of its own, by sticking it against some solid body immediately before it, it is hurried backwards and forwards with the angular motion, the sector appears divided, at equal intervals, by a great many distinct rods, almost as bright as the two lateral ones (Tab. III., Fig. 8.) resembling the spokes of a spread fan. The reason of which curious phenomenon is plainly this; that its angular motion, being alternately in the same and in a contrary direction to its particular vibrations, is alternately accelerated and retarded or stopped. In the interval, where it is accelerated, the sector must appear very dilute; and, where it is greatly retarded or brought to rest, must appear very luminous or divided by white rods, for the same reason that they appear at the sides.

Some Sceptics have disputed against the endless divisibility of quantity, because the imagination soon arrives at a minimum; alledging from thence, that our idea of extension involves the notion of indivisibles, and is as it were compounded of them. Nothing corporeal can be imagined or conceived at all which is not conceived as seen, handled, or otherways sensibly perceived. Imaginative ideas are nothing else than transcripts or images of sensations, and therefore must be limited by the same bounds and in the same manner as sensation. Now the minimum sensible is rather in all cases a confused, indistinct and uncertain transition from perceivable to not perceivable, than the clear perception of a point indivisible in magnitude; for its magnitude depends on the lustre of the object. That nothing can be conceived or imagined which is less than a certain bulk, is no more an argument against the endless divisibility of quantity, than that nothing can be felt or seen below that size; which, it is evident, from every magnifying glass and from every different distance of an object, depends not at all on the constitution of the thing perceived, but on that of the perceiver, or the means and circumstances of his perception.

Nor, though it were granted that the minimum visible is distinctly seen as an indivisible point, would it follow, that the idea of extension, received by sight, is made up of the ideas of indivisibles; for we receive the idea of extension by that motion of the eye which is necessary to direct its axis to different objects or parts of an object: and it is well known that the generation of quantity by motion is preferred by the best writers, for this very reason, that it necessarily excludes the notion of indivisibles. It should be remembered likeways, that a visible object is not divided by the eye into a number of contiguous minima visibilia; for, to whatever mathematical point in the object the eye is directed, a minimum visible may be seen there by means of a certain portion of the object immediately surrounding it.

organs which receive the first impulse from external objects cannot convey to us any ideas, if they, or the impressions made by them, be less than of a certain definite magnitude. A number of things separately intangible, if joined together, may be felt by the touch. A certain number of invisible points become sufficient to affect the sight by their united rays; and a certain number of sounds too small to be heard separately, at last form an audible sound.

Since bodies derive their colours from the original and immutable quantities of their rays which they reflect most copiously, ought they not to appear of the same colour, whether viewed at the greatest or least distances? Whence is it therefore, that the planets whose solid parts are probably covered with vegetables, and must therefore reflect a great superiority of green rays, appear almost entirely white when viewed from the earth? May this not be accounted for, in the same manner as the change of colour observable in earthly objects seen through a great tract of atmosphere? A mountain covered with the freshest verdure, at the distance of twelve or fifteen miles, looks bluish; and at twenty or thirty, especially if the air be thickened, degenerates into a dim white, so that one can hardly distinguish it from the clouds that skirt the horizon. With respect to the primary planets, it may be likeways answered, that perhaps we see them chiefly by light reflected from the air and vapours that surround them.

Why is it so hard to distinguish green bodies from blue by candle-light?

Whence proceeds the blueness of the sky? Since it is certain that no body assumes any particular colour, but because it reflects one sort of rays more abundantly than the rest; and since it cannot be supposed that the constituent parts of pure air are gross enough to separate any colours of themselves; must we not conclude, with Sir Isaac Newton,* that the violet and blue-making rays are reflected more abundantly than the rest, by the finer vapours diffused through the atmosphere whose parts

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*Opt. book 2, part 3, prop. 7.

are not big enough to give them the appearance of visible opaque clouds? Do not those who say,* that the ethereal blue proceeds from the mixture of the sun's white light reflected faintly by the atmosphere with the perfect blackness of the celestial space behind, revive, without any necessity, the antient confused notion, that all colours may be formed by certain compositions of light and shade? Although the atmosphere reflects more blue rays than what go to the formation of perfect white, it is easy to conceive how coloured bodies, illuminated by it, may not be sensibly tinctured with blue. Let us suppose, that the atmosphere reflects $\frac{1}{4}$ more of blue rays than of the other colours, and that vermilion reflects $^{19}/_{20}$ of the red rays incident upon it, and $^{1}/_{20}$ of every other colour; then, it is clear, that the red rays, reflected by the vermilion, will still exceed the blue reflected by it, as 19 exceeds $1 + \frac{1}{4}$; so that the purity of its red colour will not be sensibly impaired. But, to show that, in proper circumstances, the bluish colour of sky-light may be seen on bodies illuminated by it, as it is objected should always happen;† expose to the sun-beams, on a clear cloudless day, a sheet of white paper, and place on it any opaque body; you will perceive that the space of the shadow, which is illuminated only by the sky, appears remarkably blueish, compared with the rest of the paper which receives the sun's direct rays. If certain white and black paints mixed together produce blue, it is because the black is not perfect shade, but a dark blue or purple.‡ Any mixture of whiteness and true black can only form a fainter white or grey, which has no more affinity with blue than with red or any other colour.

Is not the opinion which Sir Isaac Newton seems to have had,§ and, since him, the generality of philosophers, concerning the cause of the various colours reflected by the clouds at sun-

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* Nature displayed, vol. iv. And Muschen. Phys., 1403.

† Muschen., Phys., 1403.

‡ Muschen., 1172. Newt. Opt., book 2, part 3, prop. 7.

§ Opt., book 2, part 3, prop. 5., near the end.

rising and setting, liable to great difficulties? For, why should the particles of the clouds become, at that particular time and never at any other, of such magnitude as to separate these colours? And why are they rarely, if ever, seen tinctured with blue and green, as well as red, orange and yellow? Is it not more credible that the separation of rays is made in passing through the horizontal atmosphere? and that the clouds only reflect and transmit the sun's light, as any half transparent colourless body would do in their place? For, since the atmosphere, as was laid in the last query, reflects a greater quantity of blue and violet rays than of the rest, the sun's light, transmitted through it, ought to draw towards yellow, orange, or red; especially when it passes through the greatest tract of air; accordingly, every one must have remarked, that the sun's horizontal light is sometimes so deeply tinctured, that objects directly illuminated by it appear of a high orange or even red; at that instant, is it any wonder that the colourless clouds reflect the same rays in a more bright and lively manner? It is observable, that the clouds do not commonly assume their brighter dyes till the sun is some minutes set; and that they pass from yellow to a flaming golden colour; and thence, by degrees, to red; which turns deeper and deeper, though fainter, till the sun leaves them altogether. Now it is plain, that the clouds, at that time, receive the sun's light through a much longer tract of air than we do at the instant of setting, perhaps by the difference of a hundred miles or more; as may be computed from their height or the duration of their colours. Is it not, therefore, natural to imagine, that, as the sun's light becomes always somewhat yellowish or orange in passing through the depth of the atmosphere horizontally, it ought to incline more and more from orange towards red, by passing through a still greater length of air; so that the clouds, according to their different altitudes, may assume all the variety of colours, observed in them at sun-rising and setting, by barely reflecting the sun's incident light as they receive it? I have often observed with pleasure, when in Switzerland, that the snowy summits of the Alps turn more and more reddish after sun-set, in the same manner as the clouds. What makes the same colours much more rich and copious in the clouds, is their semi-transparency joined with the obliquity of their situation.

Does it not greatly confirm this explication, that these coloured clouds immediately resume that dark leaden hue which they receive from the sky as soon as the sun's direct rays cease to strike upon them? For, if their gaudy colours arose, like those of the soap-bubble, from the particular size of their parts, they would preserve nearly the same colours, though much fainter, when illuminated only by the atmosphere. About the time of sun-set or a little after, the lower part of the sky, to some distance on each side from the place of his setting, seems to incline to a faint sea-green, by the mixture of his transmitted beams, which are then yellowish, with the ethereal blue: at greater distances, this faint green gradually changes into a reddish brown; because the sun's rays, by passing through more air, begin to incline to orange: and, on the opposite side of the hemisphere, the colour of the horizontal sky inclines sensibly to purple; because his transmitted light which mixes with the azure, by passing through a still greater length of air, becomes reddish; as we have said above.

To understand distinctly why the sun's rays, by passing through a greater and greater quantity of air, change by degrees from white to yellow, thence to orange, and lastly to red, we have only to apply to the atmosphere, what Sir Isaac says (Book 1 of his Optics, part 2, prop. 10.) concerning the colour of transparent liquors in general.

Is it not the same coloured light of the rising and setting sun which tinctures the clouds, that, being thrown by the refraction of the atmosphere into the earth's shadow, gives the moon sometimes in total eclipses, the obscure reddish colour of brick? As the rays which pass through the greatest tract of air, become reddish; those which pass through the least, yellowish; and the intermediate ones, orange: the red must converge fastest into the shadow; after them, the orange; and lastly, the yellow: so, that the whole space of the earth's shadow, from the point of the cone to several semidiameters from the earth, being filled with a faint light, whose colours verge always more to red in approaching the earth; the colour of the moon, in total eclipses, must needs vary likeways, according to her distance from the earth at the time of observation; and, if I mistake not, be always more inclined to red at entering and leaving the shadow, than in the middle. Let astronomers determine, whether the phenomena agree with this theory. It is not surprising that this refracted light is very faint and obscure at the distance of the moon; since its mean density there, will be as much less than the density of the light of the setting sun, as the annular space of the lower air through which it passes, drawn into the moon's horizontal parallax, is less than the area of a great circle of the earth drawn into four times the excess of the horizontal refraction of the atmosphere above the same parallax.

I have observed, when at sea, that, though I pressed my body and head firmly to a corner of the cabin, so as to be at rest in respect of every object about me, the different irregular motions of the ship, in rolling or pitching, were still discernible by the sight: How is this fact to be reconciled to optical principles? Shall we conclude, that the eye, by the sudden motions of the vessel, is rolled out of its due position? Or, if it retains a fixed situation in the head, is the perception of the ship's motion owing to a vertigo in the brain, a deception of the imagination; or to what other cause?

Has not gold been reduced, by beating, to a degree of thickness little exceeding that which must be ascribed to its colorific parts, according to Sir Isaac Newton's theory? But, how can it cohere into a continuous leaf, so as to leave no visible pores, unless there be many of its component particles contained in its thickness?

When one looks steadfastly at Sirius or any bright star not much elevated above the horizon, its colour seems not to be constantly white, but appears tinctured, at every twinkling, alternately with red and blue: To what is this appearance owing? Is not the separation of colours by the refraction of the atmosphere too small to be perceived?

Bodies become black by burning; because they are reduced* into very small parts: but, whence is it, that most bodies, when further burned to ashes, assume a grey or whitish colour?

Since the cause of blackness in bodies is the smallness of their transparent parts, which renders them incapable of reflecting any colour; how can black bodies, solid or fluid, be at the same time opaque? Can light be finally stifled by the refractive powers of the particles alone? or, ought it not rather to make its way through the body, if their be no reflection, without any sensible loss, although the several rays might issue in various directions? And, may it not be demanded, in like manner, concerning all coloured opaque bodies, how all sorts of light can be stifled and stopped within a body, whose internal parts are fitted to reflect only one or two colours, and transmit all the rest?

If the parts and pores of pellucid bodies be much less than the least interval between the fits of reflection and transmission; it is plain, that rays of light, entering a part or pore in a fit of transmission, will not be reflected at its back surface: and thus it may be understood, how all rays that enter the first surface of a transparent body continue to be transmitted through its substance to the greatest distances, *viz.*, if the rays are always put into a new fit of most easy transmission at entering every new pore or particle. But, is not that supposition contrary to what Sir Isaac teaches elsewhere? That the fits of reflection and transmission continue to return at equal intervals, after a ray has entered a transparant body, and are thus regularly propagated to the greatest distances?† And, if this be true, how can the rays be transmitted to any sensible distance, since they must often arrive in fits of easy reflection at the common surfaces of pores and particles? But, although it could be understood by the doctrine of the fits in light why there is no reflection from

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*Newt. Optics, b. 3, part 2, prop. 7.

†Newt. Opt., book 2, part 2, prop. 12.

the interior parts of water and other pellucid medium,* does not the rectilinear transmission of light through these bodies in all directions, and consequently in all degrees of obliquity, to their internal parts, prove, that these parts, upon account of their minuteness, lose their powers of refraction as well as reflection? And to what known property of light or bodies can this be attributed?

If the fits are produced by an alternate acceleration and retardation of the particles of light, some of the particles, which are swift enough to be transmitted at the first surface of a transparent medium, must overcome the reflecting power more easily than others; namely, those that happen to be in their point of greatest celerity or nearest to it: Now, must not rays that are moving with different velocities be differently bent from their course, as we argued above with respect to simple-coloured rays, by the same refractive power? Why therefore is not every beam of light, homogeneal or heterogeneal, diffused by refraction into innumerable rays, according to the respective velocities with which they entered the refracting surface? Is it a sufficient answer to this query, that rays which are farthest from their point of greatest swiftness will be most bent in a direction contrary to that of refraction, by the reflecting power, and will therefore only return to the direction of swifter rays by a greater degree of refraction?

Sir Isaac Newton justly argues, that light must be reflected at a distance from bodies; because the most polished surface, being extremely rough and uneven in respect of the particles of light, would disperse them indifferently in all directions, if they rebounded from it by striking: But, will not the like difficulty still remain, *viz.*, how light can be reflected or refracted regularly by the best-polished surface, if the power of the body proceeds from an attraction or repulsion belonging to each physical point? It might be perhaps supposed, that the repulsive power produces reflection at a distance so great, in respect of the inequalities that are left in polished bodies, that the direction of force,

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* Newt. Opt. book 2, p. 3, prop. 4.

resulting from their joint action, may be very nearly perpendicular to the general surface of the body ; and this might tend to account for the regular reflection from the anterior surface of a denser medium. But, will this supposition suffice for explaining the regularity of refraction and of reflection, from the posterior surface of a denser medium : in both which cases, the light must actually enter the pores of the attracting body, and therefore approach much nearer to one inequality than another ; since the pores, by which it enters, are certainly much less than those inequalities ? In water and other transparant liquids, this must certainly be the case, if their globular particles touch one another, as is commonly concluded from their incompressibility : for, as a number of spheres laid together leave no rectilinear passages between them, the transmitted light must pass through the component particles ; and therefore the pores, by which it enters, must be much less than the whole hemispherical surfaces of the particles which evidently constitute the inequalities of the general surface of the liquor.*

How does light preserve its rectilinear course in passing through air, æther and other elastic fluids ? Will not the difficulty still continue, whatever subtility or rarity is ascribed to these mediums ; since the powers from whence their elasticity arises, must prevail through all the free spaces that intervene between their particles ? Must we not, therefore, suppose, that the rays of light are not subject to these repulsive powers, though they pass through the sphere of their action ? Does not the refraction of light towards the perpendicular, out of the celestial spaces into air, even prove that it is attracted by the particles of air ? Would it not be extravagant and incongruous beyond measure to imagine the æther so subtile, in respect of light, that, though it be driven out of the way by the rays, as

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* We are certain, that the inequalities of a craggy rock or rough wall are much greater than the particles of air or their distance from one another, by which their repulsive powers are probably terminated (Newt. Princip.) : Why is sound, therefore reflected so regularly from such bodies, that the echo is faintly heard, except at an angle of incidence equal to the angle of reflection ?

air is by common projectiles, it is not capable of retarding them sensibly in their motion from the most distant fixed stars to our eye? Do not these and many other difficulties, in the physical part of optics, whose solution is sought for in vain from any principles hitherto discovered, show the necessity of extending our views and enlarging our stock of principles by further experimental inquiry? Such objections are not to be considered as demonstrations of the falsehood of our present theory; but as proofs of its narrowness, partiality and imperfection.

Des Cartes, contenting himself with a superficial and inaccurate knowledge of the laws of impulse, vainly dreamed, that he had got possession of the universal cause from whence all effects in Nature are derived; when, in truth, he was unable to deduce from them the simplest cases of collision. Many in this age, who write and speculate on physical subjects, seem to fall into a like error; while they employ their whole study in endeavouring to reconcile all phenomena with the new principles discovered by Sir Isaac Newton: and, when they find, to their mortification, that this will not always succeed; phenomena must be disguised, and Nature tortured, to hide their ignorance. From the lazy method of philosophizing in the closet, among books and diagrams, there never arose, there never will arise, any discovery of consequence. Great inventors usually understand the extent of their own principles too well, to leave much of the application of them to others.

The discovery of the different refrangibility of the rays, was an inestimable addition to natural knowledge; as it serves, at once, for explaining innumerable phenomena in Nature which flow from it as immediate and necessary consequences: and, if it shall be demonstrated by the observation proposed in No. 49, that the differently-coloured rays really move with different velocities, our theory of light will be still further improved; as the different refrangibility can be thence mechanically explained.

The whole system of Nature is one immense series of causes and effects, whose beginning and end are equally hid in the depths of infinity. Only a small, a very small portion of it, comes under our immediate observation; being exposed alike to the sight and other senses of all mankind. Almost every phenomenon is, at once, the cause of manifold effects; and one effect, among many, of a superior cause. The business of Science is to extend our views, by unfolding the latent causes which exist in Nature; and thence explaining their manifest effects. The discovery of one such real cause, unknown before, if it be of general or very extensive influence, as that of universal gravity, is to be esteemed a great advancement of natural philosophy. To undervalue such a discovery, as some have done, because the cause of that cause cannot yet be assigned, is highly absurd: since the same objection must forever lie against all causes, except primary ones; which are certainly removed far beyond the reach of human inquiry. The proper office, and highest boast of true philosophy, is, to bring us still nearer to the Deity, by leading us upwards, step by step, in the mighty scale of Nature.