
I.

PAPERS OF THE PHYSICAL CLASS.

I. EXPERIMENTS *and* OBSERVATIONS *on the* UNEQUAL REFRACTINGIBILITY of LIGHT. By ROBERT BLAIR, M. D.

[*Read Jan. 3. and April 4. 1791.*]

BY the discovery of the different refrangibility of light, Sir ISAAC NEWTON laid open the true cause of the principal imperfection of refracting telescopes; and having inferred from the experiments which he made, that the refraction of the different rays composing the prismatic spectrum, was always in a given ratio to the refraction of the mean refrangible ray, this great philosopher was led to conclude, that the imperfection which he had discovered in dioptrical instruments was without remedy.

IF Sir ISAAC NEWTON had been questioned concerning the possibility of refracting light, without any divergency of the heterogeneous rays, his reply without doubt would have been, that all his experiments, whether by single refractions or by opposite refractions, tended to establish the contrary conclusion. But that he would have asserted nothing beyond this, may safely be inferred from his own memorable words: "Although
" the arguing from experiments and observations by induction
" be no demonstration of general conclusions, yet it is the best

“ way of arguing which the nature of things admits of, and
 “ may be looked upon as so much the stronger by how much
 “ the induction is more general; and if no exception occur
 “ from phenomena, the conclusion may be pronounced gene-
 “ rally; but if at any time afterwards any exception shall
 “ occur from experiments, it may then begin to be pronounced
 “ with such exceptions as occur.”

THIS is the general doctrine which he lays down as applicable in all experimental enquiries; and so far was he from considering the particular case above mentioned as an exception to this general rule, that from some expressions he makes use of, it evidently appears, that he was not without suspicion, of what has since been discovered to be the truth.

IN his sixth letter to Mr OLDENBURGH, dated from Cambridge in the year 1662, he expresseth himself in the following words: “ Mr HOOK thinks himself concerned to reprehend
 “ me for laying aside the thoughts of improving optics by re-
 “ fraction. What I said there was in respect of telescopes of
 “ the ordinary construction, signifying that their improvement
 “ is not to be expected from the well figuring of glasses, as op-
 “ ticians have imagined. But I despaired not of their im-
 “ provement by other constructions, which made me cautious
 “ to insert nothing that might intimate the contrary. For al-
 “ though successive refractions which are all made the same
 “ way, do necessarily more and more augment the errors of
 “ the first refraction, yet it seemed not impossible for contrary
 “ refractions so to correct each others unequalities, as to make
 “ their difference regular; and if that could be conveniently
 “ effected, there would be no farther difficulty. Now to this
 “ end I examined what may be done, not only by glasses alone,
 “ but more especially by a complication of diverse successive
 “ mediums; as by two or more glasses or crystals, with water,
 “ or some other fluid, between them; all which together may
 “ perform the office of one glass, especially of the object glass,
 “ on

“ on whose construction the perfection of the instrument chiefly depends. But what the results in theory or by trials have been, I may possibly find a more proper occasion to declare.”

IN the year 1757, the late Mr JOHN DOLLOND, in consequence of some strictures on Sir ISAAC NEWTON from abroad, repeated the noted experiment of refracting a ray of light through prisms of glass and water, placed with their refracting angles in opposite directions, and so proportioned to each other, that the ray, after these opposite refractions, emerged parallel to the incident ray. According to the Newtonian doctrine, there ought here to have been no divergency of the heterogeneous rays, and no colour produced by these equal and opposite refractions.

BUT his was not the result of the experiment. The ray was coloured very sensibly; and the author of the experiment finding that he could, by these opposite refractions, produce colour, notwithstanding the parallelism of the incident and emergent light, with reason concluded that he might, by properly proportioning the refracting angles of his prisms, effect an inclination of the refracted to the incident light, without any colour or divergency. The event turned out as he expected.

PUSHING his experiments farther, he discovered, some time afterwards, that a colourless refraction might be produced by a combination of different kinds of glass, as well as by a combination of glass and water, which seemed to remove completely the great obstacle to the perfection of the refracting telescope, discovered by Sir ISAAC NEWTON.

As it was found soon afterwards, that the other principal imperfection which limits the performance of telescopes, namely, the aberration arising from the spherical figures of lenses, might be corrected by properly proportioning to each other the sphericities of the convex and concave lenses, of which the compound object glass is composed; it was expected by men of science, that an increase of the aperture and power of the instrument,

strument, would be the necessary consequence of such important steps, towards the perfection of its theory. These expectations have not hitherto been fully answered.

IF the theory of the achromatic telescope is so complete as it has been represented, may it not reasonably be demanded, whence it proceeds, that HUGENIUS and others could execute telescopes with single object glasses eight inches and upwards in diameter, while a compound object glass of half these dimensions; is hardly to be met with? or how it can arise from any defect in the execution, that reflectors can be made so much shorter than achromatic refractors of equal apertures, when it is well known that the latter are much less affected by any imperfections in the execution of the lenses composing the object glass, than reflectors are by equal defects in the figure of the great speculum?

THE general answer made by artists to enquiries of this kind, is, that the fault lies in the imperfection of glass, and particularly in that kind of glass of which the concave lens of the compound object glass is formed, called flint-glass.

It was in order to satisfy myself concerning the reality of this difficulty, and to attempt to remove it, that I engaged in the following course of experiments. The result of this investigation I now do myself the honour of submitting to the Royal Society.

THE imperfections of glass for optical purposes arise partly from its want of perfect transparency, and from being more or less affected with a tinge of some particular colour, but principally from irregularities which are frequently found in its refractive density. This last imperfection is so constant an attendant upon flint-glass, and every other kind of glass which possesses the disperfive quality in a considerable degree, that it has been suspected, not without appearance of reason, to arise necessarily from that ingredient in its composition on which this

this quality depends. It is certain that great labour and expence have been bestowed on this object without the desired effect.

CONSIDERING therefore that it is not impossible to introduce a fluid medium to supply the place of one of the lenses, in the compound achromatic object glass, I was desirous of searching whether nature afforded fluids possessed of the requisite qualities.

It appears from the passage already quoted, that Sir ISAAC NEWTON not only suspected that optical instruments might admit of improvement by a combination of solid and fluid mediums, but had actually made experiments on the subject, and considered this as the most likely means of carrying these instruments to their greatest perfection.

Dr DAVID GREGORY, Savilian professor of astronomy at Oxford, entertained similar ideas on this subject, as appears from his treatise, entitled, "*Catoptricæ et Dioptricæ Sphæricæ Elementa.*" In this work, which was published at Edinburgh in the year 1713, he treats of optical instruments, both by refraction and reflection; and, after shewing the advantages of the latter in theory, concludes his treatise with the following words: "*Quod si ob difficultates physicas, in speculis idoneis*
torno elaborandis et poliendis, etiamnum lentibus uti oporteat, fortassis media diversæ densitatis ad lentem objectivam componendam adhibere utile foret, ut a natura factum observemus in oculi fabrica, ubi cristallinus humor (fere ejusdem cum vitro virtutis ad radios lucis refringendos) aqueo et vitreo (aquæ, quoad refractionem, haud absimilibus) conjungitur, ad imaginem quam distinctè fieri potuit, a natura nihil frustra molienti, in oculi fundo depingendam: sed et alii sunt in animalis oculo, prædicti artificii usus, qui non sunt hujus loci."

THIS coincidence of opinion of these great opticians respecting the ultimate perfection attainable by the telescope, deserves

to be remarked. Various attempts of this kind have been made by later philosophers and artists. Indeed, the structure of the eye, composed of solids and fluids variously combined, seems to present so obvious and instructive a pattern for imitation, that it is no wonder if the expectations entertained of the productions of art, rose in proportion as they could be made to approach the construction of this exquisite model of Divine workmanship.

Mr DOLLOND's first experiments went no farther than to prove to him, that glass disperses the heterogeneous rays of light more than water, when the refraction of the mean refrangible ray is equal in both mediums. With these scanty data, this able artist zealously went to work to construct telescopes on this new discovered principle. But on this occasion his attempts were not attended with any degree of success. This need not much be wondered at. Besides the difficulty he mentions, arising from the spherical aberration, (which, by the by, if he had considered the matter more attentively, he would have seen to be easily surmountable) he would find between plate-glass and water, but an inconsiderable difference of dispersive power; and if he made use of flint-glass he would have all those difficulties to struggle with, which his successors have not been able to remove, though fully apprized of their cause.

THIS want of success in his first trials with fluids, and the discovery he soon after made of a difference in the dispersive power of different kinds of glass, which he was more successful in applying to the improvement of telescopes, seems to have put an end to all thoughts of the use of fluids, nor has any thing of that kind been since attempted, as far as I have been able to learn, some unsuccessful trials excepted, to construct those small perspectives called opera glasses, on a plan similar to that of Mr DOLLOND, by including spirit of wine between two concave meniscuses of flint-glass, the fluid supplying the
place

place of crown-glass, and the advantage proposed being a saving of the light lost by reflection.

THE experiments of Mr DOLLOND proved, that the dispersive power of water is less than that of the glass with which he made his experiments; and it seems wonderful that this should have been almost the only attempt made to investigate this quality in fluid mediums. We find many tables ascertaining the mean refractive density of fluids, from experiments made both before the discovery of DOLLOND and since. But though some of the fluids examined were possessed of the dispersive quality in a remarkable degree, this is passed over unobserved, and it would seem unsuspected, if we except the very ingenious conjecture of Mr MICHEL; to whom it occurred, that the apparent difference in the experiment above mentioned, made by Sir ISAAC NEWTON, from the same experiment repeated by Mr DOLLOND, might arise from the former using, instead of pure water, a solution of Saccharum Saturni, which he mentions his having sometimes made use of to increase the refraction. Mr MICHEL suspected that lead, even in this form, might increase the dissipative refraction, as it does in the composition of glass. The result of his experiments on this subject may be seen in the additions to Dr PRIESTLEY's Optics, at the end of the second volume.

Of the methods employed for investigating the optical qualities of different mediums.

IN ascertaining the mean refractive and dispersive qualities of fluids, I made use of two kinds of apparatus. Where the properties of the fluids were entirely unknown, prisms were employed to come to a gross knowledge of their properties, and those fluids which promised to be of use in the practical part of optics, were more critically examined by means of lenses, where

the effect, from being magnified, becomes more conspicuous.

THE prismatic apparatus consists of a small prism of brass, whose three angles are equal. Through this prism, and parallel with one of its sides, are bored two holes at a small distance from each other, equal in size to the pupil of the eye. The sides of the prism are ground flat, and there are two bits of glass with parallel sides, of the same dimensions as the sides of the prism. There are also prisms of the same size, and with the same angles of different kinds of glass, and some crown-glass prisms, with smaller angles, which, by being applied to the large prism, or to each other, vary the refracting angle at pleasure.

WHEN it is proposed to try the properties of any fluid, one of the small plates of glass is applied over the holes on the side of the brass prism. A few drops of the fluid are then dropped into the hole; and when it is full, the other plate is laid over the holes upon the opposite side, and the whole is secured by tying a bit of pack-thread round the ends. One of the glass prisms is now to be applied to the brass prism, contiguous with one of the parallel plates, the refracting angles of the two prisms being placed in opposite directions, so as to form a small parallelepiped.

NOTHING farther is necessary than to apply the eye to the hole which contains the fluid, in such a way as to observe through it any bright well defined object. The bars of the window answer the purpose very well in the day-time, and the moon, or a candle in the night. The intention of the two holes is for the sake of greater expedition. The properties of two fluids may thus be examined and compared at the same time.

As the prismatic portion of fluid and the glass prism have equal refracting angles, and refract in opposition to each other, it will easily be understood, that if the object seen through the

two

two prisms coincides with the same object seen directly, the mean refractive density of both mediums will be the same. When this is the case, if the object seen through these prisms appears free from prismatic colour, the dispersive power of the fluid medium is also the same with the dispersive power of the glass prism. But otherwise they will be different.

THOSE mediums, it is to be observed, are said to have the same mean refractive density, which, under equal obliquities of incidence, equally refract the mean refrangible rays, and two mediums are said to have the same dispersive power, which produce an equal inclination of rays of the same colour, to the mean refrangible ray, when the whole refraction of the mean refrangible ray is equal in both.

WHEN an object, seen through the equal wedges of glass and fluid, appears coloured, one of the smaller glass wedges is to be applied and shifted till the object appears colourless. It is easy to distinguish, by the order in which the prismatic colour lies, whether the small prism is to be applied in such a way as to increase the dispersion of the rays occasioned by the fluid, so as to enable it to counterbalance that of the glass; or whether the refracting angle of the glass prism requires to be enlarged, to enable it to counteract the dispersion occasioned by the fluid.

By proceeding in this way to shift the angles of the prisms, till, first, the direct and refracted images of an object coincide, without regarding the colour; and, next, till the refracted image appears colourless, without regarding the coincidence; the ratio of the mean refractive and dispersive powers of that kind of fluid, and that kind of glass, with which the experiments are made, will be obtained, from the angles of the prisms being given in both cases.

In order to ascertain the absolute refractive density of glass, or any other medium, that is to say, the general ratio of the sines of the angles of incidence to the sines of the angles of re-

fraction of the mean refrangible ray, which obtains in that medium, I took a direct method, similar in principle to that employed by Sir ISAAC NEWTON, and described by him in the seventh proposition of the first book of his Optics, and likewise in his Optical Lectures, p. 54. ; but which I may venture to say will be found much easier, and perfectly accurate.

INSTEAD of causing the rays to pass through the sights of a large and accurate quadrant, at the distance of ten or twelve feet, as directed by Sir ISAAC NEWTON, I employed a HADLEY's quadrant, in the following manner :

FIG. I.— I represents the index-glass and H the horizon-glass of a HADLEY's quadrant. S I represents a solar ray, incident on the index-glass, thence reflected to the horizon-glass H, and from it to the eye at E. The line sg represents another solar ray, incident on the prism P, and through it refracted to the eye at E. When the prism is turned slowly round its axis, till the spectrum G appears at its greatest height, this is its proper position. The angle formed by the direct and refracted ray is then the least possible, and the angles of incidence and emergence are equal. Let the prism be secured in this position. A slight inspection of the figure will shew, that when the reflected and refracted images of the sun are made to coincide, the angle marked by the index of the quadrant, is the same which the incident ray sg forms with the refracted ray PE produced. For SZH is the angular distance of the sun and his doubly reflected image, marked by the index ; and the angle sgG, which the ray incident on the prism forms with the refracted ray produced, is equal to it ; sg and SI being parallel, and PZ and HZ being coincident.

THE manner in which the ratio of the sines of the angles of incidence and refraction may be computed from the above angle, and the refracting angle of the prism being given, is fully explained in the celebrated works which have just been quoted.

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It may be proper here to remark, that as it is the ratio of refraction of the mean refrangible ray which is wanted, the centre of the reflected image of the sun ought to be made to coincide with the centre of the coloured spectrum, as represented in the figure; and if, instead of this, the coincidence is formed with the most or least refrangible ray, or any of the intermediate rays, it will be the ratio of refraction of these rays, and not of the mean refrangible ray, which will be found from the observation. Hence this method might be practised for determining the disperse power, as well as the mean refractive density of any transparent substance, whether solid or fluid; but I have preferred a combination of prisms or lenses, because it is the relative ratios, more than the absolute ratios, which are most immediately wanted.

Experiments on the disperse powers of fluids.

I EXAMINED, by the prismatic apparatus which has been described, the optical properties of a great variety of fluid mediums. It will suffice to mention the most remarkable of these. Many solutions of metals and semi-metals, in different forms, were subjected to trial, and these were always found to be more disperse than crown-glass. The solution of some salts in water, as for instance of crude sal ammoniacum, greatly increases its disperse power. The marine acid disperses very considerably, and this quality increases with its strength. Hence I found the most disperse fluids to be those in which the marine acid and the metals are combined. The chemical preparation called *causticum antimoniale* or *butyrum antimonii*, in its most concentrated state, when it has just attracted sufficient humidity to render it fluid, possesses the quality of dispersing the rays in such an astonishing degree, that three wedges of crown-glass are necessary to remove the colour produced by one wedge of this substance.

substance, of an equal refracting angle, opposed to them. The great quantity of the semi-metal retained in solution, and the highly concentrated state of the marine acid, seem to be the cause of this scarce credible effect.

CORROSIVE sublimate mercury, added to a solution of crude sal ammoniacum in water, possesses the next place to the butter of antimony among the disperfive fluids which I examined. It may be made of such a degree of strength, as to require a wedge of crown-glass, of double the refracting angle, to remove the colour which a prism of it produces. The mercury and marine acid contained in this solution, are manifestly the cause of its disperfive power. For neither the water nor the volatile alkali, which are its other component parts, will be found capable, if tried separately, of contributing towards this effect.

THE essential oils were found to hold the next rank to metallic solutions, among fluids which possess the disperfive quality. The most disperfive I found to be those obtained from bituminous minerals, such as the native petrolea, pit-coal and amber. When the refraction is without colour, the proportion of the refracting angle of a prism of these, to the refracting angle of a prism of crown-glass acting in opposition, is about two to three. The disperfive power of the essential oil of saffras, is not much inferior to these. The essential oil of lemons, when genuine, requires the refracting angles of the prisms necessary to produce a colourless refraction, to be as three to four. In oil of turpentine, this proportion is as seven to six; and the essential oil of rosemary is still less disperfive.

SOME expressed oils which were examined, were found not to differ sensibly in disperfive power from crown-glass, which was also the case with rectified spirits, and with nitrous and vitriolic æther.

A VARIETY of other fluids were examined in the same way ; but not having yet collected them into a table, I have only mentioned, in general terms, the most remarkable.

HAVING been thus successful beyond my hopes, in discovering fluids capable of removing the great imperfection of telescopes, arising from the different refrangibility of light, the next object was, to select from this variety those which seemed best adapted to optical purposes.

THERE can be no doubt that those mediums which most disperse the rays, are, *ceteris paribus*, to be preferred. It will also be found, when the method of correcting those errors, which arise from the spherical figures of lenses, comes to be considered, that there is apparently an advantage in using a dispersive medium, whose mean refractive density exceeds the mean refractive density of crown-glasses.

As the antimonial caustic possesses both these advantages, in a degree far beyond what was to be expected in any fluid, I included some of it between two double convex lenses of crown-glass, whose radii of convexity were as two to one. The least convex sides of these were turned towards each other, and they were kept at a proper distance by means of a glass-ring. The cavity was then filled with the strongest butter of antimony. Here it is evident that there is a concave lens of the dispersive fluid, acting in opposition to the two convex lenses of crown-glass, and that the proportion of the radii of these is the same which was found by the prisms to correct the colour, namely, three wedges of crown-glass, to one of the butter of antimony.

THIS compound object-glass being put into a tube, an eye-glass was applied, and, according to expectation, the colour was found to be removed. But I was surprised to find, on directing the instrument to a planet, and using a deep eye-glass, that this fluid, in its highly concentrated state, was subject, like
flint-

flint-glass, to great irregularities in its density, discoverable by streams of light, like comet's tails, issuing in different directions from the disc of Venus, which was the planet observed. By shaking the object-glass, these might be, in a great measure, removed, but soon returned; and after standing all night, broad veins, in different parts of the included fluid, were perceptible to the naked eye.

It was necessary on this account to reject very dense fluids. The antimonial preparation I found might be reduced to a sufficient degree of fluidity, by mixing it with spirit of wine or vitriolic æther, into which a small quantity of the marine acid had been previously dropped. This prevents any precipitation of the semi-metal in the form of a calx. In this diluted form, either this preparation, or the solution of corrosive sublimate mercury alone, in spirit of wine, or in water, with the addition of crude sal ammoniacum, may be employed for producing refraction without colour, and without being subject to that irregularity of density to which flint-glass, and very dense dispersive fluids, are subject.

BUT as solutions of saline substances in this diluted state do not differ materially in dispersive power from the essential oils, these two kinds of fluids may be used indifferently.

THERE is, however, a particular case, in which water or vitriolic æther, impregnated with antimony or mercury, will have the advantage, from being less dense than essential oils; and that is, where it is required to produce a single refraction, in which there shall be no difference of refrangibility of heterogeneous light. As this expression may sound strange in the ears of opticians, I shall, before proceeding farther in the application of the experiments which have been recited, explain what is meant by it.

Cases

Cases of refraction in which the violet rays are least refrangible, and the red rays most refrangible; or in which all the rays are equally refrangible; or in which the red rays are refracted from the perpendicular, and the violet rays towards the perpendicular, while the mean refrangible rays suffer no refraction.

It has been mentioned, that when prisms of crown-glass and oil of turpentine refract in opposition, the transmitted light is colourless, when the proportion of the refracting angles of these prisms is as seven to six. Hence, if oil of turpentine be included between two double convex lenses, the radii of whose convexities are as six to one, and the deep sides of these be placed inwards, so as to be in contact with the fluid; in the refraction through this compound lens, the aberration from the difference of refrangibility will be removed. I can prove the truth of what I write, by a compound object glass of this kind, which I have had in my possession above four years. It is twenty inches in focal length, and its performance as a telescope, with one inch and a half of aperture, is not contemptible. Now, it has long ago been ascertained, that the mean refractive density of oil of turpentine is less than that of glass; and thence I affirm, that when light passes from crown-glass into oil of turpentine, a considerable refraction of the whole pencil from the perpendicular takes place, and the violet rays are, in this case, the least refrangible, and the red rays the most refrangible.

THIS is manifest from the facts which have just been stated. In the object-glass above mentioned, there are four refractions, all of which are made in the same direction; namely, two refractions at the two external surfaces of the lenses, which are in contact with air, and two at the internal surfaces, which are in contact with oil of turpentine.

IN the refractions which take place in the confine of glass and air, it has been put beyond all doubt, by Sir ISAAC NEWTON's experiments, that the red rays are least refracted, and the violet rays most refracted ; and it is equally clear, from what has just been mentioned to be the result of trials with prisms, and from the correction of colour in the above mentioned object-glasses, that when light passes obliquely out of crown-glass into oil of turpentine, it is refracted from the perpendicular, and the red rays are most refracted, and the violet rays least refracted. If this were otherwise, the heterogeneous rays, which are made to diverge in two refractions, which take place in the confine of glass and air, could never have this divergency removed by the refractions made in the confine of glass and the fluid. It is manifest, that if, in these last mentioned refractions, the separation of the heterogeneous rays were in the same order as in the refraction from air into glass, the colour and divergency of the rays, instead of being removed by them, would be increased.

I SHALL not enter upon the application of this fact to the best received theories of refraction ; but it may be worth while to remark the great importance of minute accuracy in observing the results of experiments. Dr HOOK attempted to make object-glasses of telescopes, by interposing a fluid between a plano-convex lens, and a piece of glass, both sides of which were plane and parallel. The convex side of the lens was turned inwards ; and the author seems to have had no other view in this scheme, but to obviate the difficulty which was found in giving a good figure to lenses ground to very long radii. The refraction being thus reduced to that which takes place in the confine of glass and the fluid employed, may be diminished in any proportion, and consequently the focal length of the object-glass lengthened at pleasure. One of the fluids which he appears to have made use of, was oil of turpentine. The difference between the phenomena attending an object-glass of this
construction

construction and a simple lens, if they had been attentively observed, would have led Dr HOOK to the truth ; and a man of his zeal and invention would not have failed to apply the discovery to the improvement of optics, not to mention the triumph it would have afforded the opponent and rival of NEWTON, to have asserted, and had it in his power to make good his assertion, that in some cases the violet rays are the least refrangible, and the red rays the most refrangible.

EVEN Mr DOLLOND could not conceive that the prismatic colour could be corrected by refractions which are all made the same way ; and still less would he have admitted that single refractions may take place without divergency or colour *. As this continues to be the opinion of the best informed opticians of the present day, it will be necessary to enter into a more explicit investigation of the subject.

FIG. 2. Let ABC represent a glass prism, and BCD a prism of water in contact with it ; and let the angles of these prisms be so proportioned to each other, that a ray of light SI, which enters the glass prism perpendicularly, shall, after, being refracted from the perpendicular at the point G, in passing out of the glass into the water, emerge at K, perpendicular to the side CD of the water prism, which is supposed to be confined by parallel plates of glass. As the ray both enters and emerges from the refracting mediums perpendicularly, it will suffer no refraction, excepting when it passes from the glass into the water, where its incidence is oblique. Here it will be refracted from the perpendicular, and will emerge coloured, the violet rays being most refracted, and the red rays least refracted.

LET the water be now impregnated with antimony or mercury, to increase its dispersive power. As this will also increase its mean refractive density, and occasion a diminution of the

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refraction

* Philosophical Transactions of London, vol. 1. page 740.

refraction in passing into it from the glass, conceive the angle BCD to be diminished as the refraction diminishes, so that the refracted ray GK shall still emerge perpendicular to DC. When the angles of the glass prism and prism of dispersive fluid bear to each other a certain proportion, the ray will be found to emerge colourless; and when this happens, it is evident that all the rays are equally refracted at the point G, in passing out of the glass into the fluid. For they suffer no other refraction whatever.

THIS is a necessary consequence of the glass and fluid differing in their mean refractive density, and of the rarer medium possessing the requisite degree of dispersive power.

THIS case of a single refraction taking place, without any difference of refrangibility of the rays, may be illustrated by Sir ISAAC NEWTON's explication of refraction, by means of attraction, in the following manner. He supposes refraction to arise from an attracting force acting on light, in lines perpendicular to the surface of the medium; and the cause of one kind of rays being more refracted than another, to arise from their being more attracted.

WHEN the medium is surrounded by a vacuum, the refraction will be proportioned to the whole attracting force of that medium. But when light passes from one refracting medium into another, it will only be attracted by the difference between their attracting forces, as they act in opposition to each other.

Now, if the difference of attraction of the most and least refrangible rays were, in all mediums, proportioned to the whole attraction of the mean refrangible ray, it would be impossible to produce refraction without colour*. But subsequent experiments

* THIS at least is true as to sense in those small refractions which take place in telescopes and microscopes; and it would be mathematically true in all cases, if the angles of incidence and refraction were proportional. But as it is not the angles themselves which are so, but their sines, it is a mistake to suppose that colourless refraction cannot be produced by large contrary refractions of the same medium, properly disposed for the purpose.

experiments have proved, that this supposed general law of refraction does not hold in nature.

IN the instance before us, if we suppose the force with which glass attracts the red, green and violet rays to be represented by the numbers five, six and seven ; then may the force with which the disperse fluid attracts these rays, be represented by the numbers four, five and six. For the reason why all the rays are equally refracted in their transition from one of these mediums into the other, is because the rare medium has the property of refracting the violet rays more, and the red rays less, than the dense medium, when the obliquity of incidence is so proportioned to their density, that the mean refrangible ray shall suffer the same refraction in both.

Now, in the case above stated, the attraction of the rare medium for the several rays, is so proportioned to the attraction of the dense medium for these same rays, that the difference of these attractions is every where equal, and consequently the refraction arising from these differences of attraction is also equal. Thus the green ray is attracted by the dense medium with the force six, and by the rare medium with the force five, the difference of which is one ; and there is the same difference between the attracting forces acting on the red and violet rays in the two mediums, being in one case the difference between five and four, and in the other between six and seven ; so that the difference of attracting force, and consequently the refraction supposed to arise from it, is the same in all the rays, being always that which will be produced by an attracting force, represented by unity.

IF the disperse power of the rare medium, of which the prism B C D is formed, be still farther increased, the red rays will become the most refrangible, and the violet rays the least refrangible ; a law of refraction, which, as has been already explained, obtains when light is refracted in the confine of crown-glass and oil of turpentine, and of many other fluids.

IF

If the mean refractive density of the disperfive fluid, contained in the prism B C D, be so far increased as to become equal to the mean refractive density of the glass prism A B C, the mean refrangible ray will suffer no refraction in passing obliquely from the one medium into the other at the point G, but the violet ray will be refracted towards the perpendicular, and the red ray will be refracted from the perpendicular. The reason of which is, that the disperfive medium refracts the violet ray more, and the red ray less than the other medium; so that the former may be considered as an equally dense medium with the latter relative to the green ray, but more dense relative to the violet ray, and less dense relative to the red ray.

THIS case of refraction takes place in the confine of crown-glass and butter of antimony, when the latter is so far diluted as to have the same mean refractive density with crown-glass; that is to say, when both mediums equally refract the green ray, under equal obliquities of incidence.

THESE varieties of refraction will possibly be better comprehended by the assistance of diagrams.

FIG. 3. represents a prism of crown-glass, which is entered perpendicularly by a red, green and violet ray, moving parallel with each other. As their incidence on the second surface of the prism is oblique, they will, in passing from the glass into air, be refracted from the perpendicular. This deflection of the light from its rectilinear course, is supposed to be produced by the perpendicular attracting forces, represented by the numbers five, six and seven. The violet ray will therefore be most deflected, the green next, and the red ray least.

FIG. 4. represents a prism of disperfive fluid, which the three rays enter with the same degree of obliquity which they had before they emerged from the glass prism. The attracting forces of the fluid for the several rays, are represented by the numbers

numbers four, five, six ; and each of them will be deflected towards the perpendicular, in a degree proportioned to the force acting on it.

FIG. 5. represents the two prisms in contact, and the three rays entering the glass prism perpendicularly, and emerging perpendicularly from the fluid ; so that the only refraction they suffer in their passage, is in the confine of the two mediums.

At the point of contact, the rays will be acted on by both mediums, with the same forces which they exerted when separate. But these forces will act in opposition, and therefore the rays will only be affected by their difference ; and as the difference of attraction of the two mediums is the same in all the rays, they will all be equally refracted. The red ray is attracted towards the glass by the difference between the forces four and five, the green by the difference between five and six, and the violet by the difference between six and seven, each of which differences is equal to unity, as represented in the figure.

If the dispersive power of the fluid, contained in the prismatic vessel, be diminished by decreasing the proportion of mercury or antimony which it contains, the violet ray will begin to be more refracted, and the red ray less refracted, than the green ray. But if that quality be increased, the contrary of this will happen ; the red ray now becoming the most refrangible, and the violet ray the least refrangible.

If the dispersive medium employed, be of that precise degree of strength, which enables it to refract the green ray in the same degree in which it is refracted by crown-glass ; in this case it has been asserted, that when light passes obliquely from the one of these mediums into the other, the green rays will suffer no refraction, but the red rays will be refracted from the perpendicular, and the violet rays towards the perpendicular. The reason of this will appear from inspecting the three following diagrams.

FIG.

FIG. 6. represents a prism of crown-glass, in which the red, green and violet rays, at their emergence into air, are attracted, as before, with the forces five, six and seven.

FIG. 7. represents a prismatic vessel filled with butter of antimony, whose mean refracting force is equal to that of the crown-glass, so that the green ray is attracted by it with the force six. But in consequence of its great disperfive power, the red and violet are attracted, (we shall suppose for the sake of round numbers) with the forces four and eight.

FIG. 8. represents the two prisms in contact, and consequently acting in opposition to each other. Now, the force with which each of the mediums acts on the green ray, is represented by six; the difference between which being nothing, the green ray will proceed in its rectilineal course, as it would do in the same uniform medium.

BUT as the red ray is attracted by the crown-glass with a force represented by five, and by the disperfive medium with a force equal only to four, it will, in passing out of the former into the latter, be deflected towards the crown-glass, by the difference between these forces, which is equal to unity.

THE violet ray, on the contrary, is attracted by the crown-glass with the force seven, and by the disperfive medium with the force eight, and will therefore be refracted towards the latter, in the same degree in which the red ray is refracted from it, as represented in the figure. It is a circumstance worth remarking, that a particle of red light, and a particle of violet light, under precisely the same circumstances of exposure to the action of gross bodies, should be urged in contrary directions.

I HAVE tried these several cases of refraction likewise with compound object-glasses, which shew the effect better than the prisms. Thus, if a plano-convex lens have its plane side turned

ed towards a distant object, the rays will enter it, as to sense, perpendicularly, and will therefore suffer no refraction. If the convex surface of this lens be brought in contact, with a fluid of less mean refractive density than the glass, but exceeding it in dispersive power, in that degree which occasions an equal refraction of all the rays, all these rays will then be converged to the same point, which are incident at the same distance from the axis of the lens. The focal distance of this compound lens will be greater or less in proportion to its radius of convexity, and to the difference of refraction between it and the fluid made use of. While the fluid is confined on one side by the plano-convex lens, let the lens which is brought in contact with it on the opposite side, have one of its sides ground convex, and the other concave; the radii of their sphericities being equal to the focal distance at which the rays are made to converge, by the refraction which takes place, when light passes from the plano-convex lens into the fluid. It is manifest that the light will now both enter into this compound lens, and emerge from it perpendicularly, and will therefore suffer no refraction, except in the confine of the convex side of the plano-convex and the dispersive fluid, where all the rays are equally refrangible. A compound lens of this kind, is represented in the ninth figure, which, after what has been said, will require no farther explanation; excepting only, that instead of being spherical, it is represented with that curvature which converges homogeneous rays, incident at all distances from the axis, to the same point. If the required curvature could be given to lenses with sufficient accuracy, this figure seems to represent as perfectly a construction of the object-glass of a telescope as can be desired. But there is reason to think that a spherical figure may be communicated, not only much easier, but with greater accuracy than a spheroidal or hyperboloidal, which would be required; and even if this difficulty could be got over, there would still remain a fundamental fault in the theory. Before relating the

observations by which this was detected, it will be requisite to explain the method of removing the spherical aberration, by a combination of convex and concave lenses. For next to the indistinctness arising from the unequal refrangibility of light, this aberration, occasioned by the spherical figures of lenses, is the great obstacle to the advancement of the powers of vision.

Of the aberration from the spherical figure.

THIS subject has been treated of in all the variety of cases which can occur in single glass lenses, by the great HUGENIUS, in his Dioptrics, a posthumous work. He there demonstrates that the quantity of this aberration is very different in different lenses of the same focal distance, according to the convexities or concavities of their two sides, and the manner in which these are exposed to parallel rays.

IN convex lenses, those rays which pass at a distance from the axis, are converged to a point nearer to the lens than its geometrical focus. The distance between the point at which the external ray of a pencil incident on a lens, intersects its axis and the geometrical focus, is called the linear aberration of that lens.

HUGENIUS demonstrates, that when a plano-convex lens is exposed to parallel rays, with its plane side towards them, this aberration will amount to four times and a half the thickness of the glass. By the thickness of a convex lens is meant its greatest thickness in the middle, after subtracting its thickness, if it has any, at the outer edge; and by the thickness of a concave lens, is meant its thickness at the external edge, after deducting its thickness in the middle.

ON turning the convex side of the lens towards the light, the linear aberration will only exceed the thickness of the lens by one sixth part.

WHEN

WHEN both sides of a lens are convex, and the proportion of their convexities is as one to six, if the most convex side be exposed to parallel rays, the aberration will exceed the thickness of the lens one fourteenth, which is the smallest possible aberration of any convex lens.

IF it is required to increase the aberration, this may be done by grinding one side of the lens convex, and the other side concave, to a longer radius. Such a lens, with its concave side turned towards parallel rays, will have more aberration than any plano-convex or double convex lens of the same focal distance.

HUGENIUS proceeds to shew, that the same aberration is produced by concave lenses as by similar convex ones. When a plano-concave lens is exposed to parallel rays, with its plane side outward, the external ray of the pencil, being produced backward after refraction, will intersect the axis of the lens nearer to it than its focus, by four times and a half the thickness of the lens. But if its concave side be exposed to the parallel rays, the aberration will only exceed the thickness of the lens one fourteenth part. A double concave, whose radii are as one to six, with the most concave side turned outward, disperses the rays with the least aberration; and a concave meniscus, with its convex side outward, produces more aberration than any plano-concave or double concave lens, of an equal focal distance.

THESE are sufficient data for correcting the aberration from the spherical figure, in cases where both a convex and concave lens are required, in the construction of the compound object-glasses.

FIG. 10. Let AB represent a convex lens receiving a pencil of rays from the object S, and converging rays incident near the axis, as ST, to the point F; and external rays, as SB, to the point

D; so that DF represents the greatest linear aberration in this case.

AGAIN, let GH (Fig. 11.) represent a concave lens, receiving the parallel rays SH, RK, which it refracts in the lines HX and KV. This ray KV being produced backward, will intersect the axis of the lens nearly at the point N, which is called the virtual focus of the concave; and the external ray HX produced backward, will intersect the axis in some point P nearer to the lens than its focus, PN being the linear aberration.

It may here be observed, that the convex is in that position which produces the least aberration, and the concave in the position which produces most aberration. Hence, to render the aberrations DF (Fig. 10.) and PN (Fig. 11.) equal, the focal distance of the convex must be much shorter than that of the concave; and if the distances of the points F and N from the convex and concave lenses be required to be the same, as represented in the figures, then must the object be placed much nearer to the convex. Hence the image of the near object S, is represented at the same distance from the convex lens in figure tenth, as the virtual focus of the concave in figure eleventh, where it is represented as receiving parallel rays, which are supposed to come from an infinitely distant object.

Now, when the distance between K and N, which is the point from which parallel rays are made to diverge by the concave lens, is equal to the distance between T and F, which is the point to which rays issuing from S are made to converge by the convex; and when the aberrations DF and PN are also equal; I say, that in this case, if the two lenses be placed contiguous, in the manner represented in the twelfth figure, parallel rays, incident on these lenses, will be converged to the point S, without any aberration of the external ray.

FOR

FOR it is an axiom in optics, that if a ray of light after refraction be returned directly back to the point of incidence, it will be refracted in the line which was before described by the incident ray.

IF therefore we conceive the whole of the light emitted from the point S (Fig. 10.), and converged by the convex lens towards the points D and F, to be returned directly back from these points, it will be accurately converged to the point S, whence it issued. Now, the parallel rays SH, RK, (Fig. 11.) after their emergence from the concave lens, in the lines HX, KV, are precisely in the same relative situation, as the rays supposed to be returned directly back from F and D are in, at their incidence on the convex; and therefore, when these lenses are placed contiguous, in the manner represented in the twelfth figure, parallel rays incident on the concave lens, and immediately after their emergence from it, entering the convex lens, will be accurately converged to the point S, without any aberration.

THIS, which is the most simple case, will suffice to explain the nature of that aberration, which arises from the spherical figures of lenses, and a method of obviating it by combining a convex and concave.

THE demonstration is perfect as far as regards the external ray, which is here represented passing from the external part of the concave into the external part of the convex, in immediate contact with it; and if the surfaces of the two lenses, which respect each other, were either in contact or parallel, it would be true with regard to all the rays. But as this is not the case, there arises a small secondary aberration, the effect of which only becomes sensible in large apertures.

HENCE may be understood the reason why the indistinctness arising from the spherical figures of lenses, may, in the common achromatic telescope, be more nearly removed in those constructions of object-glasses in which three lenses are employed.

ployed, than in those composed only of two ; and also the advantages in this respect, which may be derived from introducing fluid mediums, which differ from glass in their mean refractive density, and in the quantity of aberration produced by their refractions. For it will be found upon computation, that when the fluid medium is rarer than glass, the aberration from the spherical figure is increased, and becomes greater in proportion as its density diminishes. Now, by making the density of the fluid medium approach nearer and nearer to the density of the glass with which it is in contact, we may increase the rarity of our refracting medium, or, which amounts precisely to the same thing, diminish the difference of density of the two mediums at pleasure.

It will appear from what has been explained, that the aberration from the figure cannot be corrected by interposing a dispersive fluid between two convex lenses, of a greater refractive density than the interposed fluid. For all the refractions being made the same way, tend to converge the external rays to points nearer the lens than its geometrical focus. Hence, when rare fluids are made use of to remove the aberration from the difference of refrangibility, some farther contrivance becomes necessary to correct the spherical aberration.

THE most obvious way, and which on trial I found successful, is to include the rare dispersive fluid between two glasses, ground concave on one side and convex on the other, and thus form such a concave as shall be required. By combining this with a convex, an achromatic object-glass may be formed, as represented in the sixteenth figure. The objection to this construction is, that one of the advantages arising from the use of fluids is given up, namely, the prevention of that loss of light by reflection, which is a consequence of the fluid being in immediate contact with the glass; whereas in the present case, the space between the convex and concave is occupied by air.

ON

ON this account I attempted to introduce a third medium, by filling this vacancy with a fluid of the least disperfive kind, and of less mean refractive density than the disperfive fluid. For this purpose I employed sometimes rectified spirit of wine, and sometimes vitriolic æther; and by giving to the lenses the proper degree of curvature, in which great variety may be introduced, I succeeded in forming object-glasses, in which both aberrations are removed, and hardly any more light lost than in a simple object-glass.

HAVING gained this point, I now determined to try how far the aperture of the object-glass might be increased, without increasing its focal length, expecting, at least, to equal reflectors in this respect. But the first trials to execute object-glasses on this principle, though they left no reason to complain of want of success, when compared with such instruments as are now in use, surprised me with new phenomena, and new obstacles to the perfection of the theory of telescopes, more unaccountable and perplexing than any I had before encountered. These I shall now proceed to give an account of.

Of the imperfect correction of prismatic colour which is obtained by a combination of mediums of different disperfive powers.

I TOOK a compound object-glass of the construction last mentioned, composed of three lenses, two of them plano-convex and the other a meniscus. The radius of convexity of one of the plano-convex lenses is about four inches, and the convex side is turned towards the object. The radii to which both sides of the meniscus are ground, are about five inches, one side being convex and the other side concave. The concave side is made to respect the plane side of the above mentioned plano-convex, and the vacancy between them is filled with vitriolic æther. The third plano-convex lens is ground to a radius of six inches. Its convex side is turned towards the convex side of the
the

the meniscus, and the vacancy between them is replenished by a fluid of the requisite degree of disperseive power, which is confined by means of a ring of glass. These lenses are two inches and seven eighths of an inch in diameter, and the focal length of the compound object-glass is ten inches; the curvatures of the lenses being so proportioned, as nearly to correct the aberration from the spherical figure.

THE fluid I employed to remove the colour arising from the different refrangibility of light, was an essential oil, whose disperseive quality I could easily increase or diminish, by mixing it with others differing in their disperseive qualities, though of nearly the same mean refractive density; by which means, the correction of the error from the figure was not disturbed, by varying the strength of the disperseive fluid. I now expected perfectly to remove the colour, by adding a little of one or other of the disperseive fluids, as occasion might require.

BEFORE relating the event of this trial, it will be proper to explain the manner of examining the disperseive power of fluids by means of lenses, and of distinguishing when the colour is perfectly corrected.

WHEN the image of a lucid point is formed in the focus of a simple lens, the violet rays are converged to a focus nearest to the lens, and the deep red rays are converged to a focus at the greatest distance from it. The consequence of this is, that if this image be examined by an eye-glass nearer to the lens than is required for distinct vision, it will appear surrounded with a red fringe, which is the prevailing colour of the least refrangible rays; and if the eye-glass be placed at a distance beyond that which is required for distinct vision, it will be surrounded with a blue fringe, which is the prevailing colour of the most refrangible rays.

THE reason of this will appear more clearly from inspecting the thirteenth figure, where the red rays appear outermost within the focus at A, and the violet rays appear outermost beyond

yond the focus at B. These colours may also be seen, when an image of any luminous object, as the sun, is formed by a lens upon a white ground; and they will be so much the more conspicuous, by how much the diameter of the lens is greater, in proportion to its focal distance.

JUST the reverse of this will happen in a compound object-glass, if, in correcting the colour, the medium employed disperses more than it ought to do. A blue fringe will then appear round a luminous object, when the eye-glass is pushed in; and a red fringe, when it is drawn out beyond what is necessary for distinct vision.

IN this way, the correction of the colour may be examined, and the qualities of refracting mediums investigated, to an extreme degree of accuracy; yet the effect will be rendered still more sensible, by covering half the object-glass. For when this is done, the colour produced by the uncovered half of the object-glass appears, without being mixed with that of the opposite side, even when the eye-glass is adjusted to distinct vision. Thus, in Fig. 13. the colours produced by both sides of the lens, are mixed at the general focus F. But if the rays coming from one side be intercepted, those which are refracted by the other side will appear in their proper colours. By these means, and by employing a very luminous object, surrounded by a dark ground, and a high magnifying power, the least uncorrected colour may be rendered sensible.

My first observations, which clearly proved the correction of colour which is obtained by the combination of two mediums differing in disperseive power, to be only partial, were made in the summer of the year 1787, at Merchiston.

I HAD, some time before, found it impossible to succeed, in this respect, with prisms composed of crown and flint glass. But as I neither was able to make the phenomena so apparent by this method as with lenses, nor had a command of prisms with that great variety of refracting angles necessary to put it

beyond all doubt, that the colour observed might not proceed from the angles of the prisms not being precisely those, which would render the correction of colour most perfect, I paid no farther attention to the subject at that time.

IN examining the object-glass above mentioned, the object observed was a small window in a white wall, at the distance of several hundred yards to the eastward of my station, the sun shining upon the wall from the west. The circumstances of the phenomena, which I have extracted from memorandums written at the time of making the experiments, were as follow :

“ *July 28. 1787.* IN construction A, (by this is meant the ten inch object-glass above described), when rendered as achromatic as possible, a purplish light appears on one side the focus, and a greenish light on the other.”

IN the next observation of this kind of incorrigible colour, the flame of ARGAND's lamp was used as an object, the great brilliancy of its light rendering the phenomena more conspicuous. A cylinder of brass was placed over the glass tube, which intercepted all the light, excepting what passed through a small round hole opposite to the flame. I found no object preferable to this for the purpose, except the planet Venus, which cannot always be commanded. My observation mentions, that “ with the patent lamp, the colour is deep carmine within the focus, and greenish yellow without it.”

ANOTHER memorandum on this subject runs thus : “ Construction 10. (by this is meant another object-glass, composed, like the former, of crown glass, an essential oil, and spirit of wine, instead of æther, but a few inches longer than it, and more perfect) discovers a great deal of colour of some kind, in covering half the object-glass. The object, though coloured, is then more distinct than upon uncovering the other half ; the colour is thus converted into mistiness. On altering the dispersion of the fluid, the colour on one side alters from purplish
violet

violet to reddish violet, and on the other from greenish orange to greenish blue. As the dispersion is diminished, the red gains on the violet within the focus, and the greenish blue upon the orange without it, and *vice versa*; and there is a considerable latitude, within which, varying the dispersion, makes little difference in the distinctness."

As this last observation put it beyond doubt that an investigation of the cause of these appearances was of the last importance to the improvement of optics, I now began to reason concerning them.

THE first conjecture that offered was, that this colour might somehow proceed from the surfaces of the convex glass lenses, and the concave lenses of dispersive fluids, not corresponding at different distances from the centre, as the plane surfaces of prisms every where do. In order to examine what effect this might have, I procured two pieces of plate-brass, with which I could cover the whole of the object-glass; and out of one of these I caused a ring, of a quarter of an inch in breadth, to be cut towards the centre, and out of the other, a ring of the same breadth, close to the circumference. For I perceived that, if the colour arose from the cause above mentioned, its appearance ought to be different through these two rings, when there is an accurate correction of colour in that part of the object-glass, which is equi-distant from the centre and the circumference. But upon trying the experiment, the same purple and green colour appeared through both these rings, as through the whole object-glass, and the colours lay in the same order in both cases. My remark upon this experiment is in the following words: "Upon trying with a ring either external or internal, the appearances remain the same, as when the whole aperture is used; which seems to prove that this colour arises from the dispersion not being proportional, and not, as was supposed, from the surfaces not corresponding. It is evidently the greatest bar to increasing the aperture, and giving high powers; there

is only a partial correction of colour ; the differently refrangible rays cannot all be converged to one focus."

THE next method that occurred to me of determining the point in question was more decisive. This was to observe whether any of this green and purple colour appeared through the most perfect kind of achromatic object-glass above described, and represented in the ninth figure, in which there is only one refraction. This I found to be the case ; and therefore considered myself as in possession of sufficient authority for concluding, that the theory advanced by Mr DOLLOND, and generally received, was defective. For with the large aperture and high power made use of in these experiments, the colour that appears in viewing a bright object is not weak and hardly sensible, but a beautiful bright purple inclining to crimson, and a strong full green, and these in such a quantity as evidently to be the obstacle to increasing the aperture of the object-glass.

THIS was the conclusion I was then led to, and which I have found confirmed by numerous experiments made since. But before entering farther on the subject, it will be necessary to explain what is meant by different mediums not dispersing the heterogeneous rays of light proportionally.

LET *AB* and *CD* (Figures 14. and 15.) represent the surfaces of two mediums, both of which equally refract the mean refrangible ray. This we shall suppose to be the green ray, though, in this explication, it is not material which is called the mean refrangible ray. The angles of incidence *KGL*, *MNR*, will then be equal, and the angles of refraction of the green ray *HGg*, *PRγ*, will also be equal in both these mediums.

LET one of these mediums *CD* exceed the other *AB* so much in disperseive power, as to make the difference of the angles of refraction of the green ray, and extreme violet ray, in the medium *CD*, double of what it is in the medium *AB* ; that is to say, the angle $\nu R \gamma$ double the angle $\nu G g$. Then

if

if the difference of the angles of refraction of the green ray and deep red ray, in the medium CD , be also double of the difference of the angles of refraction of these rays in the medium AB , that is to say, the angle $\gamma R g$ double the angle gGr ; I should say that the two mediums dispersed these three kinds of rays, namely the red, green and violet rays proportionally. But if, when the difference between the angles of refraction of the green ray, and extreme violet ray, in the medium CD , is double of what it is in the medium AB ; the difference of the angles of refraction of the green ray, and deep red ray in the medium CD , shall be found to exceed the difference between the angles of refraction of these rays, in the medium AB , only one half, for example; then I would say that the two mediums do not disperse these differently refrangible rays proportionally.

FOR in this case the medium CD disperses or separates the green ray, and extreme violet ray, twice as much as the medium AB does; whereas the separation of the green ray, and deep red ray, in this same medium CD , exceeds only by one half their separation in the medium AB .

It is farther manifest, that the red, green and violet rays cannot be rendered parallel by any combination of the refractions of the two mediums, upon the last mentioned supposition. The whole refraction, through a prism composed of the medium CD , may be such as to give exactly the same inclination of the red and violet rays, which a prism composed of the medium AB does, when both rays suffer a greater refraction through the latter; and therefore both these rays may be equally refracted and converged to the same point by means of a convex lens of the least dispersive medium AB , and a concave lens duly proportioned to it, formed of the most dispersive medium CD .

BUT if we now add to these the green ray, it is evident that it too cannot be refracted parallel with the red and violet rays.

FOR

FOR when the whole refraction of the least disperse medium AB is such as just to unite the red and violet rays, the green ray, which is more refracted by this medium AB, in proportion to the whole refraction of the red and violet rays in the medium AB, than it is refracted by the disperse medium CD, in proportion to the whole refraction of the red and violet rays in the medium CD, will, when the red and violet rays are united by contrary refractions through these two mediums, be refracted too much; the balance of refraction being always, in this case, in favour of the least disperse medium; and therefore the green light will emerge from this compound refraction more refracted than the united red and violet light, and the inclination of the emergent green light to the emergent united red and violet light, will be greater or less according as the ratio in which the red, green and violet light are separated by the refraction of the two mediums, approaches more or less to equality. What this inclination amounts to, in any particular instance, must be determined by experiment.

HENCE if the case of unproportional dispersion, above stated, should be found to hold true in fact, we shall arrive at this new truth in optics, That though in the refraction of a pencil of solar light, made in the confine of any medium, and a vacuum, the deep red rays are always the least refrangible, and the violet rays are always the most refrangible; yet it depends entirely on the specific qualities of the medium, which shall be the mean refrangible ray; the very same ray, which in the refraction through one medium is the mean refrangible ray, being found in others among the less refrangible rays. For it is manifest that the ray which bisects the angle formed by the most and least refrangible rays, and falls in the middle of the coloured spectrum, is to be accounted the mean refrangible ray.

THUS, in Fig. 14. the green ray Gg is the mean refrangible. But in Fig. 15. the green ray $R\gamma$ is found among the
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less refrangible rays, and some other ray, R_{ω} , which is one of the more refrangible rays in the medium AB, is the mean refrangible ray in this medium CD.

THE most obvious way of examining the optical properties of different mediums, is by means of prisms. But I have not found this method either so easy or so accurate as that by means of lenses, which has been already explained. It has been shewn, that the image of a lucid point (see the thirteenth figure) is every where, between the lens and that point where the rays cross, surrounded with a fringe of the colour of the least refrangible rays; and that every where beyond the point of crossing, the image is surrounded with a fringe of the colour of the most refrangible rays; and that these colours appear more distinctly at the focus itself, when one half of the lens is covered. Hence, in order to determine which rays are the most or least refrangible, after refraction through any lens, whether simple or compound, it is only necessary to examine the colours of these fringes, which is the more easily done, as they are greatly magnified by the eye-glass.

IN single lenses, the fringe within the focus, which is composed of the least refrangible rays, will always be found to be of a red colour, with a mixture of orange; and the fringe beyond the focus, composed of the most refrangible rays, will be found to be of a blue colour. These are the colours which, it is well known, are produced by simple refraction, made in the confine of every known medium and a vacuum.

FROM what hath been already related, it appears, that colour is likewise produced in what has been termed achromatic refraction, though it be less in quantity, in proportion to the whole refraction; and the rays which are found most and least refrangible, in these two cases, differ very widely.

IN a compound object-glass, formed of a concave, which disperses the rays in a greater degree, and a convex, which disperses the rays in a less degree, there was always found, when
the

the correction of colour was rendered the most perfect possible, a fringe of purple within the focus, and a fringe of green beyond the focus; and these coloured fringes appeared, whether the concave consisted of flint-glass, or of an essential oil. Therefore, in this kind of compound refraction, the rays of light, when their union is rendered the most perfect possible, emerge differently refrangible; and the rays which emerge most refrangible, have the property of exciting in us the idea of a green colour; and the rays which emerge least refrangible, have the property of exciting in us the idea of a purple colour.

WHEN, for the sake of brevity, I speak here, or elsewhere, of the union of the red and violet rays, as if it were performed by a single refraction, whereas, in general, the most that can be effected is to render them parallel by opposite refractions, I would be understood to refer to the most simple and perfect case of achromatic refraction, in which the extreme red and violet rays are really equally refracted, and consequently united, by a single refraction, as already explained in the references to the fifth and ninth figures.

THE fringe of purple light is formed in part by an union of the red and violet rays, which in simple refraction differ most in refrangibility, but which are here equally refrangible; and partly of the united orange and indigo light, which are also united, and form the second order of coloured light in this secondary spectrum.

THE green fringe is composed in part of the homogeneal green rays, which, in common refraction, are the mean refrangible, or nearly so, but are now the most refrangible of all. The remainder of this green fringe is formed by an union of the yellow and blue rays, composing what may be termed an heterogeneal green.

It will appear from the foregoing statements, in what manner this disposition of the rays is a necessary consequence of the

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the concave and convex lenses being composed of mediums which do not disperse the rays proportionally, as before explained. But the matter will be best understood, by recurring to the case above mentioned, of single achromatic refraction. Thus I continue to denominate it, though the Society will perceive that this term *achromatic*, is here used with manifest impropriety; and will also make proper allowance for the sense in which I have employed the term *homogeneous light*, in conformity to the common language of optics.

It was formerly asserted, that when two mediums differ in mean refractive density, and the dispersive power of the rare medium exceeds that of the dense medium in a certain proportion, light of all colours will be equally refracted in the confine of the two mediums; and it is true that the red and violet rays will be equally refracted, and the rays of other colours as nearly so as by any combination of two mediums of different dispersive powers. But on account of the two mediums not attracting, and consequently separating the rays of different colours in a given ratio, the same green and purple-coloured fringes appear in an object-glass of this kind, as in one in which opposite refractions are employed; so that in the refraction which takes place in the confine of two such mediums, the rays of light are still unequally refrangible. But instead of the degree of refrangibility being, as in common refraction, according to the order of the colours, red, orange, yellow, green, blue, indigo, violet, the prismatic spectrum is, as it were, doubled, the rays being, at the same time, compressed nearer to each other; and their degrees of refrangibility being now according to the following order: Red and violet united, the least refrangible; next to these in refrangibility, the orange and indigo united; then the united yellow and blue; and, lastly, the homogeneous green rays, which are the most refrangible.

Of the perfect correction of the aberration arising from the unequal refrangibility of light.

THIS fact now established on the fullest evidence, that the divergency of the heterogeneous rays is not to be removed by a combination of crown-glass with flint-glass, or with those dispersive fluids employed in the object-glasses, with which the experiments above related were made, discovered a most important problem in optics, namely, the entire removal of the aberration from the difference of refrangibility of light, by any combination of mediums whatever.

THIS problem, it was evident, was only to be attempted by again having recourse to the volume of nature, and searching out the hidden qualities of refracting mediums. Though in all the compound object-glasses which were examined, after being rendered as achromatic as possible, the same colours appeared, and in the same order; yet every trial could only be considered as speaking for itself, if the expression may be allowed. The experiments were indeed numerous, and will, I hope, be found to have been made with sufficient care and attention; yet to have formed from them any general conclusion, that in every endeavour to unite the rays of all colours, by a combination of mediums differing in dispersive power, the green rays will emerge most refracted, and the red and violet least refracted, as above explained, could only serve to prevent farther investigation, by representing the perfection of the theory of optical instruments by refraction as a desperate attempt.

THE order in which I proceeded farther to explore this subject was the following:

HAVING found fringes of colour, as above described, in combinations of crown-glass with the essential oils, and in combinations of crown-glass and flint-glass, when the refraction is rendered

rendered as colourless as possible, I began by trying other disperseive mediums, which owe this property to different metallic or saline particles with which they are impregnated, in hopes of finding some disperseive medium, which might separate the differently refrangible rays in the same proportion in which crown-glass does, and thus afford a method of refracting all of them alike, and consequently without colour. But I was disappointed. The compound object-glasses, formed of a variety of disperseive fluids and crown-glass, exhibited green and purple fringes, as before, which proved the disperseive power of the two mediums not to be proportional.

My next step was to vary the combination by rejecting glass entirely as a refracting medium, and only employing it to confine the fluids. As a fluid medium was here to be used as a convex lens, those which had been found least disperseive, were to be made choice of. Accordingly, water, spirit of wine, nitrous and vitriolic æther, and all the limpid indisperseive fluids I could come at, were made trial of. But still the result was the same. The green and purple fringes appeared, on covering half the object-glass.

I THEN substituted some other of the more perfect indisperseive kinds of glass instead of crown-glass; but with no better success.

NEXT I combined two essential oils, both of them more disperseive than crown-glass, but differing so considerably in this respect between themselves, that the less disperseive could be used as a convex, while the other was so disposed as to perform the office of a concave. For it will easily be understood, that lenses of any kind may be formed of fluid mediums, by including them between glasses, which have one side formed convex, and the other concave, to the same radius, and thus serve merely to confine the fluids, without producing themselves any effect in refracting the light. If a flat side is wanted, a piece of plain glass with parallel sides must be used, and in

concave lenses of this kind, the farther contrivance of a glass-ring to confine the fluid is required.

THE effect of the above combination, which was of oil of turpentine with a mineral oil, I immediately perceived to be different from what was observed in the preceding trials. The green and purple fringes still appeared, and they lay in the same order as before ; but their breadth was greatly diminished, I judged about one half.

THIS new fact was the only fruit of this last set of experiments, which were attended with much trouble and loss of time. For to make them with the requisite degree of precision, pains must be taken, not only to get the refraction as colourless as the qualities of the mediums will admit, but also to compute the error from the spherical figure, and procure lenses accurately ground to the spheres which are required. Unless these points are duly attended to, accuracy in the results is not to be expected.

I NOW considered how this diminution of the breadth of the coloured fringes, observed in the last mentioned experiment, might best be turned to account. In the first place, it was obvious, that an object-glass, formed by a combination of the mediums used in that experiment, would have an advantage over others, in which the correction of the aberration from the difference of refrangibility is more imperfect. But as this fault, though greatly diminished, would still prevent the use of high magnifying powers, I weighed the circumstances more attentively, and the matter appeared to me in the following light :

A CONVEX lens, formed of the least disperse of the two essential oils, being so combined with a concave lens, formed of that which is most disperse, as to unite the red and violet rays, leaves fringes of uncorrected colour, much narrower than those produced by compound object-glasses of the same focal distance, formed by a combination of either of these fluids
with

with glafs. Hence I was led to conclude, that if I took an achromatic convex lens, composed of the two essential oils, and combined it with an achromatic concave lens of a longer focal distance, composed of crown-glafs and either of the essential oils, I should be able, through such a double compound object-glafs, to converge the rays to a focus, without any aberration whatever from the difference of refrangibility of light. For if the compound convex and compound concave are properly proportioned to each other, the secondary spectrums, or fringes of green and purple, may be rendered of the same breadth in both lenses; and from the observations before related, this will happen when there is a considerable balance of refraction in favour of the convex lens. For it is composed of materials which form a much narrower secondary spectrum, under an equal refraction of the whole pencil, than those mediums do, of which the compound concave is formed.

THIS will be understood, by attending to what takes place in the refractions of light through the lenses, without again recurring to the more simple case of prisms.

FIG. 17. represents a compound concave lens, formed of a concave lens of glafs, and a concave lens of a dispersive fluid, but of a shorter focus than the concave lens, and so proportioned as to produce a refraction as free from colour as can be obtained by a combination of these two mediums. This lens being exposed to parallel rays, will make them diverge, after refraction, from its virtual focus, and the united red and violet rays will be the least refracted, and will be inclined in a certain angle to the green rays which are most refracted, as represented in the figure.

FIG. 18. represents a compound convex lens, formed of a convex of an essential oil, which disperses the rays in a lesser degree, combined with a concave of an essential oil,
which

which disperses the rays in a much greater degree. The convexity of this compound lens is such, as to unite, at a convenient distance, rays diverging as from the virtual focus of the compound concave. The whole refraction through the convex is consequently much greater than through the concave. But notwithstanding this, the angle formed by the green ray with the united red and violet rays, is represented equal in the two lenses. For as the effect of the mediums of which the compound concave is formed, is to separate the united red and violet rays from the green rays, much more than those of which the compound convex is formed, when the refraction of the pencil is equal, it becomes necessary, in order to render this separation equal in both lenses, to diminish the refraction through the concave.

AN object-glass formed of such a compound concave and compound convex, appears more complicated than it is in reality. It may be rendered complete without employing more than two fluid mediums and three glass lenses, which were found necessary merely to correct the aberration from the spherical figure. Thus, in the nineteenth figure, the two compound lenses are represented in contact; and it is manifest, that the pieces of plain glass with parallel sides, which were necessary to confine the fluid when the lenses were separate, are now useless; for it is the very same fluid which is on both sides of these plain pieces of glass; and as they produce no effect in refracting the light, they are better removed, as represented in this figure.

PARALLEL rays incident on the concave lens, are here represented converged to a focus, without any aberration whatever. This is a necessary consequence of what hath been related concerning the properties of the refracting mediums, of which this compound object-glass is formed.

IN both the concave and convex, the red and violet rays are united, and form the least refrangible rays, and in both, the
green

green rays are the most refrangible. But as the angle formed by these most and least refrangible rays, would be much greater in the concave if the whole refractions were equal, the whole refraction is here represented to be precisely that which is requisite for giving the same inclination of the green rays to the united red and violet rays, which takes place after refraction through the convex. Hence, as these refractions are equal and opposite, they destroy each others effect. The rays proceed after refraction without any divergency from unequal refrangibility; and the aberration from the spherical figure being also corrected by means of the concave glass lens, which is more dense than either of the fluids, they are converged to the same point.

THE construction represented in these figures, is not, however, the most perfect and convenient for the purpose. The best method is to divide the concave glass necessary for removing the secondary colour, by making two of the lenses, or all three of them, concave meniscuses. But throwing the whole concave glass into one lens, and exhibiting the compound convex and compound concave lenses separately, answers best the present purpose of explaining the principle on which the aberration from unequal refrangibility may be totally removed. On the same account, the difference of the dispersive power of the two fluids, is represented greater than it is in reality.

HAVING completed an object-glass of this kind, I carefully examined whether any colour was yet discernible. For though the red and violet and green rays were now united, it was a thing possible, that rays of other colours might still have a small inclination to these. But I could discover no colour by the most rigid test; and therefore conclude the refraction of all the rays of the spectrum to be now equal. If there be any deviation from this equality of refraction, it is insensible; and insensible errors, in those cases where sense is the only judge, may be accounted no errors at all.

I HAD now attained the object I was in search of, namely, a method of refracting equally all the rays of which light is composed. Nor was the construction of object-glasses for telescopes, which it afforded, liable to any very material objection. The principal inconvenience arose from the necessary depth of the spheres of the lenses required, which was now the only remaining obstacle to shortening the refracting telescope at pleasure.

IN the first trials I made to discover a dispersive medium which should separate the rays in the same proportion in which glass does, I was in hopes of perfect success, and therefore not at all curious in observing the breadths of the coloured fringes, still hoping that the next trial might afford a refraction without any colour whatever. I therefore thought it expedient to repeat some of them, with greater attention to that circumstance.

THE first fluid I happened to make trial of, was a metallic solution with a mixture of marine acid. Upon comparing an object-glass, rendered achromatic by this solution, with another as nearly similar to it as possible, in which an essential oil was employed for that purpose, the breadth of the coloured fringes appeared indisputably much narrower in the former than the latter*. I repeated the experiment frequently, to enable me to judge of the proportion of focal distance of a compound concave, necessary to correct this secondary colour, upon the principle which hath just been explained. Upon a comparative trial, I found it better to form the compound convex of a combination of this fluid and glass, than of a combination of two essential oils. The convex was not only shorter itself, with the same depth of spheres, but required a shallower compound
concave

* THE cause, at that time unknown, was, that the solution happened to contain an unusual proportion of the marine acid; as will be understood from what follows.

concave lens to remove the colour entirely. The colour may be totally removed, and the aberration from the figure corrected, by a concave which lengthens the focal distance of the convex only one third.

FROM what hath been explained respecting the total correction of colour, it will be understood, that if the concave lengthens the focal distance beyond what is required, fringes of green and purple ought to begin to appear in an inverted order. This, which may be styled the *experimentum crucis* in this matter, I now had it in my power to try without difficulty. The result turned out exactly as I expected. Upon applying a compound concave, which nearly doubled the length of the compound convex, a fringe of green appeared within the focus, and a fringe of purple beyond it, which sets the theory of the correction of this secondary colour in the most satisfactory light.

THE compound concave in this and all the preceding experiments, was formed of glass and an essential oil.

I NOW happened, merely with a view of diversifying the experiment, to apply a compound concave, formed of glass combined with the muriatic acid, which has been mentioned as a fluid possessing a considerable degree of disperseive power. This opened a new and unexpected scene. The colours appeared in the same order as in the last experiment, but the fringes were so very broad as greatly to surprise me, and create a suspicion that every thing was not as I had hitherto taken for granted. Without delay I included some of the marine acid between two convex lenses, whose radii were duly proportioned to the disperseive power of that fluid, for the purpose of correcting the colour. Upon applying an eye-glass I found my suspicion verified. The fringes of green and purple appeared nearly of the usual breadth, but in an inverted order, there being now a green fringe within the focus, and a purple fringe beyond it. I was the better pleased at being thus led to the

detection of this singular property of the acid of sea-salt, because, in making the same experiment before, this inversion of the order of the colours had entirely escaped me. I was then examining it, to find whether it dispersed the several orders of rays, in the same ratio in which glass does; and being satisfied that it did not, from observing the green and purple fringes, as in other combinations, a circumstance so little looked for, as the inversion of the order of the colours, did not strike me.

THIS observation affords a remarkable exception to what I had begun to consider as very probably a general law of nature. In the refraction which takes place in mediums of the least dispersive kind, the green rays, or rather perhaps the rays in the confine of green and blue, are the mean refrangible, and these same rays, in the more dispersive mediums, were always found among the less refrangible rays; and hence when, by a proper combination of two such mediums, the red and violet rays are united, these united red and violet rays constitute the least refrangible rays, and the green constitute the most refrangible rays, as before explained.

BUT in the muriatic acid, the case is just the reverse of this. Then the green rays, which in mediums that disperse the least, are the mean refrangible, and which in essential oils and metallic impregnations are found among the less refrangible, appear amongst the more refrangible. Whence in such a combination of the muriatic acid and an indispersive medium as shall unite the red and violet rays, these united red and violet rays emerge most refrangible, and the homogeneal green rays emerge least refrangible, being just the reverse of what takes place in combinations of crown-glass with flint-glass, or with essential oils, or saturated metallic solutions.

THIS unusual property of the marine acid does not, however, seem to admit of any immediate application to the improvement of optical instruments. It is true that, instead of having recourse to a compound concave for correcting the secondary

condary colour, this may be effected by a compound convex, which, instead of lengthening, will shorten the focal distance of the compound object-glass. But in a construction of this kind, the correction of the spherical aberration would be attended with more difficulty.

HAVING thus found an exception to the general result of my former experiments, which was, that those rays which in the least disperse mediums constitute the mean refrangible rays, are in more disperse mediums found amongst the less refrangible rays, it seemed not improbable that disperse mediums might exist, which would separate the differently coloured rays exactly in the same proportion in which they are separated by indispersive mediums.

I HAD now indeed got hold of a pretty sure clue to lead me to mediums possessed of this property. It will appear from what has been said concerning attraction, that when in a metallic solution or an essential oil, which separate the red and violet rays in the same degree in which they are separated by the marine acid, the green rays are found amongst the less refrangible rays in the former fluids, and amongst the more refrangible in the latter fluid, the cause of this difference must be, that the green light is more attracted by the marine acid than by essential oils or metallic solutions, when the attraction for the red and violet light is the same in all these mediums.

HENCE it seemed reasonable to conclude, that in a medium compounded in a due proportion of the particles composing these two kinds of disperse mediums, the attraction for the green rays would be in an intermediate degree, and might be rendered the same, in proportion to the attraction for the red and violet rays, which obtains in crown-glass and other indispersive mediums.

It might be found a matter of no small difficulty to unite the essential oils with the marine acid, so as to form a colour-

less transparent fluid. But nothing can be better adapted for this purpose than metallic solutions.

I FIRST made trial of butter of antimony, and found the result to be what I expected. On increasing the proportion of muriatic acid, the fringes of green and purple grew narrower and narrower till they entirely disappeared, and if more was then added they re-appeared in an inverted order. I tried the same thing with a solution of crude sal ammoniac and mercury sublimata. If the solution contains a certain proportion of these two substances, the rays of all colours emerge from the compound object-glass equally refracted. If the proportion of the ammoniacal salt, and consequently of the muriatic acid which it contains, be increased, the green rays, which were the mean refrangible in the dispersive fluid, as well as in crown-glass, draw nearer to the violet, making a part of the more refrangible half of the spectrum, and consequently emerge less refracted than the united red and violet rays, and are converged to a focus at a greater distance from the object-glass; so that the green fringe now appears within the focus, and the purple fringe beyond it. But on increasing the proportion of mercurial particles, these same green rays shift their situation to the less refrangible half of the spectrum, which appears from their now emerging most refracted, and being converged to a point nearer to the object-glass than the united red and violet, whose refrangibility does not appear to be affected by these admixtures which occasion such remarkable fluctuations in the refrangibility of the green rays and other intermediate orders. It may possibly seem strange at first view, that the green rays should emerge most refracted from the compound object-glass, when their refrangibility in the dispersive medium is diminished, and least refracted under the contrary circumstances. The cause of this is, that the principal refraction of the compound object-glass is performed by the indispersive convex lens,
which

which is opposite to the refraction produced by the disperfive concave.

It was formerly observed, that in the confine of a rare disperfive medium, and a dense indisperfive medium, there may be a single refraction, in which all the rays are equally refrangible; and it has since been explained with what limitation this is to be understood, in consequence of the unproportional dispersion which generally takes place in such mediums; of which I was then ignorant. The explanation^o which refers to the second, third, fourth and fifth diagrams, and to the object-glasses represented in the ninth figure, is to be considered as strictly just, when, in the fluid employed, the metallic particles are so far diminished, and the particles of marine acid so far increased, as to render the refraction of the several orders of rays proportional in both mediums.

I HAVE got an object-glass of this kind, which is represented in the twentieth figure. There are two refractions in the confine of glass and the fluid, but not the least colour whatever. Hence it is manifest that in the refraction which takes place in the confine of glass and this fluid, and which, on account of the difference of their densities, is very considerable, there is no unequal refrangibility of light. The rays of different colours are bent from their rectilineal course with the same equality and regularity as in reflection.

As custom has already appropriated the word *achromatic* to that kind of refraction in which there is only a partial correction of colour, in order to avoid confusion, I shall beg permission to distinguish this entire removal of aberration by the term *aplanatic* *, till a better can be thought of.

BEFORE closing this enquiry concerning the optical properties of transparent substances, I examined more minutely than I had done before, the qualities of the other mineral acids. The nitrous acid, when of the same mean refractive density as
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* From the Greek α privative, and the verb $\Piλανάω$.

the marine acid, does not disperse the red and violet rays quite so much. The green ray, as in the marine acid, is found among the more refrangible rays; but it approaches nearer to the place of the mean refrangible ray in the nitrous acid than in the marine. The green ray is also nearer to the place of the mean refrangible ray, than it is in essential oils or in saturated metallic solutions; and therefore the nitrous acid appears by these experiments to disperse the several orders of rays more nearly in the same proportion in which crown-glass does, than any uncompounded dispersive medium, and would, I have no doubt, do so exactly, if slightly impregnated with mercury, though this I have not tried.

THE vitriolic acid is scarcely to be classed among dispersive mediums. The following experiment is the last I made on the subject. In a very good object-glass, of that kind before described, in which spirit of wine is one of the mediums employed, I substituted successively for this spirit the vitriolic acid and a solution of fixed alkaline salt, both of them of nearly the same mean refractive density as the spirit of wine. These three fluids, although they differ so widely in their chemical properties, have their optical properties so nearly alike, that I found it difficult to determine which was the medium employed. For when the secondary colour is not corrected, as was the case in this object-glass, the change of colour produced in the green and purple fringes to render it apparent, must be considerable, a slight shade of difference not being easily distinguishable. I therefore repeated the trial with an object-glass, in which this green and purple light is totally removed; and then both the vitriolic acid, and the solution of fixed alkali, when of equal mean refractive density with spirit of wine, appeared very sensibly more dispersive than the spirit. The difference in this respect between the acid and the alkali was scarcely to be distinguished; and the effect of a solution of caustic alkali appeared to be nearly the same as that of mild
alkali

alkali of equal density. By similar trials, the phosphoric and acetous acids were found to be considerably more dispersive than spirit of wine.

ALTHOUGH these experiments with compound object-glasses of very large apertures, afford both the readiest and most accurate method of investigating the optical properties of refracting mediums, it would be both amusing and instructive to repeat them with compound prisms. I could have wished in particular, had my present situation been convenient for the purpose, to have taken the dimensions of the secondary spectrum, under given angles of incidence and refraction. For by comparing these with the dimensions of the primary spectrum, accurately ascertained by Sir ISAAC NEWTON, the degree of superiority of an object-glass composed of crown and flint glass, over a simple object-glass, and of one in which there is a regular refraction of all the rays, over both, might be ascertained. At present, I can only state the circumstances of a comparison I made between two compound object-glasses of equal apertures, but very unequal lengths. One was composed of crown-glass, spirit of wine and an essential oil. The focal length is about fourteen inches, and the aperture two inches. The other object-glass was of crown and flint-glass; its focal length thirty-two inches, and its aperture two inches. I had it for a good one of its kind, and upon examination found no particular defect in its structure.

THE short telescope has a manifest advantage in the night, especially in viewing fine objects, such as double stars of inferior magnitudes, where the uncorrected colour is less hurtful.

BUT I was surprised, on viewing an object in bright sunshine, to find considerably more of that mistiness which arises from the unequal refrangibility of light, than appeared in the long telescope. I therefore diminished the aperture of the short one to one inch and a half, and comparing them again, there appeared no more of this mist in the one than in the other.

other. I farther reduced the aperture of the short one to one inch, when it became manifestly clearer than the long one, though, upon examining the coloured fringes, by covering half the object-glass, they still appeared of such a breadth as must necessarily hurt the distinctness.

I HAVE here given the result of this experiment as I find it noted down. Being made with no view to the determination of the point in question, the accuracy necessary for that purpose was not observed. It would appear, however, from this gross and indirect trial, that the aberration from unequal refrangibility would not differ very materially in these object-glasses, supposing their apertures and focal distances to be equal; though in one the partial correction of colour is effected by a combination of flint-glass and crown-glass, and in the other by a combination of crown-glass and spirit of wine, with an essential oil. If this aberration were exactly equal in both combinations, the misty indistinctness proceeding from it ought to be the same in both object-glasses, when the apertures and magnifying powers applied, are as the square roots of their respective focal lengths.

It would appear that the aperture of an object-glass, composed of crown and flint-glass of thirty-two inches in focal length, ought not to exceed two inches, and therefore that three inches is too large an aperture for one of forty-two inches focal length; for the lengths in these two cases ought to be as four to nine. In some telescopes of this latter kind, I have observed a great deal of uncorrected colour, which prevents them from bearing magnifying powers, in proportion to the aperture of the object-glass. It is indeed but seldom that the union of the differently refrangible rays is so perfect as the construction admits. I have met with others in which the real aperture is so far contracted, by diaphragms placed within the tube, as scarcely to exceed two inches.

FROM

FROM inspecting the tables of the lengths and apertures of telescopes with simple object-glasses, it will appear, that the required length for an aperture of two inches is about thirteen feet. This exceeds two feet and an half, the length given to an achromatic telescope, whose object-glass is two inches in diameter, between five and six times. The length of the standard Hugenian telescope, whose aperture is three inches, is thirty feet. This is between eight and nine times the length of an achromatic telescope, the aperture of which is likewise three inches, and its length three and a half feet. But if the aberration from unequal refrangibility be diminished to the same degree as in the thirty inch telescope, the length must be increased, from three and a half feet to about five and a half. For its length must be to thirty inches, the length of the two inch aperture, as the square of two to the square of three, and then the telescope with the simple object-glass will only exceed it in length between five and six times as before.

THE observations which have been mentioned put it beyond a doubt, that the limit to the apertures and magnifying powers of what have been improperly called achromatic telescopes, is the very same which limits the performance of telescopes with simple object-glasses, namely, the unequal refrangibility of light; and it would seem, that the aberration from this cause may be diminished, by a combination of lenses of crown and flint glass, between five and six times.

Sir ISAAC NEWTON, by accurate experiments, hath determined the diameter of the least circular space within which parallel rays of all kinds can be collected by a simple lens, to be one fifty-fifth part of the diameter of the aperture of the lens. If the aberration, from unequal refrangibility in a compound object-glass, vitiates the distinctness less than in a simple object-glass, in the proportion of one to six, it may seem a reasonable conclusion, that the least circular space within which parallel rays of all kinds can be gathered by an object-glass composed

of crown and flint glafs, ought to be one fixth of one fifty-fifth part of its aperture. The difference in the focal lengths of the eye-glaffes will then render the indiftinctnefs nearly equal in the two kinds of object-glaffes with equal magnifying powers, in all cafes where their apertures are equal, and their lengths as one to fix.

THERE is, however, a circumftance of the greateft moment to be taken into account before this conclufion can be admitted, which is, that not merely the diameter of the circle of aberration is to be confidered, but alfo the fpiffitude of the rays, both within that circle in general, and at different diftances from its centre. The rarity of the light in the fimple fpectrum is fuch, that the aberration hurts much lefs than might be expected. But in the fecondary fpectrum, as two orders of coloured light are united, the imperfect union of the rays by the compound object-glafs, will hurt the diftinctnefs much more, in proportion to the extreme divergency.

ON this account, it is to be expected, that the proportional lengths of the fpectrums, when the experiment comes to be properly made, will turn out lefs than as one to fix; notwithstanding the degree in which the diftinctnefs is hurt in the two kinds of telescopes, from the unequal refrangibility of light, may be nearly in that proportion.

THE principal improvment of refracting telescopes, pointed out by the preceding experiments, confifts in an entire removal of this aberration from the unequal refrangibility of light. It appears from the performance of the fmall telescope above mentioned, in which the fecondary colour is not removed, that confiderable advantages may alfo be expected from fubftituting a more perfect medium for flint-glafs; from a more perfect correction of the aberration from the fpherical figure; from preventing that lofs of light by reflection, which takes place when light enters into, or emerges from denfe mediums furrounded
with

with air ; and from diminishing those errors which arise from faults in the workmanship.

THE disadvantages under which reflecting telescopes labour, arise from their requiring larger apertures to transmit the same quantity of light ; from being found to be more affected by imperfections of the atmosphere than refracting telescopes, and being liable to tarnish ; but principally from imperfections in the workmanship of the object speculum hurting their performance much more than equal imperfections in the object-glass hurt refractors.

THE deviation of a ray from its intended course, occasioned by an imperfection in the figure of a reflecting speculum, is to its deviation, arising from an equal imperfection in a lens, as four to one, when the ray passes from glass into air, and in the proportion of six to one, when it passes from air into glass. At a medium, therefore, it may be stated as five to one. It follows from hence, that supposing all other causes of imperfection removed but this of workmanship, and that the metal of speculums were capable of as good a polish as glass, and of reflecting as much light as glass transmits, still the perfection of the images of objects formed by refraction would greatly exceed those by reflection.

SUCH is the case in the refractions which take place in the confine of glass and air. But in the refractions made in the confine of glass, and mediums of greater density than air, the difference is still much greater.

THE proportion of the sine of the angle of incidence to the sine of the angle of refraction of a ray in passing out of one medium into another medium, is composed of the proportion of the sine of the angle of incidence to the sine of the angle of refraction out of the first medium into any third medium, and of the proportion of the sine of the angle of incidence to the sine of the angle of refraction, out of that third medium into the second medium.

THUS, if the sine of the angle of incidence of any ray, in passing out of glass into air, be to the sine of its angle of refraction as twenty to thirty-one, and the sine of the angle of incidence of the same ray, in passing from air into oil of turpentine, be to the sine of its angle of refraction as twenty-five to seventeen, the proportion of the sine of the angle of incidence of that ray, to the sine of its angle of refraction, in passing out of glass into oil of turpentine, will be as five hundred to five hundred and twenty-seven.

HENCE the point to which light is converged by the refraction of a spherical segment of glass, surrounded with oil of turpentine, will be found to be above eighteen semi-diameters of the sphere from the apex of the lens, when light passes from oil of turpentine into glass, and seventeen semi-diameters of the sphere distant from the spherical segment, when light passes from glass into oil of turpentine; whereas in glass surrounded by air, the focal distance in these two cases is only two semi-diameters, and three semi-diameters; and when light is converged to a point by a concave reflecting speculum, the focal distance is only half a semi-diameter of the sphere to which the speculum is ground concave. Now, in all these cases, the errors of the rays arising from imperfections in the workmanship of object-glasses, or object-speculums, are as the focal distances to the radii of convexity; so that what Sir ISAAC NEWTON mentions, of his having nearly despaired of reflecting telescopes from this consideration, need not be wondered at.

THE great pains, however, which he took with his own hands, and the ingenious methods which he suggested, and which have been so ably prosecuted since his time, have gone farther than could be expected towards obviating this fundamental fault of reflectors. Whatever can be performed by reflection, may be expected from the long experience and indefatigable exertions of Dr HERSCHEL, aided by the countenance

nance and liberal support of the Royal Founder of our Society, the general Patron of Science.

I APPREHEND there is a cause which will render short telescopes always more distinct than long ones, where all other circumstances are, as nearly as possible, alike; and that it has operated in favour of reflecting telescopes. It is well known that gross bodies act on light at a distance. Some phenomena I have observed, appear to me to put it beyond doubt, that light also acts upon light, in such a way as to propagate this action of gross bodies much farther than is imagined. But I must delay entering farther on this subject; and shall only observe, that it was principally with an eye to this circumstance, that I endeavoured in my attempts to execute object-glasses on the above principles, to strain the increase of aperture to the utmost.

It will be understood, that when the aberrations from the difference of refrangibility of light, and from the spherical figures of lenses are removed, there remains no farther limit to shortening telescopes, excepting from the requisite depth of the spheres and thickness of the glasses.

I FIND that in small object-glasses of about nine inches focal length, the aperture may be increased as far as three inches, and hardly beyond this, on account of the quick increase of depth of the spherical surfaces, and thickness of the glass. From the difficulty found in procuring good glass of sufficient thickness, it may perhaps be better to make the aperture for common purposes less than this. I shall therefore state it at two inches. Hence the lengths necessary for increased apertures may readily be found, as the increase of length is in the same ratio as the increase of aperture, a double aperture requiring a double length, and so forth. These lengths and apertures may be compared with the lengths and apertures necessary in single lenses, and in different kinds of reflectors, by the common tables.

It appears from the preceding experiments, that in compound object-glasses of crown and flint-glass, there is only a partial correction of the aberration from unequal refrangibility, and therefore in them, and others of that kind, the apertures and magnifying powers must only be increased in a subduplicate ratio of the increase of length, as in single lenses.

I WILL not pretend to state with absolute certainty the precise aperture which an achromatic telescope of a given length ought to have. This must be determined by experience. If two inches be taken for the greatest aperture which ought to be given to a telescope of this kind two and thirty inches long, then three inches will be too much for one of forty-two inches, as hath been already observed. But whichever of these lengths and apertures be taken as the standard, it is certain, that if we would avoid a greater degree of that indistinctness which is occasioned by the aberration from difference of refrangibility, the aperture and magnifying power must not be increased in a greater proportion than the square root of the increased length. Besides, therefore, that this imperfect correction renders such telescopes incapable of bearing high magnifying powers for those of moderate lengths, large instruments, if they were to be attempted, would still be unmanageable, on account of their immoderate lengths. The focal length of an object-glass of this kind, four feet in diameter, would require to be upwards of fifteen hundred feet, in order to enable it to bear the magnifying power adapted to that aperture, with the same distinctness that is found in an object-glass two inches in diameter, and thirty two inches in focal length. But when the aberration from difference of refrangibility is totally removed, the focal length of an object-glass four feet in diameter, need not exceed twenty feet.

HAVING mentioned to some friends the imperfect correction of the aberration from difference of refrangibility, which is obtained by the common combination of two mediums which differ

differ in dispersive power, I was informed, that something of the same kind had been observed by some foreign philosophers, and in particular by the celebrated M. CLAIRAUT and M. BOSCOVICH.

THE observation of the former appears in a Memoir of the French Academy of Sciences, of so old a date as the year 1757. As the passage relating to this subject is short, and does great credit to the author, as an accurate observer of the results of experiments, I shall beg permission to transcribe it. “ Il y a encore un fait important que nos experiences nous ont appris, c’est que les corrections des iris faites par les prismes combinés, ne sont jamais aussi parfaites qu’on le croiroit d’après les termes de M. DOLLOND. Dans le cas du prisme de verre placé dans l’eau ; par exemple, après avoir fait varier les plaques qui déterminent l’angle du prisme d’eau, jusqu’au point où les objets vus à travers les deux prismes, ne paroissent point décolorés, du moins aux vues ordinaires, on trouve en plaçant ces prismes dans la chambre noire, qu’il reste toujours quelque petit limbe de couleur vers les bordes de l’image du soleil, ce qui vient sans doute de ce que les parties du spectre que chaque matiere réfringente donne, ne sont pas exactement proportionnelles aux longueurs totales de ces spectres. Mais ces inégalités qui diminuent à mesure que les angles des prismes sont plus petits, doivent être comme insensibles dans le cas des lentilles adossées, vu la petitesse des angles de réfringence qui ont lieu alors.” I shall only remark on this passage, that M. CLAIRAUT would have observed the uncorrected colour better, if he had made use of a much smaller pencil of light than he appears to have done, and would not have concluded so hastily, that this uncorrected aberration was of little consequence to the performance of telescopes, if he had recollected, that the smallness of the angles of the lenses is greatly overbalanced by the magnifying power of the eyeglasses.

M.

M. BOSCOVICH formed an hypothesis concerning a perfect correction of colour, by a combination of mediums, which appears to have greatly misled him. As a combination of two mediums is necessary to unite two of the unequally refrangible rays, he imagines three mediums necessary to unite three, four to unite four, and, in short, that to effect a perfect union of the rays of the spectrum, as many mediums are required as there are unequally refrangible rays composing it, that is to say, an indefinite number. He supposes, however, than an union of three of the rays only, by means of three mediums, would greatly improve telescopes. This author seems to have founded his hypothesis on the same kind of loose analogical reasoning, which had before led the celebrated EULER into a similar mistake.

THE eye is composed of three humours and several coats; and M. BOSCOVICH takes it for granted, that a more perfect union of the rays than what takes place in a combination of crown and flint glass, is effected by their means. But this is a supposition very remote from the truth indeed. So far is this secondary colour from being corrected in the human eye, that in the construction of this admirable organ, it hath been deemed unnecessary to introduce any contrivance for the correction of the Newtonian aberration. *Natura nihil agit frustra.* The perfection of the Contriver equally appears from a manifestation of his power, and of his œconomical exertion of that power. On account of the shortness of the focal distance of the humours of the eye, in proportion to the aperture of the pupil, the aberration from the spherical figure would be enormous; and we find it obviated by the very elaborate artifice of rendering the chrystalline humour more dense towards the centre. The aberration from difference of refrangibility might have been removed, by imparting a proper degree of disperfive power to the vitreous humour. But this, being unnecessary for the common purposes of life, is withheld.

Dr

Dr MASKELYNE has taken the pains to compute the quantity of this aberration in the eye, and is of opinion that it is not incompatible with distinct vision *. But as it has been just asserted as a matter of fact, that the aberration from difference of refrangibility is not corrected in the human eye, it will be expected that the proofs on which this assertion is founded, should be explained. These are so ample as to leave no cause of uncertainty ; nor are the necessary experiments attended with much trouble. For it happens that the humours are better placed for the purpose in the natural eye, than art could dispose them elsewhere.

WHEN I take the penknife which now lies before me, and hold it between me and the sky, at the distance to which the eye is conformed for distinct vision, the blade appears distinct, and well defined. If the eye be now accommodated to a more distant object, the blade of the knife begins to be surrounded with a penumbra ; and if this penumbra be carefully attended to, it appears to be coloured, and the colour next to the knife is red inclining to orange, which is the colour of the least refrangible rays.

If the eye be again accommodated to the distance necessary for seeing the knife distinctly, the bars of the window, which is at a greater distance than the knife, are surrounded with a penumbra, and the colour of this penumbra is blue, which is the prevailing colour of the most refrangible rays. The same appearances will be observed in all cases where the confine of a dark and luminous object is carefully examined, and will be so much the more conspicuous by how much the contrast of light and darkness is stronger. It requires, however, a capacity of viewing with attention an object to which the eye is not conformed, which must be acquired by habit. The following easy experiment may be tried by any one. Shutting one eye, observe with the other the four well defined black parallel

VOL. III.

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* Philosophical Transactions of London, Vol. lxxix. p. 256.

parallel lines which denote four o'clock in the enamelled dial-plate of a watch, and make the watch approach the eye very slowly. So long as the eye can conform itself to the distance, the black lines will appear distinct and of their proper colours. But when the watch, continuing to approach, is brought too near for the eye, by any effort, to see the lines distinctly, the coloured fringes will begin to make their appearance, and the spreading of the less refrangible rays into the black strokes, and the more refrangible rays into the white intervals, will make them appear to change their colours from black and white to orange and blue.

If any doubt should remain concerning the prismatic colour produced by the refraction of the humours of the eye, let the observer look at a bar of the window, where it is opposed to the sky, and holding his hand parallel with the bar, bring it slowly over his eye, he will observe, just before the bar disappears, one side of it edged with red inclining to orange, and the other with blue, and these colours in as great quantity as would be produced by a prism of a pretty considerable refracting angle. The application of these observations to what was before said of the fringes of colour produced by simple and compound lenses, is obvious. If the aberration from difference of refrangibility were perfectly corrected, no colour whatever would appear, either in the penumbras, or on covering part of the pupil. Had this been effected, it is probable that the vitreous humour would be found sufficiently dispersive to correct the colour produced by the aqueous and crystalline humours, and that the ratio in which it separated the rays which form the coloured spectrum, would be the same as in them. Such a colourless refraction might then be produced as has been found to arise from a combination of crown-glass with a fluid medium, containing a due proportion of metallic particles and particles of marine acid.

If

IF the coloured penumbras, instead of being red when the eye is conformed to a greater distance than that of the object observed, and blue when conformed to a less distance, had been purple in the former case, and green in the latter, it would be reasonable to conclude, that the vitreous humour was a dispersive medium of the same kind with essential oils, and such as owe this property to metalline particles with which they are impregnated.

BUT if the purple fringe had appeared round the object, when the eye is conformed to too small a distance for seeing it distinctly, and with a green fringe under the contrary circumstances, this would indicate a dispersive power in the vitreous humour, similar to that of the muriatic acid.

IN some animals, and particularly in birds of prey, the images of objects on the retina are required to be more perfect than in the human eye. It would be an object of some moment in comparative physiology, to determine whether there be any partial or total correction of aberration from the difference of refrangibility in the eyes of these animals, which, if found necessary, will without doubt be the case. In some experiments which I once attempted with the vitreous humour, I found irregularities arise in the refraction, from giving it a figure different from its natural one. Possibly such difficulties might be obviated by diluting the humours with some mild fluid of known optical properties.

THE aberration from unequal refrangibility not being corrected in the eye, is one cause why vision through a good telescope is more perfect, independent of magnifying power, than naked vision when most perfect; a fact which must appear so extraordinary, that it can scarcely be expected to be credited, except by those who have convinced themselves of it by experience.

IN order to explain this, it must be observed, that the ultimate effect required to be produced by a telescope or microscope,

is not a perfect union of the rays at the focus of the object-glass, but at the retina. This is to be effected by so disposing the rays at their emergence from the eye-glass, that the humours of the eye shall accurately converge each of the pencils to one point of the retina. If we conceive a point of the retina to become a radiant point whence the rays issue, the rays of different colours, at their emergence from the cornea, will be inclined to each other in a certain degree, on account of their unequal refrangibility, and will continue to diverge, till they arrive, we shall suppose, at the eye-glass. Now, this is exactly the state in which rays emerging from the eye-glass, and tending towards the eye, ought to be, in order to insure their perfect union at that point of the retina from which the above mentioned rays were supposed to radiate.

ANOTHER cause which operates in favour of telescopic vision, is the smallness of the pencil where it enters the eye. When the diameter of the pencil is equal to that of the pupil, the rays, in passing the edge of the iris, are inflected, that is to say, they are made to deviate from their rectilineal course, some of them being bent towards the iris, and others from it, and thus throw a scattered light round the image on the retina. The radiation of the bright fixed stars proceeds partly from this cause. This source of indistinctness is totally removed in a telescope, where the diameter of the pencil, at its entrance into the eye, is so much less than the pupil, that none of the rays pass near enough the iris to suffer any inflection. The size of the pencil must not, however, be diminished too far; for if this is done beyond a certain degree, the distinctness will be quite destroyed, as was first observed by HUGENIUS.

I SHALL now recapitulate, and present in one view, the contents and scope of this discourse.

THE unequal refrangibility of light, as discovered and fully explained by Sir ISAAC NEWTON, so far stands its ground uncontroverted,

controverted, that when the refraction is made in the confine of any medium whatever, and a vacuum, the rays of different colours are unequally refracted, the red-making rays being the least refrangible, and the violet-making rays the most refrangible.

THE discovery of what has been called a different disperseive power in different refractive mediums, proves those theorems of Sir ISAAC NEWTON not to be universal, in which he concludes that the difference of refraction of the most and least refrangible rays, is always in a given proportion to the refraction of the mean refrangible ray. There can be no doubt that this position is true with respect to the mediums on which he made his experiments ; but there are many exceptions to it.

FOR the experiments of Mr DOLLOND prove, that the difference of refraction between the red and violet rays, in proportion to the refraction of the whole pencil, is greater in some kinds of glass than in water, and greater in flint-glass than in crown-glass.

THE first set of experiments above recited, prove, that the quality of dispersing the rays in a greater degree than crown-glass, is not confined to a few mediums, but is possessed by a great variety of fluids, and by some of these in a most extraordinary degree. Solutions of metals, essential oils, and mineral acids, with the exception of the vitriolic, are most remarkable in this respect.

SOME consequences of the combinations of mediums of different disperseive powers, which have not been sufficiently attended to, are then explained. Although the greater refrangibility of the violet rays than of the red rays, when light passes from any medium whatever into a vacuum, may be considered as a law of nature ; yet in the passage of light from one medium into another, it depends entirely on the qualities of the mediums, which of these rays shall be the most refrangible, or whether there shall be any difference in their refrangibility.

THE

THE application of the demonstrations of HUGENIUS to the correction of the aberration from the spherical figures of lenses, whether solid or fluid, is then taken notice of, as being the next step towards perfecting the theory of telescopes.

NEXT it appears from trials made with object-glasses of very large apertures, in which both aberrations are corrected as far as the principles will admit, that the correction of colour which is obtained by the common combination of two mediums which differ in dispersive power, is not complete. The homogeneous green rays emerge most refracted, next to these the united blue and yellow, then the indigo and orange united, and lastly the united violet and red, which are least refracted.

IF this production of colour were constant, and the length of the secondary spectrum were the same in all combinations of mediums when the whole refraction of the pencil is equal, the perfect correction of the aberration from difference of refrangibility would be impossible, and would remain an insurmountable obstacle to the improvement of dioptrical instruments.

THE object of the next experiments is, therefore, to search, whether nature affords mediums which differ in the degree in which they disperse the rays composing the prismatic spectrum, and at the same time separate the several orders of rays in the same proportion. For if such could be found, the above mentioned secondary spectrum would vanish, and the aberration from difference of refrangibility might be removed. The result of this investigation was unsuccessful with respect to its principal object. In every combination that was tried, the same kind of uncorrected colour was observed, and it was thence concluded, that there was no direct method of removing the aberration.

BUT it appeared in the course of the experiments, that the breadth of the secondary spectrum was less in some combinations than in others, and thence an indirect way opened, leading to the correction sought after; namely, by forming a compound

pound concave lens of the materials which produce most colour, and combining it with a compound convex lens formed of the materials which produce least colour ; and it was observed in what manner this might be effected by means of three mediums, though apparently four are required.

IN searching for mediums best adapted for the above purpose, a very singular and important quality was detected in the muriatic acid. In all the disperse mediums hitherto examined, the green rays, which are the mean refrangible in crown-glass, were found among the less refrangible, and thence occasion the uncorrected colour which has been described. In the muriatic acid, on the contrary, these same rays make a part of the more refrangible ; and in consequence of this, the order of the colours in the secondary spectrum, formed by a combination of crown-glass with this fluid, is inverted, the homogeneous green being now the least refrangible, and the united red and violet the most refrangible.

THIS remarkable quality found in the marine acid led to complete success in removing the great defect of optical instruments, that dissipation or aberration of the rays, arising from their unequal refrangibility, which has rendered it impossible hitherto to converge all of them to one point, either by single or opposite refractions. A fluid in which the particles of marine acid and metalline particles hold a due proportion, at the same time that it separates the extreme rays of the spectrum much more than crown-glass, refracts all the orders of rays exactly in the same proportion as the glass does ; and hence rays of all colours, made to diverge by the refraction of the glass, may either be rendered parallel by a subsequent refraction made in the confine of the glass and this fluid, or by weakening the refractive density of the fluid, the refraction which takes place in the confine of it and glass, may be rendered as regular as reflection, while the errors arising from unavoidable imperfections of workmanship, are far less hurtful than in reflection,
and

and the quantity of light transmitted by equal apertures of the telescopes much greater.

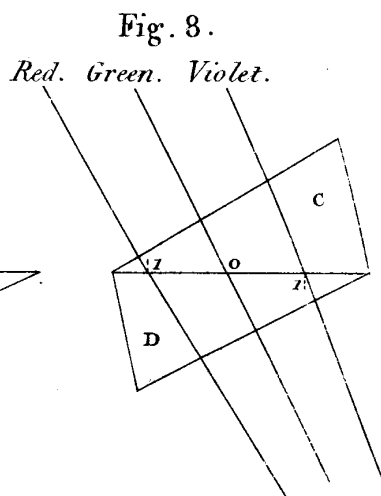
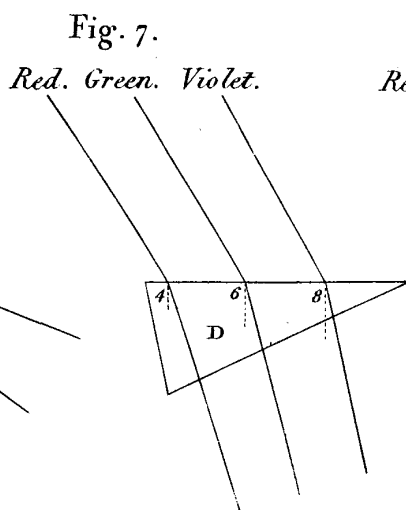
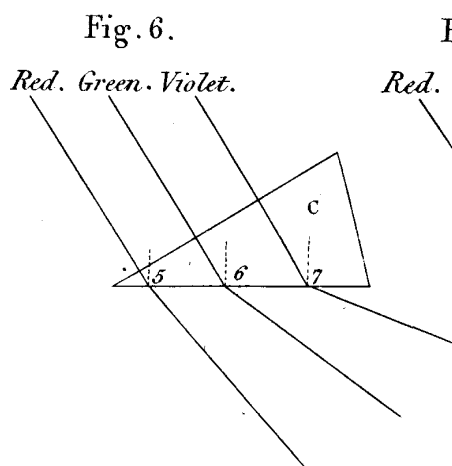
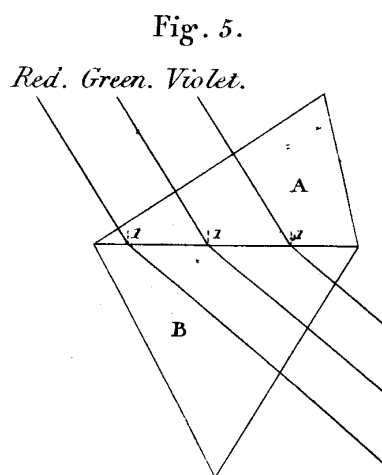
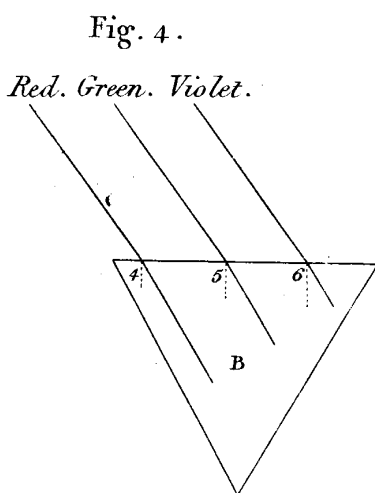
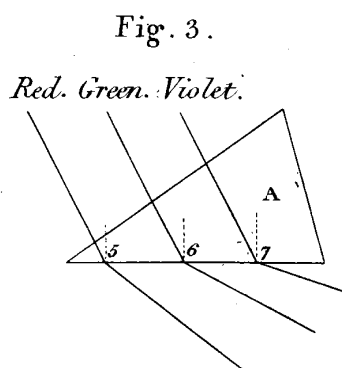
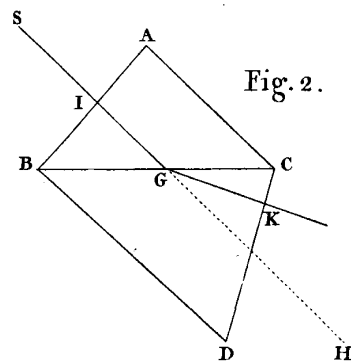
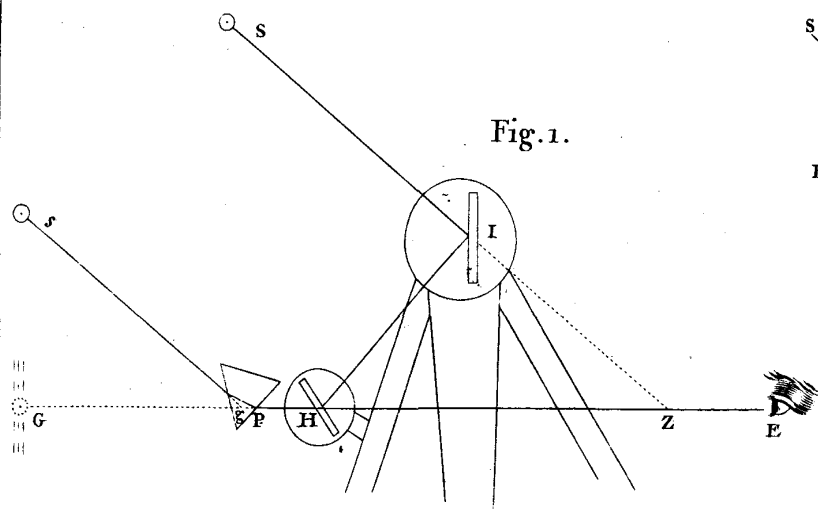
SUCH are the advantages which the theory presents. In reducing this theory to practice, difficulties must be expected in the first attempts. Many of these it was necessary to surmount before the experiments could be completed. For the delicacy of the observations is such, as to require a considerable degree of perfection in the execution of the object-glasses, in order to admit of the phenomena being rendered more apparent by means of high magnifying powers. Great pains seem to have been taken by mathematicians to little purpose in calculating the radii of the spheres requisite for achromatic telescopes, from their not considering that the object-glass itself is a much nicer test of the optical properties of refracting mediums than the gross experiments made by prisms, and that the results of their demonstrations cannot exceed the accuracy of the data, however much they may fall short of it.

I SHALL conclude this paper, which has now greatly exceeded its intended bounds, by enumerating the several cases of unequal refrangibility of light, that their varieties may at once be clearly apprehended.

IN the refraction which takes place in the confine of every known medium and a vacuum, rays of different colours are unequally refrangible, and the red-making rays are least refrangible, and the violet-making rays are most refrangible.

THIS difference of refrangibility of the red and violet rays is not the same in all mediums. Those mediums in which the difference is greatest, and which, by consequence, separate or disperse the rays of different colours most, have been distinguished by the term *dispersive*, and those mediums which separate the rays least have been called *indispersive*. Dispersive mediums differ from indispersive, and still more from each other, in another very essential circumstance.

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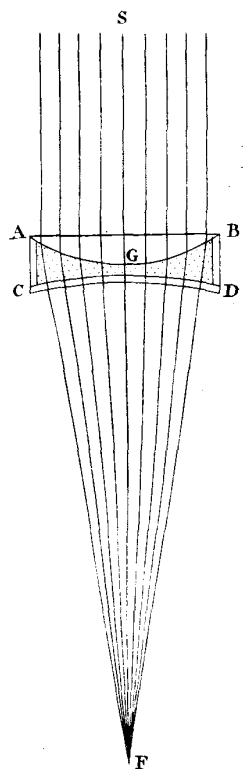


Fig. 9.

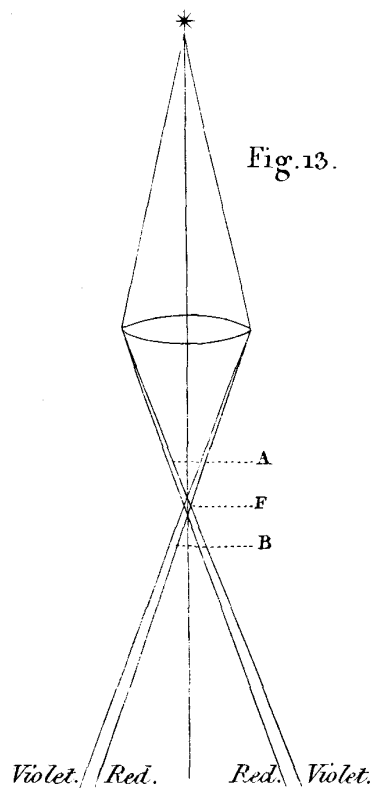


Fig. 13.

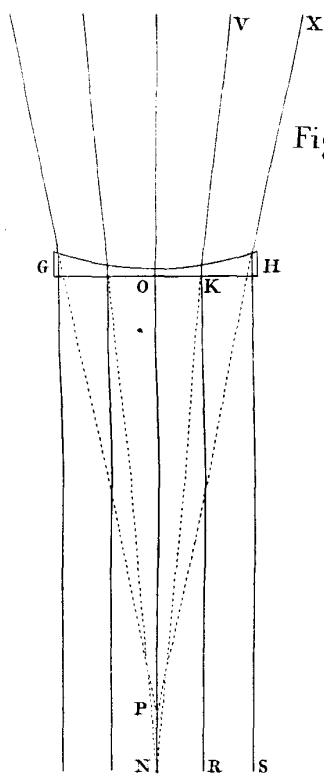


Fig. 11.

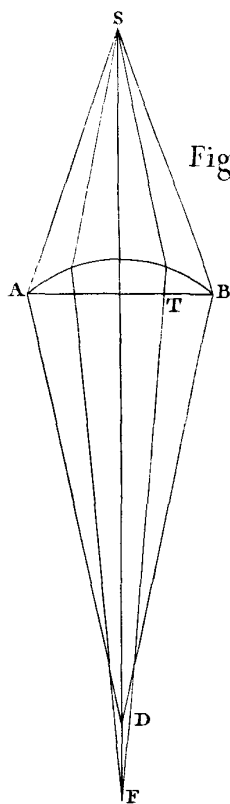


Fig. 10.

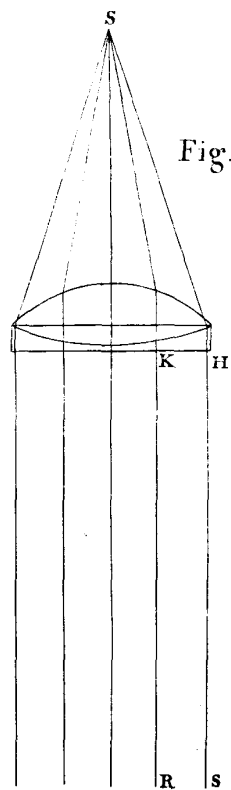


Fig. 12.

Fig. 20.

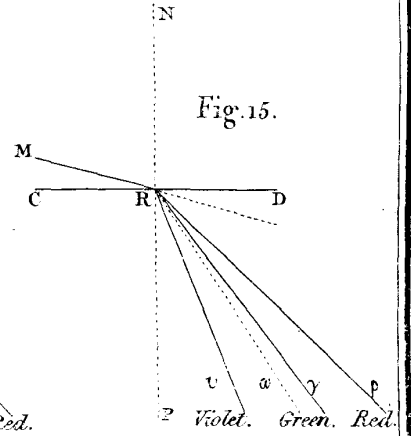
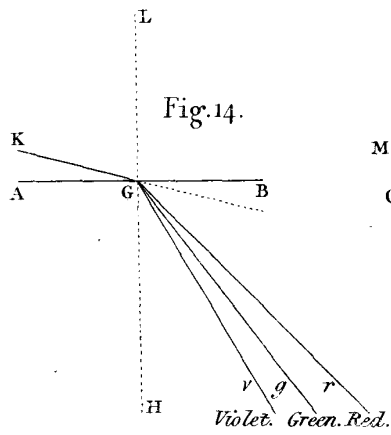
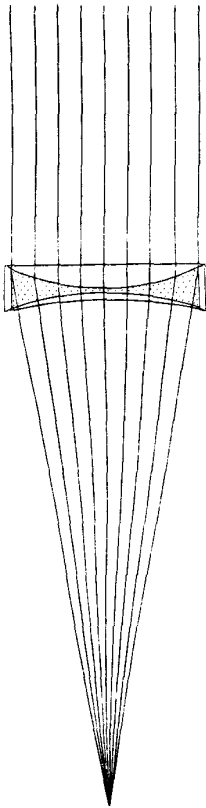


Fig. 16.



Red and Violet united.
Green.

Fig. 17.

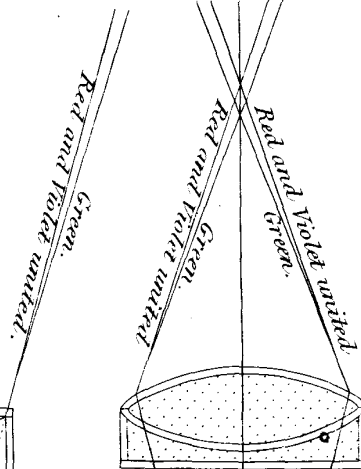
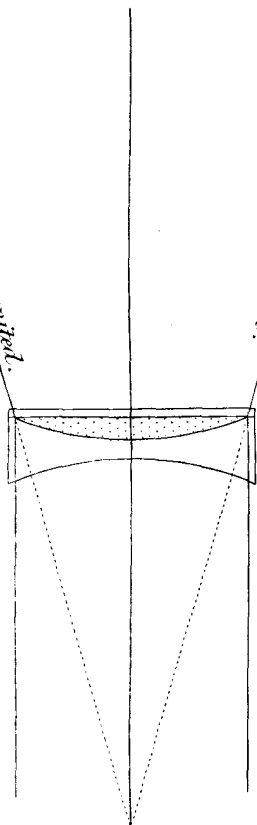


Fig. 18.

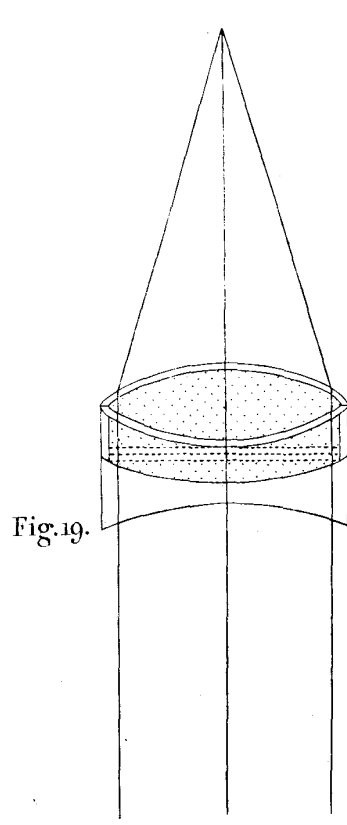


Fig. 19.

It appears from the experiments which have been made on indispersive mediums, that the mean refrangible light is always the same, and of a green colour.

Now, in by far the largest class of dispersive mediums, including flint-glass, metallic solutions, essential oils, the green light is not the mean refrangible order, but forms one of the less refrangible orders of light, being found in the prismatic spectrum nearer to the deep red than the extreme violet.

In another class of dispersive mediums, which includes the muriatic and nitrous acids, this same green light becomes one of the more refrangible orders, being now found nearer to the extreme violet than the deep red.

THESE are the varieties in the refrangibility of light, when the refraction takes place in the confine of a vacuum; and the phenomena will scarce differ sensibly in refractions made in the confine of dense mediums and air.

BUT when light passes from one dense medium into another, the cases of unequal refrangibility are more complicated.

IN refractions made in the confine of mediums which differ only in strength, not in quality, as in the confine of water and crown-glass, or in the confine of the different kinds of dispersive fluids more or less diluted, the difference of refrangibility will be the same as above stated in the confine of dense mediums and air, only the whole refraction will be less.

IN the confine of an indispersive medium, and a rarer medium belonging to either class of the dispersive, the red and violet rays may be rendered equally refrangible. If the dispersive power of the rare medium be then increased, the violet rays will become the least refrangible, and the red rays the most refrangible. If the mean refractive density of the two mediums be rendered equal, the red and violet rays will be refracted in opposite directions, the one towards, the other from the perpendicular.

THUS it happens to the red and violet rays, whichever class of disperseive mediums be employed. But the refrangibility of the intermediate orders of rays, and especially of the green rays, will be different when the class of disperseive mediums is changed.

THUS in the first case, where the red and violet rays are rendered equally refrangible, the green rays will emerge most refrangible, if the first class of disperseive mediums is used, and least refrangible if the second class is used. And in the other two cases, where the violet become least refrangible, and the red most refrangible, and where these two kinds of rays are refracted in opposite directions, the green rays will join the red, if the first class of disperseive mediums be employed, and will arrange themselves with the violet, if the second class be made use of.

ONLY one case more of unequal refrangibility remains to be stated; and that is, when light is refracted in the confine of mediums belonging to the two different classes of disperseive fluids. In its transition, for example, from an essential oil, or a metallic solution, into the muriatic acid, the refractive density of these fluids may be so adjusted, that the red and violet rays shall suffer no refraction in passing from the one into the other, how oblique soever their incidence be. But the green rays will then suffer a considerable refraction, and this refraction will be from the perpendicular, when light passes from the muriatic acid into the essential oil, and towards the perpendicular, when it passes from the essential oil into the muriatic acid. The other orders of rays will suffer similar refractions, which will be greatest in those adjoining the green, and will diminish as they approach the deep red on the one hand, and the extreme violet on the other, where the refraction ceases entirely.

THE manner of the production of these effects, by the attraction of the several mediums, may be thus explained.

WE

WE shall suppose the attractive forces, which produce the refractions of the red, green and violet light, to be represented by the numbers eight, twelve and sixteen, in glass; six, nine, fourteen, in the metallic solution; six, eleven, fourteen, in the muriatic acid; and six, ten, fourteen, in a mixture of these two fluids. The excess of attraction of glass for the red and violet light is equal to two, whichever of the three fluids be employed. The refraction of these two orders of rays will therefore be the same in all the three cases. But the excess of attraction for the green light is equal to three, when the metallic solution is used, and therefore the green light will be more refracted than the red and violet, in this case. When the muriatic acid is used, the excess of attraction of glass for the green light is only one, and therefore the green light will now be less refracted than the red and violet. We shall next suppose the metallic solution and the acid to adjoin each other. The attractions of both these mediums, for the red light being six, and for the violet light fourteen, these two orders of rays will suffer no refraction in the confine of the two fluids, the difference of their attractions being equal to nothing.

BUT the attractive force of the metallic solution for the green ray being only nine, and that of the muriatic acid for the same ray being eleven, the green light will be attracted towards the muriatic acid with the force two; and therefore the difference between the refraction of the green light and the unrefracted red and violet light which takes place in the confine of these fluids, will greatly exceed the difference of refraction of the green light, and equally refracted red and violet light, which is produced in the confine of glass and either of the fluids.

LASTLY, in a mixture of the two kinds of fluids, the attraction for the red, green and violet rays, being six, ten and fourteen, and that of the glass, eight, twelve and sixteen, the excess of the attraction of the glass for the green rays, is the same

which it is for the red and violet rays. These three orders of rays will therefore suffer an equal refraction, being each of them attracted towards the glass with the force two; and when this is the case, it appears from the observations, that the indefinite variety of rays of intermediate colours and shades of colours, which altogether compose solar light, will also be regularly bent from their rectilinear course, constituting what has been termed *aplanatic refraction*.

THESE cases of attraction might be farther illustrated by means of diagrams. But after the explanation already given of the second, third, fourth, fifth, sixth, seventh and eighth figures, this would be unnecessary. And it need scarcely here be observed, that the above rough statements in round numbers, are intended to give a clear idea of the nature of the various cases of unequal refrangibility, and not to ascertain its quantity in any particular case. A full investigation of the subject, and an account of some digressions less immediately connected with the principal object which occurred in the course of the enquiry, could not be brought within the compass of the present communication.