X. *Experiments and Observations on the Inflection, Reflection, and Colours of Light. By* Henry Brougham *Jun. Esq. Communicated by Sir* Charles Blagden, *Knt. Sec. R. S.*

Read January 28, 1796.

It has always appeared wonderful to me, since nature seems to delight in those close analogies which enable her to preserve simplicity and even uniformity in variety, that there should be no dispositions in the parts of light, with respect to inflection and reflection, analogous or similar to their different refrangibility. In order to ascertain the existence of such properties, I began a course of experiments and observations, a short account of which forms the substance of this paper. For the sake of perspicuity I shall begin with the analytical branch of the subject, comprehending my observations under two parts: *flexion*, or the bending of the rays in their passage by bodies, and *reflection*. And I shall conclude by applying the principles there established to the explanation of phænomena, in the way of synthesis.

As in every experimental inquiry much depends on the attention paid to the minutest circumstances, in justice to myself I ought to mention, that each experiment was set down as particularly as possible immediately after it was made; that they were all repeated every favourable day for nearly a year, and before various persons; and as any thing like a preconceived opinion, with respect to matter of theory that is in dispute, will, it is more than probable, influence us in the manner of drawing our conclusions, and even in the manner of recording the experiments that lead to these, I have endeavoured as much as possible to keep in view the saying of the Brahmin: "that he who obstinately adheres to any set of opinions, may "bring himself at last to believe that the fresh *sandal wood* is "a flame of fire."*

PART I. *Of Flexion.*

In order to fix our ideas on a subject which has never been treated of with mathematical precision, we shall suppose, for the present, that all the parts of light are equally acted upon in their passage by bodies; and deduce several of the most important propositions which occur, without mentioning the demonstrations.

Def. 1. If a ray passes within a certain distance of any body, it is bent inwards; this we shall call Inflection. 2. If it passes at a still greater distance it is turned away; this may be termed Deflection. 3. The angle of inflection is that which the inflected ray makes with the line drawn parallel to the edge of the inflecting body, and the angle of incidence is that made by the ray before inflection, at the point where it meets the parallel. And so of the angle of deflection.

Proposition I. The force by which bodies inflect and deflect the rays acts in lines perpendicular to their surfaces.

Prop. II. The sines of inflection and deflection are each of them to the sine of incidence in a given ratio; (and what this ratio is we shall afterwards shew).

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* Asiatic Researches, Vol. I. p. 224.

Prop. III. The bending force is to the propelling force of light, as the sine of the difference between the angles of inflection (or deflection) and incidence, to the cosine of the angle of inflection (or deflection).

Prop. IV. The rays of light may be made to revolve round a centre in a spiral orbit.

Prop. V. If the inflecting surface be of considerable extent, and a plane, then the curve described may be found by help of the 41. Prop. Book I. *Principia;* provided only, the proportion of the force to the distance be given. Thus, if the bending force be inversely as the distance, the curve cannot be found; for in order to obtain its equation, a curvilinear area must be squared, which in this case is a conic hyberbola; the relation, however, between its ordinates and abscissæ may be obtained in fluxions, thus; $y\dot{y} + by = a^2\dot{x}^2$.

If the force (which is most probable) be inversely as the square of the distance, the curve to be squared is the cubic hyperbola; Species LXV. genus III. of NEWTON's Enumeration; and this being quadrable, the curve described by the light will be the *parabola campaniformis pura;* Species LXIX. of NEWTON.

If the force be inversely as the cube of the distance, the curve is a circular arch, and that of deflection is a conic hyperbola.* If the inflecting body be a globe or cylinder, and the force be inversely as the square of the distance from the surface, then by Prop. 71. Book I. *Principia,* the attraction to the centre is inversely as the square of the distance from that centre; and therefore, by Prop. 11. and 13. of the same book, the ray moves in an ellipse by the inflecting, and an hyperbola

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* *Principia,* Lib. I. Prop. 8.

by the deflecting force, each having one focus in the centre of the body. The truth of these things mathematicians will easily determine.

Prop. VI. If a ray fall on a specular surface, it will be bent before incidence into a curve, having two points of contrary flexure, and then will be bent back the contrary way into an equal and similar curve; as in fig. 1. (Tab. VII.)

Corollary to these propositions. If a pencil of rays fall *converging* on an interposed body, the shadow will be less than the body by twice the sine of inflection.

And if a pencil fall *diverging* on the body, the shadow will be greater than the body by twice the sine of inflection; but less than it should be, if the rays had passed without bending, by twice the sine of the difference between the angles of inflection and incidence.—The sine or angle of incidence is greater than the sine or angle of inflection, when the incident rays make an acute angle with the body; but when they make an obtuse or right angle, then the sine or angle of inflection is less than that of incidence. The sine of incidence is greater than that of deflection, if the angle made by the incident ray with the body is obtuse, but less, if that angle be acute or right.—If a globe or circle be held in a beam of light the rays may be made to converge to a focus.

Hitherto it has been supposed, that the parts of which light consists have all the same disposition to be acted upon by bodies which inflect and deflect them; but we shall now see that this is by no means the case.

Obs. 1. Into my darkened chamber I let a beam of the sun's light, through a hole in a metal plate (fixed in the window-shut) of $\frac{1}{40}$th of an inch diameter; and all other light being absorbed by black cloth hung before the window, and in the room, at the hole I placed a prism of glass, whose refracting angle was 45 degrees, and which was covered all over with black paper, except a small part on each side, which was free from impurities, and through which the light was refracted, so as to form a distinct and tolerably homogeneous spectrum on a chart at six feet from the window. In the rays, at two feet from the prism, I placed a black unpolished pin (whose diameter was every where one-tenth of an inch) parallel to the chart, and in a vertical position. Its shadow was formed in the spectrum on the chart, and had a considerable penumbra, especially in the brightest red, for it was by no means of the same thickness in all its parts; that in violet was broadest and most distinct; that in the red narrowest and most confused, and that in the intermediate colours was of an intermediate thickness and degree of distinctness. It was not bounded by straight, but by curvilinear sides, convex towards the axis to which they approached as to an asymptote, and that, nearest in the least refrangible rays, as is represented in fig. 2. where AB is the axis, IKLMNA and HGFEDA the two outlines. Nor could this be owing to any irregularity in the pin, for the same thing happened in all sorts of bodies that were used; and also if the prism was moved on its axis, so that the colours might ascend and descend on these bodies, still wherever the red fell it made the least, and the violet the greatest shadow.

Obs. 2. In the place of the pin, I fixed a screen, having in it a large hole on which was a brass plate, pierced with a small hole $\frac{1}{42}$ of an inch in diameter; then causing an assistant to move the prism slowly on its axis, I observed the round image made by the different rays passing through the hole to the chart; that made by the red was greatest, by the violet, least, and by the intermediate rays, of an intermediate size. Also when at the back of the hole I held a sharp blade of a knife, so as to produce the fringes mentioned by GRIMALDO and NEWTON; those fringes in the red were broadest, and most moved inwards to the shadow, and most dilated when the knife was moved over the hole; and the hole itself on the chart was more dilated during the motion when illuminated by the red than when illuminated by any other of the rays, and least of all when illuminated by the violet. Now in Obs. 1. the angle of incidence of the red rays was equal to that of the violet and all the rest, and yet the angle of inflection was greatest, and least in the violet; and indeed the difference between the two was greater than appears at first from the experiment; for that part of the shadow which was formed by the violet fell at a greater distance from the point of incidence, than did that part which was formed by the red, from the divergency of the different rays upwards by the refraction, as appears in fig. 3. where DE is the window, FG the beam propagated through the hole F, refracted by the prism KIH, and painting on the chart OP *qs;* the spectrum *vr* being separated into L*r* the red rays incident on the pin CD at C, and M*v* the violet incident at D; the shadow of DC being formed in *vr*, so that *v* being farther from D than *r* is from C, therefore (by the propositions formerly laid down) the shadow in *v* should be considerably less than that in *r*, if the rays were equally inflected. Lastly, in Obs. 2. the angle of the red's incidence was nearly equal to that of the violet's, by the motion of the prism, and the consequent motion of the colours; only that, if there was any difference, it was on the side of the violet;

and yet the violet was least inflected, and the red most inflected; and so of the second inflection by the knife blade: wherefore I conclude that the rays of the sun's light differ in degree of inflexibility, and that those which are *least refrangible* are *most inflexible.*

Obs. 3. My room being darkened as before, and a conical beam propagated through the small hole in the window-shut; at this hole I placed a hollow prism, made of broken plates of mirror, and of such an angle, that when filled with distilled water, it cast a spectrum on an horizontal table, and was there received on a chart seven feet from the window. I then placed on the same table, and in the rays between the chart and the prism, at three inches from the chart, two sharp knife-blades with even edges, and fixed to a board with wax, so as to make an angle with one another; moving them nearer and nearer, till I saw the fringes appear in the red light on the chart, and then in the orange and other colours successively. I then withdrew one, and the fringes became faint and narrow, and not all within the shadow of the remaining knife, but at its edge, and even in the light of the spectrum. Lastly, when I slowly approached the other, they moved into the shadow, and became broader, and farther separated one from another, there being the like fringes in both shadows; this I repeated in all the rays, and plainly saw that at the approach of the knife, the fringes became broader, and farther removed from one another, and from the light, in the red than in the violet, or any of the other rays.

Obs. 4. In repeating the foregoing experiment, I observed a very curious phænomenon. When the angle of the knife-blades was so held in any of the rays as to make the hyperbolic fringes described by NEWTON,* and these being always of the colour in which they were held, moving the angle a little, so as to make the fringes out of the light that went to the top of any one division of the spectrum and also out of that which went near the bottom of the next, the fringes were made of two colours; one part was of the highest colour, and the other of the lowest, but *both* were on the ground of the highest. Thus if held on the confine of the green and blue, the upper half of each fringe was blue, the under green, but both parts in the blue division of the spectrum; and trying the same in all the rays, it was evident that the red was moved farther into the orange, and the orange into the yellow, than the blue was into the indigo, or the indigo into the violet. Now, in Obs. 3. the fringes were formed by the *inflection* of one knife, and were moved into its shadow, and separated and dilated by the *deflection* of the other; and this most in the red and least in the violet: likewise in Obs. 4. the fringes of one colour were deflected into the region of the next, and this most in the red, and least in the violet; although in both observations the violet, from the position of the chart, was farthest from the angle, and consequently had the rays been equally deflected, the violet should have been farthest moved, and most dilated by the deflection; but seeing that at equal angles of incidence in the third, and at less in the fourth observation, the red was most and the violet less deflected, it is evident that the most *inflexible* rays are also most *deflexible*.

Having thus found that the parts of light differ in *flexibility*, I wished next to learn two things; in what proportion the angle of *inflection* is to that of *deflection* at equal incidences;

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* Optics, Book III. Obs. 8.

and secondly, what proportion the different *flexibilities* of the different rays bear to one another. But the nature of the coloured fringes must first be understood, so that I defer this inquiry till after I have made use of the principles now laid down, for the explanation of natural phænomena, and proceed in the mean time to

PART II. *Of Reflection.*

That bodies reflect light by a repulsive power, extending to some distance from their surfaces, has never been denied since the time of Sir ISAAC NEWTON.* Now this power extends to a distance much greater than that of apparent contact, at which an attraction again begins, still at a distance, though less than that at which before there was a repulsion; as will appear by the following demonstration which occurs to me, and which is general with respect to the theory of BOSCOVICH.† In fig. 4. let the body A have for P an attraction, which, at the distance of AP, is proportional to PM; then let P move towards A so as to come to the situation P′, and let the attraction here be P′M′; as it is continual during the motion of P to P′, MM′ is a curve line. Now in the case of the attraction of bodies for light, and for one another, PM is less than P′M′, and consequently MM′ does not ever return into itself, and therefore it must go, *ad infinitum*, having its arc between AB and AC, to which it approaches as asymptotes; the abscissa always representing the distance, and the ordinate the attraction at that distance: let P′ now continue its motion to P″, and M′ will move to M″, and if P″ meets A, or the

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* Optics, Book II. Part III. prop. 8.

† *Nova Theoria Philosophiæ Naturalis.*

bodies come into perfect contact, P″ M″, will be infinite; so that the attraction being changed into cohesion, will be infinite, and the bodies inseparable, contrary to universal experience; so that P can never come nearer to A than a given distance. In the case of gravity, PM is inversely as the square of AP, so that the curve NMM‴ is the cubic hyperbola; but the demonstration holds, whatever be the proportion of the force to the distance. It appears then that flexion, refraction, and reflection, are performed by a force acting at a definite distance; and it is reasonable to think even *a priori*, that as this same force, in other circumstances, is exerted to a different degree on the different parts of light, in refracting, inflecting, and deflecting them, it should also be exercised with the like variations in reflecting them. Let us attend to the proof, which enables us to change conjecture into conviction.

Obs. 1. The sun shining into my darkened chamber through a small hole $\frac{1}{40}$th of an inch in diameter, I placed a pin of $\frac{1}{30}$th of an inch diameter in the cone of light (one-half inch from the hole) inclined to the rays at an angle of about 45°, and its shadow was received on a chart parallel to it, at the distance of two feet. The shadow was surrounded by the three fringes on each side, discovered by GRIMALDO; beyond these there were two streaks of white light diverging from the shadow, and mottled with bright colours, very irregularly scattered up and down; but on using another pin, whose surface was well polished, and placing it nearer the hole than before, the colours in the streaks became much brighter (and the streaks themselves narrower), being extended from one side to the other, so that, except in a very few points here and there, no white was now to be seen; and on moving the pin, the colours moved also. But they disappeared if the pin was deprived of its polish, by being held in the flame of a candle, or if a roll of paper was used instead of the pin; also, they were much brighter in direct than in reflected light, and in the light of the sun at the focus of a lens, than in his direct unrefracted light. Placing a piece of paper round the hole in the window-shut, I observed the colours continued there; and inclining the chart to the point where they left off, I saw them continued on it, and then proceed as before to the shadow. If the pin was held horizontally, or nearly so, they were seen of a great size on the floor, the walls, and roof of the room, forming a large circle; and if the chart was laid horizontally, and the pin held between the hole and it, in a vertical position, the circle was seen on the chart, and became an oval, by inclining the pin a little to the horizon.

Obs. 2. Having produced a clear set of colours, as in the last observation, I viewed them as attentively as possible, and found that they were divided into sets, sometimes separated by a gleam of white light, sometimes by a line of shadow, and sometimes contiguous, or even running a little into one another. They were spectra, or images of the sun, for they varied with the luminous body by whose rays they were formed, and with the size of the beam in which the pin was held; and when, by placing it between my eye and the candle, a little to one side, I let the colours fall on my retina, I plainly saw that they resembled the candle, in shape and size (though a little distended), and also in motion, since if the flame was blown upon, they had the like agitation. The colours therefore which fell on the chart were images of the sun; they had parallel sides pretty distinctly defined, but the ends were confused and semicircular, like those of the prismatic spectrum. Like it too, they were oblong, and in some the length exceeded the breadth six, even eight times; the breadth was, as I found by measurement, exactly equal to that of the sun's image received on a chart, as far from the pin as the image was, and the length was always to the breadth at all distances, in the same ratio, but not in all positions of the pin; for if it was moved on its axis, the images moved towards the shadow on one side, and from it on the other, becoming longer and longer (the breadth remaining the same) the nearer they came to the shadow on the one side, and shorter in the same proportion, the farther they went from it on the other.

Obs. 3. Having picked out an image that appeared very bright and well defined, I let it through a hole with moveable sides, in the upper part of a sort of desk, which moved to any opening by hinges, and had a chart for its under side, on which the image fell, and I shut the hole so close as to prevent any of the others from coming through; I then had a full opportunity of examining it, in all respects, and I counted in it distinctly the seven prismatic colours; the red was farthest from the shadow of the pin, and from the pin itself; then the orange; then the yellow, green, blue, and indigo, and the violet nearest of all; in short, it was exactly similar to a prismatic spectrum, much diminished in length and breadth, and turned horizontally on the wall opposite to the prism, with the red farthest away. In fig. 5. *se* is the pin, reflecting the rays CP and CO, which pass through PO, the hole in the desk ED, to the chart or bottom of the desk RTSD, and form there the spectrum IK divided into its colours, I being violet, and K red. On moving the hole in the desk, and letting through other images, the colours were not in all arranged the same way, but I moved the pin on its axis, and observed those where the order was inverted to move, not only with respect to the pin, but also with respect to the contiguous images; and I was surprised to see them assume the order of colours first mentioned, namely, the red outermost, and the violet innermost. In like manner the images, which before the motion were regular, on moving into the places left by the others had always the order of their colours inverted, so that the thing must be owing to some irregularities in the pin's surface; for those which were made by a small glass tube filled with quicksilver, and freed from scratches by a blow-pipe, preserved during the motion the proper order of colours. Another irregularity in the arrangement was also observable even in the glass tube; for two contiguous images, by mixing one with another for two or three successions, appeared each to have outermost a dull colour, between red and violet, and innermost a green; but here, unless the succession continued through all the images, the outermost of all was red, and the innermost image had universally violet in the inside.

Obs. 4. I placed at a hole in the window-shut a prism, to refract the rays, and received the spectrum at the distance of six feet from the window, on a chart; then, at the distance of two feet, I placed a screen with a hole in the middle of it, through which I let pass successively the different rays. At the distance of one inch from the hole, between it and the chart, I placed the reflecting cylindrical body; the images were found on the chart and walls of the room round to the sides of the hole on the screen, and were always wholly of the colour in which they were formed, except in the confines of the green, where a small quantity of white light fell, and made them of all the seven colours; but this was almost wholly prevented by using a prism with a greater refracting angle, and holding the pin and screen farther from it. I then removed the screen, and left the reflector in its place, so as it might reach through the rays; and thus there were formed images, having in them, from top to bottom, the seven colours, one after another, the lowest division being red, the highest violet. They were inclined considerably towards their tops, and were much broader at the bottom or red parts than at the tops or violet parts. And lastly, the reflector being moved so that the images might be disturbed (as in the former experiment made in the white light), the red was most, the violet least dilated. In case these effects might be owing to any peculiarities in the shape or position of the reflector, I placed at three feet from the prism a lens of four inches breadth, to collect the rays to a focus, six feet beyond which I held a chart, and there received the spectrum inverted, the red being uppermost, and the violet undermost; holding the reflector at two feet from the focus, and four from the chart, the images were formed just as before, only inverted, inclining towards the violet, of greater breadth towards the red, and more distended towards the same quarter when the reflector was moved.

Obs. 5. Things remaining as in the last part of the last experiment, at the focus of the lens I placed a second prism, which refracted the rays into a white beam,* and this I

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* Optics, Book II. Part II. Prop. 2.

received on a screen with a hole in the middle, through which a small part of it passed, and falling on the reflector placed behind, was formed by it into images, after the manner of the first experiment, each having in regular order the seven prismatic colours. One of the brightest and most distinct I let pass through a hole in a second screen, and it fell on the chart. I then caused an assistant to intercept the red rays between the first prism and the lens, and immediately the red part of the image vanished; and when the violet was intercepted, the violet of the image vanished; and if the green was intercepted, the green was wanting in the image. In short, whatever colours were stopped, the same were missing in the image. In fig. 6, the rays passing through the hole C of the window AB, are refracted by the prism PMN, and separated into DV, DG, and DR, violet, green, and red; which being collected into a focus F by the lens L, are there again refracted by a prism P′M′N′, and formed into a white beam *abmn*, part of which is intercepted by the screen SS′, and part passes through the hole *b*, as *b*H to H on the chart XYZW, and part is reflected by the body *oq* into a set of images which are received on a screen TU, and one of them, *rgv*, let pass to WXYZ; but when an obstacle E stops DR, *r* the red vanishes; and if DG be stopped, *g* the green vanishes; and if DV be stopped, *v* disappears. Lastly, if DR and DG be stopped, *g* and *r* vanish.

Obs. 6. Having produced a set of bright images, I let one pass through the desk described in the third experiment, and received it on a small lens $\frac{1}{2}$ inch broad, to collect them into a focus, which I received on the chart, by moving it a little on its hinge; and by all the observations I could make, and all the tests I could think of, it was white inclining to yellow, and of the same nature and constitution with the sun's direct light; but if any ray was stopped before coming to the lens, the focus was a mixture of the remaining rays; and the chart being moved a little farther round, the image was formed on it, the colours being in an inverted order. At the focus I held a reflector, and there were formed images of all the seven colours, as in the sun's direct light (Exp. 1.); if the light was sufficiently strong, and the desk near the window-shut hole, one of these could even be collected by a second lens into a white focus. This experiment is rendered more uniform by substituting for the lens a concave metallic mirror, and placing at the focus another mirror to reduce the rays into a beam, which may be made of any composition we please, by stopping one or more of the colours at the hole in the desk. I observed in the course of these experiments a phænomenon worth mentioning; if a comb (as in Newton's experiment*) be very swiftly moved before one of the images, or more, a sensation of white is produced; but this is still more evident, if the pin be swiftly moved round its axis, for then the images move also, and running into one another, cause a sensation of perfect whiteness.

Obs. 7. I let an image through the hole in the desk, and viewed it through a glass prism, holding its axis parallel to the sides of the image, and its refracting angle upwards; I found that, if the image was bright and free from white light, the colours were not changed by the refraction; but, if it was mixed and diluted with white, the prism, decompounding the white, caused the image to appear violet at one side, and red

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* Optics, Book I. Part II. Prop. 5.

at the other; yet still this only confused the colours of the image, without changing them. Farther, if the prism was moved on its axis, the violet was lifted higher than the red or any of the other colours. Nor was the constitution of the colours at all changed by reflection from a pin or mirror, except in so far as they were mixed by a concave one, as mentioned in the last experiment. If a pin was held behind the hole to reflect the colours, it formed other images of the colour in which it was held, and, as far as I could judge, threw the red to the greatest distance, and breadth, and inclination. Nor were the colours of the image changed by reflection from natural bodies, for these were all of the colours in which they were held, but brightest in that which they were disposed to reflect most copiously. Likewise the rings of colours made by thin plates were broadest in the red, and narrowest in the violet; and the like happened to the fringes that surround the shadows of bodies. Lastly, the shadows of bodies were themselves broadest in the violet, and narrowest in the red.

Obs. 8. I filled with water a glass tube, whose diameter was $\frac{1}{4}$th of an inch, and consequently the radius of curvature $\frac{1}{8}$th, and whose sides were $\frac{1}{30}$th of an inch thick; then standing at four feet from a candle, I held the tube $\frac{1}{4}$th of an inch from my eye, so that the light of the candle might be refracted through it, and moved my eyelids close enough to prevent the extraneous scattered light from entering along with that which was regularly refracted. I saw several images of the candle all highly coloured, and the colours were in order, from the candle outwards, red, orange, and so on to violet; I then filled the tube with clear diluted sulphuric acid, and dropped a small piece of chalk to the bottom, when immediately an effervescence took place, by the escape of fixed air, which rose in bubbles through the tube; and looking at the candle through one of these, I saw the images formed with the colours still in the same order, but a little larger than before.

We are now to see to what conclusions these experiments lead us.—The first experiment shows, that all sorts of light, whether direct, or reflected, or refracted, produces colours by reflection from a curve surface. From the second we learn, that these colours are distinct images or spectra of the luminous body, much dilated in length, but not at all in breadth; and that the angle of incidence being changed, the dilatation of the images is also changed: and from the third experiment it appears, that each full image is composed of seven colours; red, orange, yellow, green, blue, indigo, and violet; and that the proper order is red outermost, and violet innermost, the rest being in their order. The fourth experiment shows, that these images are produced, not by any accidental or new modification impressed on the rays, but by the white light being decomposed by reflection; that the mean rays, or those at the confine of the green and blue, are reflected at an angle equal to that of incidence, and the red at a less, the violet at a greater angle. Experiments 5th and 6th prove, beyond a doubt, the decomposition and separation of the rays by reflection; for in both we see that the colours in the images are those, and those only, which were mixed in the ray by reflection or refraction, before and at incidence, whilst the 6th is (in addition) a proof that all the rays of any one image, if mixed together, compound a beam exactly similar to the beam that was at first decompounded. The 7th experiment shows, that the colours into which the rays are separated by reflection are homogeneous and unchangeable; that they differ in flexibility and refrangibility; that they bear the same part in forming images by reflection, and fringes by flexion, and colours from thin plates, which the rays separated by the prism do: and in the 8th experiment we see, that when the rays are placed in the same situation with respect to refraction, whether out of a rarer into a denser or a denser into a rarer medium, in which they before were with respect to reflection, the position of the colours produced is diametrically opposite in the two cases. Seeing then that in all sorts of light, direct, refracted, reflected, simple, and homogeneous, or heterogeneous and compounded, and in whatever way the separation and mixture may have been made, some of the rays at equal or the same incidences are constantly reflected nearer the perpendicular than the mean rays, and others not so near; and seeing that by such reflection the compound ray, of whatever kind, is separated into parts so simple that they can never more be changed; and considering the different places to which these parts are reflected; it is evident, that the sun's light consists of parts different in reflexibility, and that those which are least refrangible are most reflexible. By reflexibility, I here mean a disposition to be reflected near to the perpendicular in any degree.

Although I have given what I take to be sufficient proof of this property of light, yet I am aware that something more is requisite. It will be asked, why does neither a plain, a common convex, nor a common concave mirror separate the rays by reflection? This is what has always hindered us from even suspecting such a thing as different reflexibility. I shall, however, take an opportunity of removing this obstacle, in the second part of the plan, when I come to explain the reason of the colours made by the reflecting body, and the manner of their formation. At present I shall only caution those who may wish to repeat the above experiments, that the hole in the window-shut must be small, the room quite dark, the pin well polished, and the desk, chart, &c. placed at a distance from the pin not greater than three feet, otherwise the images will be dilute and dim; nor, on the other hand, less than six inches, otherwise they will be too short, and the colours not far enough separated one from another.

My next object of inquiry was the different degrees of reflexibility belonging to each ray. It appears, not only from mathematical considerations sufficiently obvious, but also from the experiments I have related, that though the different rays have at the same or equal incidences different angles of reflection, yet each ray is constant to itself in degree of reflexibility, and that its sine of reflection bears always the same ratio to its sine of incidence. The question then is, what are the sines of reflection of the different rays, the sine of incidence being the same to all?

Obs. 9. In summer, at noon, when the sun's light was exceedingly strong, and there was not the vestige of a cloud in the sky, I produced an uncommonly fine set of images, by fixing at an inch from the small hole $\frac{1}{50}$th of an inch diameter, a pin $\frac{1}{25}$th of an inch diameter. One of the brightest of these I let pass through the desk to the chart below at $2\frac{1}{2}$ feet from the pin, and the image was 3 inches from the shadow in a straight line. I delineated it carefully, by drawing two parallel lines for the sides, and marking the semicircular ends. Then with the point of a small needle I marked the confines of the contiguous colours on one of the parallel sides, and afterwards drew across the image parallel lines; this operation I repeated with the same and different images, at many distances from the pin, and on different days, with various sorts of pins, and sizes of holes, &c. &c. and all these repetitions were made before I once examined the result of any one measurement, that I might be unprejudiced in trying the thing over again. I then compared the sketches of divided images, which I thus obtained, and found sufficient reason to conclude, that the differences between the sines of reflection in the different rays were in the harmonical order. For the divisions were nearly as $\frac{1}{9}$; $\frac{1}{18}$; $\frac{1}{12}$; $\frac{1}{12}$; $\frac{1}{15}$; $\frac{3}{80}$, $\frac{1}{16}$; which, when compounded with the scale, give 1, $\frac{15}{16}$, $\frac{9}{10}$, $\frac{5}{6}$, $\frac{3}{4}$, $\frac{2}{3}$, $\frac{11}{18}$, $\frac{1}{2}$; and these are exactly the change of the notes in an octave, obtained by taking the sums of the octave, and a second major, a third major, a fourth, a fifth, a sixth major, a seventh major, and an eighth, instead of the difference between a double octave, and a second major, a third major, and so on. Thus the spectrum by reflection is divided exactly as the spectrum by refraction, only that the former is inverted, and the different rays have reflexibilities that are inversely as their refrangibilities.

Having settled this (I flatter myself) curious and important point, I proceeded next to inquire into the absolute reflexibility of the extreme colours; for if this be known, the angle of incidence being given, the angle of reflection of all the different rays may be found. For obtaining a solution of this problem I made the following experiment.

Obs. 10. The sun shining strongly through the small hole in the window-shut, and the rays diverging into a cone, whose base fell on an horizontal chart $2\frac{1}{2}$ feet from the hole, between the hole and chart I placed a screen, which had a plate and small hole in it; the rays passing through this, fell on a small pin, so placed that the images formed might be at right angles to the shadow; one of these I measured, together with its distance from the shadow, the distance of the shadow from the hole, the breadth of the shadow, and the diameter of the pin; these measures were as follows. In fig. 7. C is the centre, and B*en* the circumference of the pin, GM the chart, and GD a line in it, being the axis of all the images, at right angles to CD, the distance of C from D the centre of the shadow, and also to the shadow itself; GE is the parallel side of the image, G being red, E violet, and F the confine of the green and blue; C*e* is a radius parallel to ED, and CA another drawn through B, the point where OB is incident, at the angle OBA, to which (by what was before shown) ABF is equal. By measurement GE is $\frac{1}{4}$th of an inch, CB $\frac{1}{80}$th, CD $4\frac{1}{2}$; now the shadow being lessened by a penumbra, this added to half the shadow, and their sum to the distance between the penumbra and the violet, gave ED $\frac{417}{400}$th of an inch. From whence it is easy to calculate, that the angle of incidence being $77^\circ\ 20'$, the angle of the red's reflection ABG is $75^\circ\ 50'$, and that of the violet's $78^\circ\ 51'$. Now the natural sines of $77^\circ\ 20'$, $75^\circ\ 50'$, and $78^\circ\ 51'$, are as 9756, 9695, and 9811; or as 250, 248, and 251; which are very nearly as $77\frac{1}{2}$, 77, and 78; and making an allowance for the omissions made in the reductions, the errors in the operations and measurements, they may be accounted as accurately in the above proportion. Now these extremes, 77 and 78, are the very proportions of the red's refrangibility to the violet's.* So that the reflexibility of the red is to that of the violet as the re-

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Optics, Book I. Part I. Prop. 7.

frangibilities inversely. But it is obvious that the sine of incidence is not the same in the two cases; for in the one it is equal to that of the mean ray's reflection, while in the other none of the rays are refracted at an angle equal to that of incidence, otherwise they would not be refracted at all. This, however, being a consequence of the essential distinction in the circumstances, does not impair the beautiful analogy which we have seen is preserved in the two operations, and which proves them to be different exertions of the same power. Now we may find, from the data obtained, the sines of all the rays in the spectrum, by adding to 77 the lengths of the spaces into which it is divided, and which are without any sensible error as the differences of those sines. The sines of the *red* will be from 77 to $77\frac{1}{8}$; the *orange* from $77\frac{1}{8}$ to $77\frac{1}{5}$; the *yellow* from $77\frac{1}{5}$ to $77\frac{1}{3}$; the *green* from $77\frac{1}{3}$ to $77\frac{1}{2}$; the *blue* from $77\frac{1}{2}$ to $77\frac{2}{3}$; the *indigo* from $77\frac{2}{3}$ to $77\frac{7}{9}$; the *violet* from $77\frac{7}{9}$ to 78. So that the sine of incidence being given, that of the reflection of all the different rays may be found; and the angle of incidence being 50° 48′, the angles of reflection are as follows: of the extreme red 50° 21′; of the orange 50° 27′; of the yellow 50° 32′; of the green 50° 39; of the blue 50° 48′; of the indigo 50° 57′; of the violet 51° 3′; and of the extreme violet 51° 15′.

I shall conclude this part of the subject with a few remarks on the physical cause of reflexibility. As light is reflected by a power extending to some distance from the reflecting surface, the different reflexibility of its parts arises from a constitutional disposition of these to be acted upon differently by the power. And as these parts are of different sizes, those which are largest will be acted upon most strongly. I shall not hesitate to go a step farther. In fig. 8. let EC be the reflecting surface, DH the perpendicular, and AB a ray incident at B, and produced to F, and reflected into GB; draw GH parallel to FB, and GF to HB. Then HB : (HG :) BF : : sin. HGB : sin. HBG, or : : sin. GBF : sin. HBG. But GBF is the supplement of GBA, the sum of the angles of reflection and incidence; wherefore HB : BF : : the sine of the sum of the angles of reflection and incidence, to the sine of the angle of reflection; so that if I be the angle of incidence, R that of reflection, V the velocity of light, and F the reflecting force; $F = \frac{V \times \text{sin.}\,(R+I)}{\text{sin. } R.}$. By accommodating this formula to the different cases, we obtain F in all the rays; and the ratio of F in one set to F in another being required, we have (by striking out V, which is constant) $F : F' : : \frac{\text{sin.}\,(R+I)}{\text{sin. } R} : \frac{\text{sin.}\,(R'+I')}{\text{sin. } R'}$. Suppose we would know F and F′ in the red and violet respectively; $I = 50° \; 48' - R = 50° \; 21'$, and $R' = 51° \; 15'$; then $F : F' : : \frac{\text{sin. } 101° \; 9'}{\text{sin. } 50° \; 21'} : \frac{\text{sin. } 102° \; 3'}{\text{sin. } 51° \; 15'}$. Performing the division in each by logarithms, and finding the natural sines corresponding to the quotients; F : F′ : : 1275 : 1253. But the force exerted on the red is to that exerted on the violet, as the size of the red to the size of the violet (by hypothesis); therefore, the red particles are to the violet as 1275 to 1253. This may be extended to all the other colours, by similar calculations; their sizes lying between 1275 and 1253, which are the extreme red and extreme violet; thus the red will be from 1275 to $1272\frac{1}{2}$; the orange from $1272\frac{1}{2}$ to 1270; the yellow from 1270 to 1267; the green from 1267 to 1264; the blue from 1264 to 1260; the indigo from 1260 to 1258; and the violet, from 1258 to 1253.

All this follows mathematically, on the supposition that the parts of light are acted upon in proportion to their sizes; and to say the truth, I see no other proportion in which we can reasonably suppose them to be influenced; for such an action is not only conformable to the universal laws of attraction and repulsion, but also to the following arguments. If the action be not in the simple ratio, it must either be in a lower or in a higher; let it be in a lower, as that of the square root, then the size of the red would be to the size of the violet as the squares of the forces; that is, as 1625625 to 1572009: a difference evidently too great; and, *a fortiori*, of the cube or any other root. On the other hand, if the action were in a higher ratio, as that of the square, then the particles would be as the square roots of the forces, or nearly as 35.70 to 35.39, a difference evidently too small; for if the size of the red particles were only $\frac{3}{10}$ths greater than that of the violet, and the velocity of both were equal, the momentum, and consequently the intensity of the red, could not so much exceed that of the violet as we find it does, and as seems to me to be proved by the experiment of BUFFON (on accidental colours), who found, that after looking at a white object, when he shut his eyes, it first became violet, then blue, or a mixture of blue and the other colours, and last of all red; so in the impression of the white, compounded of the impressions of all the other rays mixed together, the violet was first obliterated or weakest, and the red last or strongest. To this reasoning on the intensity of the particles as owing to their size, I see only two objections that can be made. The one is, that the intensity is increased when the rays are thrown into a focus; but we must recollect that the rays in this case are mixed, and their particles so blended as to be increased in size; for the number of separate rays thrown into one place will not increase their intensity sensibly. The other objection is, that passage in NEWTON, where he says "that the orange and yellow are the "most luminous of all the colours, affecting the senses most "strongly."* Now, besides that this is an assertion opposed by the positive experiment just now quoted, I think an answer may be thus made to it; the whole light, from which the spectrum is never free, which inclines to yellow, and which is composed also of red, abounds in the yellow and orange of the spectrum; so that both of these colours derive their superior lustre rather than intensity from this circumstance; or if they have any degree of the latter more than the red, it is in fact owing to their mixture with the red and the other rays, which are all in the white.

Having endeavoured to unfold the property of flexibility, as varied in inflection, deflection, and reflection; and also the physical cause of this property; and having indulged in a speculation depending on this cause, I flatter myself neither altogether useless nor unimportant, I hasten now to the natural phænomena, the explanation of which depends on the property, whose existence and nature we have just now been investigating; and that we may treat this part of the subject with conciseness and order, we shall rank the phænomena under a division similar to that under which we laid down the principles, beginning with those appearances which are explicable on the principles of flexion.

1. It is observable, that when a body is exposed in the sun's light, so as to cast a shadow, and another body is ap-

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* Optics, Book I. Part I. Prop. 7.

proached to it; either between the sun and it, or the shadow and it, or on the same line with it, the shadow of the one body comes out a considerable way, and meets that of the other. Now it is evident, that when the bodies are held at a sufficient distance from one another, a penumbra is formed round the shadow of each, making it less than it should be were there no inflection; but when the bodies are brought so close to one another that the edge of the one is within the sphere of the other's inflection, the light being already bent by this last, the former can have none to bend, and consequently no penumbra in the part of the shadow corresponding to that part of the body which is within the other's sphere of inflection; and the rest of the shadow having a penumbra, this part that has none will be larger than it, and increase as the bodies approach, till at last it meets the other shadow; the like appearance happening when the shadows are thrown on the eye. Mr. MELVILL has endeavoured to show that it belongs simply to a case of vision;* however, we have now seen that it has no reference to the structure or position of the eye, but only to the common nature of all shadows.

Obs. 11. If we shut out all the light coming into a room from external objects, except what may pass through a small hole of $\frac{1}{2}$ or $\frac{1}{4}$th of an inch in diameter, the images of the external objects, as clouds, houses, trees, will be painted on the opposite wall, by the rays of light crossing at the hole; but if a piece of rough glass, or of very fine paper, be held so as to cover it all over, the light does not pass through; then if the paper be wetted with oil, or the glass with water, so as to give either a small degree of transparency, the first rays that come

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* Edinburgh Literary Essays, Vol. II.

through are those from red and orange objects, and last from blue and violet. Now it is evident that transparency in general, and this particular fact, are explicable by what was before laid down. It was found by NEWTON, that a body transmits the light incident on it more or less, according to the continuity of its particles, and that a strong reflection takes place on the confines of a vacuum.* How does this happen? The initial velocity of light is sufficient to carry it through the first surface or set of particles, but it is so much diminished, that it is reflected by the repulsive power of the backside of these particles, unless there be others behind at a certain distance, namely, that at which inflection or attraction acts, that is, apparent contact; this attraction renews the impetus of light, and transmits it to another set, and so on. Now this action being strongest on the largest and red particles, and weakest on the blue and violet, if the continuity be diminished, the former will be transmitted, and not the latter; which is conformable to the experiment just now mentioned.

3. The doctrine of flexibility furnishes an easy and satisfactory explanation of the different colours which are assumed by flame. Whether we suppose the light to come from the burning body, or the oxygenous gaz, the largest or red particles have the strongest attraction for bodies, the violet the weakest; when therefore the gaz and the body combine, the precipitation of light must be in the reverse order of the affinity between the particles of light and those of the bodies. If then the combination take place slowly, the violet and blue particles will be first emitted, and last of all the red; and this is consistent with fact; for any inflammable body whatever,

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* Optics, Book II. Part III. Prop. 3.

on being lighted, burns at first with a blue or violet flame, and afterwards has its flame of two or three distinct colours, blue, white, red, &c. as is seen remarkably in the case of a candle. Nay, I have observed in the flame of a blow-pipe all the seven primary colours at once. When, indeed, a body is burnt in pure oxygenous gaz, the combination is so rapid, that white light alone is precipitated undecomposed; but in common air, where the azotic gaz impedes the combustion, the above phænomena are obvious.

4. A curious phænomenon has often surprised philosophers, namely, blue shadows. These I have observed at all times, when the paper on which I received them was illuminated by the sky, and any other light; and the reason of them I take to be this, that the shadow made by one light is illuminated by the blue rays from the sky; for I have often observed purple, and even reddish ones, when the sky or clouds happened to be of those colours; and this account of the matter is confirmed by an experiment. Having received the coloured spectrum made by a prism with a large refracting angle, on a sheet of rough white paper, and held above it another sheet, I stopped all the rays that illuminated the first except the blue, and violet, and red; and if I held a body between the blue and the second paper, its shadow was red; and if I held a body between the red and the paper, its shadow was blue; and so of other colours. This I take to amount to a demonstration of the thing.*

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* Since writing the above, I find the same explanation of the matter given by Mr. MELVILL, and some of the French academicians, particularly Messieurs BUFFON and BEGUELIN; also Count RUMFORD; but I have thought fit to keep it in, on account of the experiment that occurred to me in illustration of it.

5. Passing over other phænomena of less note, I come now to one that has divided opticians more than any other; I mean the coloured fringes that surround the shadows of bodies. I made several observations on these, which enable me to conclude that each fringe is an image of the luminous body; for holding between my eye and a candle two knife blades, as I approached the one to the other, the edge of the candle seemed multiplied, and soon became coloured, coming wholly away from the candle, and as the knives approached still nearer, became distinct dilated images, highly tinctured with the prismatic colours; and just before the knives met, the candle, whose edges had been all along coloured with red and yellow, became much distended, till at last it was divided in the middle, one half seeming to be drawn away by each knife, and then it wholly disappeared. I have observed three kinds of these images; two without and one within the shadow; the first had its colours in the order from the shadow, red outermost, and violet innermost; the second and third had the colours in the contrary order, but the second was so very faint that I could never perceive it unless when let fall on my eye. All this is easily explained by the different flexibility of the rays. In fig. 9. let AD be a body, by which the rays SDT and S′D′T′ pass; and let SD be within AD's sphere of inflection, and S′D′ within its sphere of deflection; then SD will be bent into DG, but because of the different inflexibility of its parts, the red will be bent into DR, and the violet into DV, and the intermediate rays will fall between R and V, the whole forming an image RGV, separated into the seven primary colours; and in like manner, by the different deflexibility of the parts whereof S′D′ consists, an image without the

shadow, as V′G′R′ will be formed, similar to VGR, R′ being red and V′ violet, all which is both theory and experience; and the same explanation may be extended to the other cases. Now, in all these, the bending power stretching to a very small definite distance, and being of different degrees of strength at different distances from the body, several pencils or small beams, passing through different parts of the spheres, will be acted upon by the power in its different states of strength; and each beam will be disposed into an image in the way before described; of these images I have sometimes observed four, and even, by using great care, the faint lineaments of a fifth. In forming them, the power acts strongest at the smallest distances, and of consequence bends the mean flexible rays, that pass near, farther inwards or outwards than those that pass farther off; so that the extreme rays will in the former case be more separated from the mean than in the latter; and the nearer image will always be the largest and most highly coloured, which is consistent with fact. This explains fully the celebrated experiment of Sir ISAAC NEWTON with the knives, and the explanation is confirmed by the experiments which I related above on flexibility, where the bending force acted most strongly on those images formed out of red light, and least strongly on those formed out of violet and blue light. A number of other phænomena are explicable on the same principles, being only particular cases as it were of the coloured fringes or images; I shall here mention a few of the most remarkable.

6. When making some of the experiments which I have related in the course of this paper, I observed that when the sun was surrounded, but not covered, by clear white clouds,

the white image on the chart (the hole being $1\frac{1}{2}$ inch in diameter) was surrounded by two rainbows, pretty broad and bright; in the colours were red on the outside, and violet next the white of the image. These bows must not be confounded with one which sometimes appears wholly of a dull red and yellow, when the sun or moon shines through a cloud, and which is owing to the direct transmission of the red rays and reflection of the others; for not only are the colours different in species, in brightness, and in number, in the phænomena under discussion, but likewise they are formed by the hole in the window, as I knew by altering its shape into an oblong; and the colours now were not disposed in circles, but in broad lines of the same breadth as the bows had been, running along the shadow of the hole's sides, and in the same position of colours as before. It is evident that their cause is the inflection of the light which comes from the clouds by the sides of the hole (for if the sky have no clouds the colours do not appear), which separate the white light into the parts of which it is composed.

7. It is observable, that when we look at any luminous body, at a distance greater than one or two feet, its flame appears surrounded by two bows of faint colours, the innermost of them terminating in a white which continues to the flame; and the colours are red outermost, and green and blue innermost: the appearance is most remarkable if we look at a small hole in the window-shut, the room being otherwise dark; and if the eye be pressed upon, and then opened, the colours are more lively than before, as DES CARTES observed;[*] from which both he and NEWTON concluded, that the appearance

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[*] *De Meteoribus.*

was owing entirely to wrinkles formed on the surface of the eye by the pressure.* But this could neither form the bows with the regularity in which they always appear, nor could the colours be in the order above mentioned from the different refrangibility of the rays; it will also be obvious to any one who tries the thing, that the pressure only increases the brightness and breadth of the bows, but does not form them. The true solution of the difficulty seems to be this: the rays which enter the pupil, are inflected in their passage through the fibres, which extend over the cornea, and which are very minute, but opaque; by these they are decompounded into fringes, having the red outermost, and the violet innermost; and the fringes formed by each fibre being joined together, form the bow. How then does the pressure enlarge and vivify them? The fibres are naturally extended over the surface of a spherical segment; when this surface is compressed into a plane circle, they are condensed into a much less space, and consequently brought nearer to one another, the rays are therefore more inflected and separated than before. If this explanation be true, it will follow, that the like bows may be produced by small hairs, like fibres, placed near one another; and this I found perfectly consistent with fact; the bows are in this case brighter than in the other; and the small hairs on a hat, or the hand, made them brighter than any other I have tried: a circumstance which I observed in both cases, seems to show clearly the identity of the causes; the white space, which reached from the interior bow to the flame, was speckled or mottled, in a manner which cannot be easily described, but which any one will perceive upon trying the experiment.

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* *Lect. Opticæ, Sect. III. ad finem.*

8. The last of these phænomena, which I shall mention, is the celebrated one observed by Sir ISAAC NEWTON, namely, the rings of colours with which the focus of a concave glass mirror is surrounded. Sir ISAAC made several most ingenious and accurate experiments to investigate their nature;[*] and finding their breadth to be in the inverse subduplicate ratio of the mirror's thickness, he concluded that they were of the same nature and original with those of thin plates, described by him.[†] The Duc de CHAULNES pursued these experiments with considerable success; he found that the rings were brighter the nearer to the perpendicular the rays were incident; and that if, instead of a concave glass mirror, a metal one was used, with a small piece of fine cambric, or reticulated silver wire stretched before it, the colours were no longer disposed in rings, but in streaks, of the same shape with the intervals between the threads; hence he concludes that they are owing to inflection; that in passing through the first surface, they are inflected and condensed by the second.[‡] I am not, I own, quite satisfied with this account of the matter: that they are produced by inflection, the Duke's experiments put beyond doubt; but that they should be formed in passing through the first surface, and reflected by the second, is quite inconsistent with the ratio observed by their breadth, this being greater in the thinnest glass, and also with the order of the colours. Besides, all the coloured images which fall on the backside of the mirror, will be (by what we before found when speaking of flexibility[§]) reflected into a white focus; so

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[*] Optics, Book II. Part IV.

[†] Book II. Parts I. and II.

[‡] *Mém. de l'Académie, pour l'année* 1755.

[§] Part II. Obs. 6 of this paper.

that, upon the whole, there appears every reason to believe that the rings are formed by the first surface, out of the light which, after reflection from the second surface, is scattered, and passes on to the chart. It will follow, 1. that a plane mirror makes them not, for the regularly reflected light, not being thrown to a focus, mixes with the decompounded scattered light, and dilutes it. 2. That the nearer to the perpendicular the rays are incident, the more light will be reflected to the focus, and consequently the less will dilute and weaken the rings. 3. That the thinner the mirror is, or the nearer the two surfaces are, the broader will the rings be. 4. That the rings farther from the focus will be broader. And lastly, that when homogeneous light is reflected, the fringes or images will be larger, and farther from one another, in red than in any other primary colour. All which is perfectly consistent with the experiments of NEWTON and CHAULNES. There is only one difficulty that may be started to this explanation: how happens it that the colours (made by the mirror) are always circular? We answer, it is owing to the manner of polishing the concave mirror, which is laid between a convex and concave plate, and then turned round (with putty or melted pitch) in the very direction in which the rings are. If it should be asked, why does the thickness of the mirror influence the breadth of the rings exactly in the inverse subduplicate ratio? We answer, that to a certain distance from the point of incidence (and the rays are never scattered far from it) this is demonstrable, to hold as a property of mathematical lines in general.

Having found that the fringes by flexion are images of the luminous body,[*] I thought that, from this consideration, a method of determining the different degrees of flexibility of the different rays might be deduced, similar to that which I had formerly used for determining their degrees of reflexibility.[†] I therefore made the following experiment.

Obs. 12. Having let into my darkened chamber a strong beam of the sun's light, through a hole $\frac{1}{40}$th of an inch in diameter, I held a hair at four feet from the hole, and receiving the shadow at two feet from the hair, I drew a line across the middle of the coloured images, and pointed off in each the divisions of the colours, as nearly as I could observe; and repeating the observation several times and at different distances, I found, by the same way I had formerly done in my experiment on reflexibility, that the axis, or line, drawn through the middle of each, was divided inversely, according to the intervals of the cords which sound the notes in an octave, *ut, re, mi, sol, la, fa, si, ut.* But as the measures in these experiments were very minute, and the operations of consequence liable to inaccuracy, I thought proper to try the thing by another test.

Obs. 13. The sun shining into the room as before, I placed at the hole an hollow prism made of fine plate-glass, and filled with pure water, its refracting angle being 55°; the spectrum was thrown on an horizontal chart eight feet from the window, and at four feet from the prism there was placed, in the rays, a rough black pin $\frac{1}{20}$th of an inch in diameter. The shadow in the spectrum was bounded by hyperbolic sides, as before described; and drawing a line, which might be the axis

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[*] Page 256.

[†] Page 247.

of the shadow, and pass precisely through its middle, I marked on one side 6 or 8 points of the shadow's outline, in each set of rays; and this being often repeated, at different distances and in different shadows, the position of the axis remaining the same, the curves formed by joining the points were all parallel; which shows that each sine of inflection taken apart has a given ratio to the sine of incidence. I afterwards divided the axis according to the musical intervals, and thus found where each colour of the spectrum had terminated, in what colour each part of the shadows had been, and by what rays formed. Then I joined the parts that I had marked, and obtained a curve, which I took to be, either nearly or accurately, an hyperbola of the 4th order. I next measured the ordinates (the axis of the spectrum and shadow being the axis of the curve) at the confines of each colour; first, the ordinate at the extremity of the rectilinear red, then that at the confine of the red and orange, and so on to that at the extreme rectilinear violet; to each of these ordinates I added the greatest one, or that in the violet, which (in fig. 10.) is VV'; that is, I produced vV to V', so that vV' is equal to vV; and through V' I drew $V'R'$ parallel to the axis VR, and produced gG to G', and rR to R'; then from V' I set off $V'g'$ equal to $G'g$, and $V'r'$ equal to $R'r$, and the other ordinates in like manner; and I found, according to the method before described,[*] that VV' was divided inversely, after the manner of the musical intervals. It is therefore evident that the inflexibilities of the rays are directly as their deflexibilities, and reflexibilities, but inversely as their refrangibilities. The same may be proved, by measuring and dividing the images made in the inside

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[*] Page 247.

of the shadows; these I have found to be, at equal incidences and distances, equal to the images on the outside, both in breadth, in distance from the edge of the shadow, and in the relation which their divisions bear to one another; wherefore, whatever be the ratio of the angle of inflection to that of incidence, the same is the ratio of the angle of deflection to that of incidence; so that the angle of deflection is equal to the angle of inflection. If farther proof of this proposition be desired, the following experiment and observations, which from the importance of the thing I do not scruple to add, may be sufficient.

Obs. 14. When two knife blades were placed by one another in a beam of light which entered the dark room, so that the one might form and the other distend the images, I made in one of the blades (with a file) a small dent, which, on the chart, cast an elliptic or semicircular outline; then I observed that the images of both blades were disturbed by it, and wound round the edges of the semicircle; and they were all affected in precisely the same manner and degree. So then the first knife deflected the images formed by the second, in precisely the same degree that it inflected those images which itself formed, and so of the other knife; otherwise the effect of the dent would have been different upon the two sets of images. We may therefore conclude, that the angles or sines of inflection and deflection, bear the same ratio to the angle or sine of incidence, and that they are equal to one another. My next object was to determine this ratio in one of these cases, and consequently in both; and it was very agreeable to find data for the solution of this problem in NEWTON'S measurements of the images and shadow; since this philosopher's well known accuracy in such matters, besides the singular ingenuity of the methods he employed, made me more satisfied with these than any experiment I could make on the subject. In fig. 11. CS is the line perpendicular to the chart SU, and passing through the centre of the body, whose half is CD or SE; EB is parallel to CS, and AI a ray incident at D; ADB or EDI is the angle of incidence; EDR that of the red's deflection; EDV that of the violet's; and EDG that of the intermediate's. According to Newton,* CD was $\frac{1}{500}$th of an inch, DE 6 inches, SI $\frac{1}{108}$th of an inch, RV $\frac{1}{170}$th, and consequently RG $\frac{1}{340}$th; GS was $\frac{1}{76}$; whence the angles IDE, EDV, EDG, and EDR, will be found to be 4′, 30″; 5′; 7′, and 9′, respectively. Now the natural sines of 4′, 30″; 5′; 7′; and 9′, are as the numbers 1309, 1454, $2035\frac{1}{2}$, and 2617, which are as the sines of incidence, deflection, and inflection of the violet, green, and red. Thus the angles of flexion of the extreme and mean rays being given, those of the other rays are found by dividing the difference between 1454 and 2617 in the harmonical ratio: for then the red will be equal to $145\frac{3}{8}$; the orange $87\frac{9}{40}$; the yellow $155\frac{1}{15}$; the green $193\frac{5}{6}$; the blue $193\frac{5}{6}$; the indigo $129\frac{2}{9}$; and the violet $258\frac{4}{9}$; and by adding to the number 1454 the violet, and to their sum the indigo, and so on, we get the flexibility of the red, from 2617 to $2471\frac{5}{8}$; of the orange, from $2471\frac{5}{8}$ to $2384\frac{2}{5}$; of the yellow, from $2384\frac{2}{5}$ to $2229\frac{1}{3}$; of the green, from $2229\frac{1}{3}$ to $2035\frac{1}{2}$; of the blue, from $2035\frac{1}{2}$ to $1841\frac{2}{3}$; of the indigo, from $1841\frac{2}{3}$ to $1712\frac{4}{9}$; and of the violet, from $1712\frac{4}{9}$ to 1454: the common sine of incidence being 1309. It is therefore evident, that the flexibility of the red is not to that of the violet as the refrangi-

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* Optics, Book III. Obs. 3.

bility of the violet to that of the red; and a little attention will convince us that we had no reason to expect the analogy should be kept up in this respect; for the refrangibility of the rays depends on the species of the refracting medium, and follows no general rule; whereas our calculation has been made concerning the action of the bending power at a certain distance, greater than that whereat the particles of media act on the rays in refracting them. It was observed, in the mathematical propositions prefixed to this paper, that the angle of flexion is less than that of incidence, when, in the case of inflection, the angle made by the ray and the body is acute, and when, in the case of deflection, that angle is obtuse; and when the ray is perpendicular or parallel, the angle of incidence vanishes in both cases. It is evident, therefore, that in both these situations of things the ratio of 1309 to 2036, being that of a less to a greater, will not enable us to find the angle of flexion, although it serves very well when the ray before inflection makes an obtuse, and before the deflection, an acute angle. I have therefore mentioned the angle made by the bent ray with the incident, which gives a general formula; for let the angle of incidence be I, and that which the bent ray makes with the incident B, then F being the angle of flexion, we have $F = B \pm I$; so that if $I = O$; $F = B$; or if the incident makes an obtuse angle with the body, in the case of deflection, and an acute in that of inflection, then $F = I - B$, and in the remaining case $F = I + B$.

These observations enable us to give a very short summary of optical science. When the particles of light pass at a certain distance from any body, a repulsive power drives them off; at a distance a little less, this power becomes attractive;

at a still less distance, it again becomes repulsive; and at the least distance, it becomes attractive as before; always acting in the same direction. These things hold whatever be the direction of the particles; but if, when produced, it passes through the body, then the nearest repulsive force drives the particles back, and the nearest attractive force either transmits them, or turns them out of their course during transmission. Farther, the particles differ in their dispositions to be acted upon by this power, in all these varieties of exertion; and those which are most strongly affected by its exertion in one case, are also most strongly affected by that exertion when varied; except in the cases of refraction, of which we before spoke; and these dispositions of the parts are in all the cases in the same harmonical ratio. Lastly, the cause of these different dispositions is the magnitude of the particles being various.

All that remains now to be done on this part of the subject is to explain one or two phænomena relating to reflexibility.

1. It has been remarked, that if we look at a candle, or other luminous body, with our eyes almost shut, bright streaks seem to dart upwards and downwards from it. NEWTON* explains this by refraction through the humours adhering to the eyelids. ROHAULT† and Mr. YOUNG‡ ascribe them to reflections. DES CARTES makes them arise from wrinkles on the eye's surface. DE LA HIRE from refraction through the moisture on the eyelids, as through a concave lens; and PRIESTLEY|| from inflection through the lashes. The truth of Sir ISAAC's explanation is obvious, because the streaks which dart from the top of the luminous body are formed

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[*] *Lect. Opt. Sect. III. ad finem.*

[†] *Physica,* p. 249. CLARK's ed.

[‡] Phil. Trans. 1793.

[||] On Vision, Vol. II.

by the under eyelid, or at least by the moisture adhering to the under ciliary process, and those which appear from the bottom of the body, by the upper eyelid; which could not be, either if they were formed by reflection from the processes, or by inflection through the lashes.

I have, however, observed another kind of streaks, mottled with broken colours of all kinds, and formed by reflection from the moisture on the processes; in these the under streak corresponds to the under process, and *vice versa:* they may be formed by any polished body held in the proper position between the pupil and luminous body. The colours are very beautiful when made by the sun, and resemble, in form and irregularity of arrangement, some of the streaks made by large half-polished bodies, as described in Part II. of this paper.

2. The next object of attention is one of the greatest importance to our theory, namely, the formation of images by reflection: three things here require explanation, the number of the images, their colours, and their variations in point of size.

Obs. 15. I have uniformly found that no reflecting surface forms them, except it be curve, and (its surface) of a structure somewhat fibrous. A plain mirror, nor a concave, nor a convex one do not make them, unless they are of that structure; and, for the same reason, quicksilver, when held so as to reflect the light incident upon it, forms them not, but by *triturating* it, so as to divide it into small particles, and by placing these in the beam of the sun's light, each particle formed an image, with the colours in the regular order and very bright: on holding a cylinder in the rays, and observing the lengths of the images, I found that if the curvature was increased, the images were also increased in size, being more distended, and highly coloured. These things immediately suggest the explanation. Each of the small fibres forms an image, which, from the different reflexibility of the rays, is divided into the seven primary colours. But why does not a plain mirror form *one* of these upon the same principles? In fig. 12. let AE be the curve surface of a very convex mirror, that is of a small fibre; GC a ray reflected by the small surface DC; it will be separated into CI red, and CK violet, by the unequal action of FC on its parts. But if DC is continued to L in a straight line, then LC's sphere of reflection extending a little way beyond it, to KC, the part nearest to C, and not to IC, will drive KC and also the indigo and part of the blue nearer to the perpendicular; then IC being within LC's sphere of inflection, will, together with the orange, yellow, and part of the green, be brought nearer to KC; so that IC and KC will both be brought to an angle equal to that of incidence, and will be reflected in a parallel white beam. If LC is removed a little, or the surface becomes more convex, IC is attracted, and KC repelled, but not so much as to reduce them to parallelism and whiteness, an image being formed narrower and less coloured than when LC is moved so far round that KC is attracted, and IC deflected or repelled. If LC is moved round so that the mirror is concave, then KC is repelled, and IC attracted, as before, unless the curvature be considerable; and then KC and IC are both repelled, and an image formed in the *caustic* by reflection. In Obs. 3. we found that certain irregularities in the surface of the reflector caused the images to be in the inverted order of colours. How does this happen? In fig. 13. let *gf*, *fe*, *er*, *ri*, and *ib*, represent the sections of the convex fibres on the surface of the reflector, and let the ray AB be reflected from *ef*, separated into B*r* red, and B*v* violet; then if AB was so inclined to *ef*, that B*r* and B*v* fell upon *er*, the side of the fibre next to *ef*, and a little larger than *ef*, it is evident that B*v* will be reflected into *v*V, and B*r* into *r*R, and an image VR will be formed, having the violet outermost and the red innermost, the intermediate colours being in their order, from V to R. Lastly, it is evident that the greater the angle of incidence is, the longer will be the image, and the farther separated its colours; for which reason the farther the images are from the shadow, the less dilated and coloured will they be. Nor will they have the same appearance at all distances from the point of incidence; very near it, they will be all in the form of fringes across the streak, the breadth being greater than the length (if I may use the expression), but as we recede from it, they will become distended, as before described, the length increasing faster than the breadth, and at one point or distance they will be just as long as broad; all which agrees with experiment; and it is needless to show by particular demonstration, the manner in which one image is divided from another, the reason obviously being the manner in which the fibres on the reflecting surface are arranged and inclined to one another.

3. A number of phænomena, involved in that of the images, are explicable by what has been said on them. If a piece of metal be scratched, and then exposed in the sunshine, a number of broken colours will be formed by the scratches, as may be seen either by letting them fall on the eye, or by receiving them on a white object. This is evidently owing to the different reflexibility of the rays incident on the scratches, which

are so many irregular specula, of great curvature; the images are therefore distorted and broken, just as a candle, &c. appears broken and coloured when viewed through a piece of irregular crystal, such as the bottom of a wine glass. If we look attentively at any object exposed in the light of the sun, provided it be not polished, we shall see its surface mottled with various points of colours, from the specular nature of its minute particles. If we look towards the sun, with a hat on our head, held down, so that the sun's direct light may not fall on our eyes, but on the hairs of the hat, and be reflected, we shall see a variety of lively colours darting in all directions from those hairs; and we may easily satisfy ourselves that they are not the consequence of flexion, by trying the same thing with unpolished threads, in which case they do not appear, provided the threads be not very small. In the same manner we may account for the colours of spider webs, of different cloths which change their colours when their position is altered, and of some fossils which appear of different streaks of colours when held in the light, such as the fire marble of Saxony, &c. All these bodies having surfaces of a fibrous structure, each fibre reflects and decompounds the rays.

4. The consideration of the foregoing phænomena inclined me to think, that upon the principles which have been laid down, the colours of natural bodies may be explained. The celebrated discovery of NEWTON, that these depend on the thickness of their parts, is degraded by a comparison with his hypothesis of the fits of rays and waves of æther. Delighted and astonished by the former, we gladly turn from the latter; and unwilling to involve in the smoke of unintelligible theory so fair a fabric, founded on strict induction, we wish to find

some continuation of experiments and observations which may relieve us from the necessity of the supposition. My speculations on this subject have by no means been completed, as I have not yet finished the demonstrations and experiments into which it has engaged me to enter; but, in order to complete my plan, I shall offer a few hints on the subject. The parts of light are affirmed, in Prop. III. Book I. Part I. of the Optics, to be different in reflexibility; that is, according to the author's definition, in disposition to be turned back, and not transmitted at the confines of two transparent media. That the demonstration involves a logical error appears pretty evident. When the rays, by refraction through the base of the prism used in the experiment, are separated into their parts, these become divergent, the violet and red emerging at very different angles, and these were also incident on the base at different angles, from the refraction of the side at which they entered; when, therefore, the prism is moved round on its axis, as described in the proposition, the base is nearest the violet, from the position of the rays by refraction, and meets it first; so that the violet being reflected as soon as it meets the base, it is reflected before any of the other rays, not from a different disposition to be so, but merely from its different refrangibility; although then this experiment is a complete proof of the different refrangibility of the rays, it proves nothing else; and indeed an experiment will convince us, that the rays all have the same disposition to be reflected, provided the angle of incidence be the same. For I held a prism vertically, and let the spectrum of another prism be reflected by the base of the former, so that the rays had all the same angle of incidence; then turning round the vertical prism on its axis, when one sort of rays was transmitted or reflected, all were transmitted or reflected. We cannot therefore apply the different reflexibility of light, to the explanation of the colours of bodies, since this property has no existence. But we have shewn that the rays differ in *reflexibility*, taking the word in the new sense, as explained above; let us see whether this principle will not solve the important problem. It is evident that the particles of bodies are specular. Now I take the colours of bodies to depend, not on the size, but on the position of these particles, or at least on only the size in as far as it influences their position; an idea perfectly familiar to mathematicians.

Obs. 16. In making some of the experiments, which I related above on the reflexibility of light, I observed, among the regular images made by most of the pins which I used, one or two all of the same colour, as red, blue, *&c.* and when the pin was moved these moved also, becoming of other colours in regular order, like the rest; which shows plainly that their being of one colour at first was owing to some fibre in the surface jutting out, or rather to several of these, which stopped the red and all the rest but the blue of several images, or the blue and all the rest but the red. Farther, I produced several regular images by two or three very small pins, and with considerable trouble I at last contrived to place them in such a position as that one blue colour of considerable size might be produced, then a red, and so on, by altering the posture of the pins; now, whether the posture or the size be altered it matters not, for the one affects the other. Is it not evident that this experiment, and the conclusion to which it evidently leads, may be transferred to the colours of natural bodies as seen by reflection? for the parts being specular and spherical, each will form an image of the luminous body; and by the position of the sides of the neighbouring ones, any six of the colours may be stopped, while the seventh emerges; and if this happens in one part, it will happen in all, since that the texture and size of the parts is the same throughout, has never been called in question. But it will be asked, how are the particles to reflect a mixture of different colours? We answer, that a particle having its sides concave, and front convex, will produce the effect; for the colours will be thus mixed in a proportion determined by the position of the others. How can whiteness and blackness be produced? If the particles be large, then the whole light incident on each will be reflected and separated, and all the images being compounded and mixed together, a confused sensation, or a sensation of white, will be the result. For the parts being transparent, and the images formed by the convex surface of the second row of particles, these will be larger in proportion to the thickness of the particles, or plates through which they have to pass before they meet with obstruction, and consequently will not be stopped by other particles; and in like manner the colour will be red if the particles are a little less, and so on. If the particles be very small, the light will be separated into images also small, with which, and with one another, the particles interfering, the light by many reflections and obstructions will be totally lost. How do bodies appear of their proper colours though no luminous body be shining, whose image may be formed by a reflection? They reflect images of the clouds, which reflect the sun's white light; for if we hold between our eye and a hole in the window, illuminated by the light of the clouds, a reflecting body, as a pin, &c. coloured images are formed of the hole distended like those of the sun, as I have often found; and the same holds of inflection. Why does cutting a body to pieces not alter its colours? This only changes the position of masses of particles, not of the particles themselves; but if by bruising them we change their magnitude and position, we change also their colour; thus the leaves of vegetables bruised in a mortar, many paints powdered, &c. Why do many bodies change colours when viewed in different positions? Because they reflect two colours, or more, of each image to different quarters; and it matters not whether their position with respect to us or our position with respect to them be changed. How do bodies appear coloured by transmitted light? Because the foregoing reasonings apply also to the flexion of the rays in their passage through the parts of bodies. These observations appear to me to furnish a very simple solution of the problem. I shall endeavour, in a future communication, to confirm what has been said, by other remarks and experiments; for it would be tedious, and perhaps superfluous, to illustrate what has been said by figures and demonstrations.*

Pursuant to these remarks, it will not be difficult to account for the rings of colours of thin plates by reflection, as we before did those of thick plates by flexion; † indeed those formed in the experiment of the two lenses, supposed by NEWTON to

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* It is obvious that the different refrangibility of the rays will not account for the bright and distinct colours of bodies: if the refracting angle of a prism be continually diminished, till, for example, it is equal to one of a minute, the refraction will produce no sensible colours; indeed almost every piece of plane glass has its sides in a small degree inclined to one another, and yet no colours are formed; much less then will refraction through the infinitely smaller parts of bodies, produce separation of the rays.

† Page 260 of this paper.

be owing to the plates of air between them, appear to have a different cause, as may be without much reasoning gathered from the curious experiments of the Abbé MAZEAS,* and even from one or two of Sir ISAAC'S own, in which he supposes some medium more subtile than air to be between the glasses.† But at present I forbear entering into the subject any farther: this paper has been already extended to a greater length than was at first intended. And I hasten to conclude, by a short summary of Propositions, containing the principal things which have been demonstrated in the course of it.

Prop. I. The angles of inflection and deflection are equal, at equal incidences.

Prop. II. The sine of inflection is to that of incidence in a given ratio (which is determined in the paper.)

Prop. III. The sun's light consists of parts which differ in degree of inflexibility and deflexibility, those which are most refrangible being least flexible.

Prop. IV. The flexibilities of the rays are inversely as their refrangibilities; and the spectrum by flexion is divided by the harmonical ratio, like the spectrum by refraction.

Prop. V. The angle of reflection is not equal to that of incidence, except in particular (though common) combinations of circumstances, and in the mean rays of the spectrum.

Prop. VI. The rays which are most refrangible are least reflexible, or make the least angle of reflection.

Prop. VII. The reflexibilities of the different rays are inversely as their refrangibilities, and the spectrum by reflection is divided in the harmonical ratio, like that by refraction.

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* *Mém. de l'Académie pour l'année* 1738.

† Optics, Book II. Part I. Obs. 10 and 11.

Fig. 1.

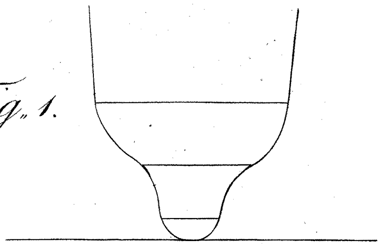
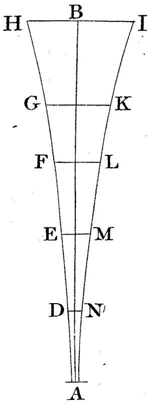


Fig. 2.



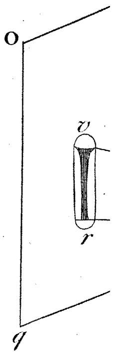
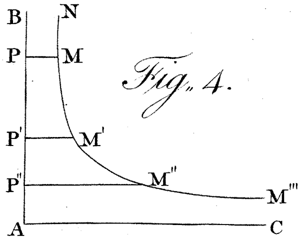


Fig. 4.



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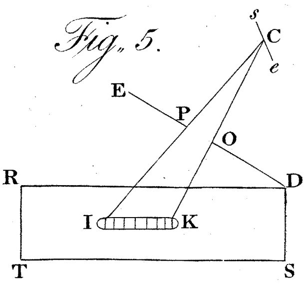


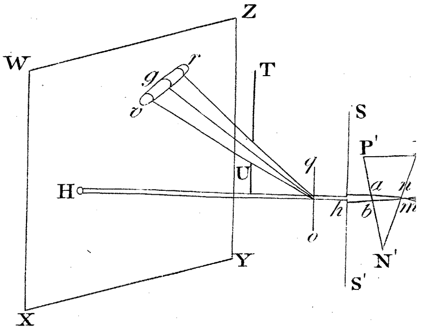
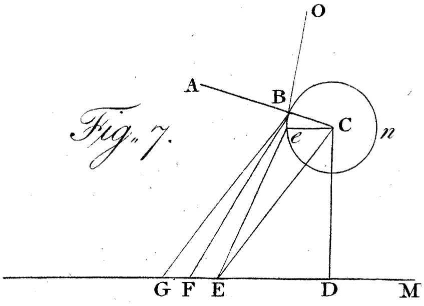


Fig. 7.



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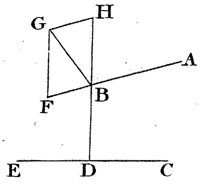


Fig. 9.

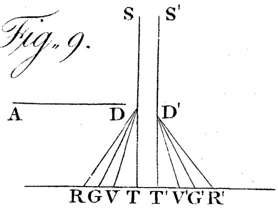


Fig. 11.

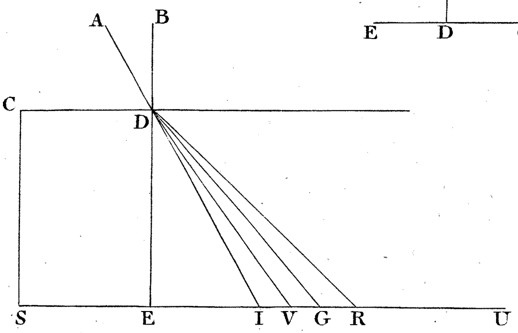


Fig. 12.

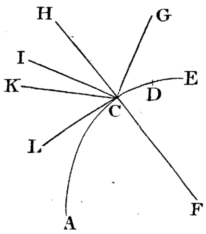


Fig. 3.

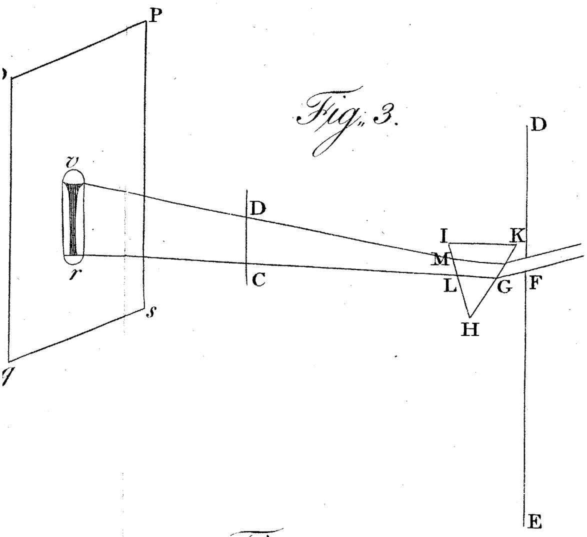


Fig. 6.

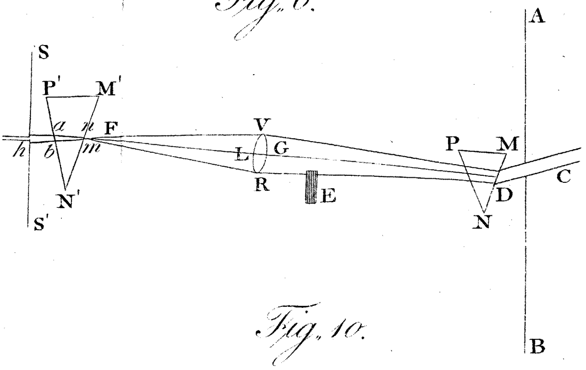


Fig. 10.

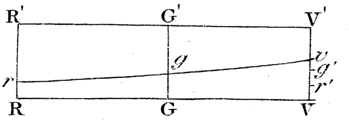
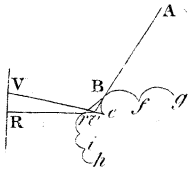


Fig. 13.



Basire sc.

Prop. VIII. The sines of reflection of the different rays are in given ratios to those of incidence (which are determined in the paper.)

Prop. IX. The ratio of the sizes of the different parts of light are found.

Prop. X. The colours of natural bodies are found to depend on the different reflexibilities of the rays, and sometimes on their flexibilities.

Prop. XI. The rays of light are reflected, refracted, inflected, and deflected, by one and the same power, variously exerted in different circumstances.

ERRATA.

PART I.

P. 143, l. 3, *for* affraïant, *read* effraïant.

Note from Henry Brougham, Jun. Esq. author of the paper on the inflection, reflection, and colours of light. See page 227, &c.

“ Owing to an error which crept into the integral calculus by which the problems on the trajectory of light were resolved, two of these solutions are erroneous, and must be corrected thus: 1. When the bending force is inversely as the distance, the curves to be squared are, a conic hyperbola, and a logarithmic, $y^2 = \frac{1}{l\frac{a}{x}}$. The trajectory, therefore, cannot be found in finite terms; its equation is $\dot{y}^2\, l\frac{a}{x} = \dot{x}^2$; and the subtangent is to the subnormal as 1 to $l\frac{a}{x}$. 2. When the bending force is inversely as the square of the distance, the curves to be squared are a cubic hyperbola, $y = \frac{1}{x^2}$, and a cubic conchoid, $y^2 = \frac{x}{a-x}$; therefore the equation to the trajectory is $(a-x)\,\dot{y}^2 = x\,\dot{x}^2$, which belongs to a *cycloid*, the radius of whose generating circle i *a*. In general, if the force be inversely as the *m*th power of the distance, the equation of the trajectory will be $(a^{m-1} - x^{m-1})\,\dot{y}^2 = x^{m-1}\,\dot{x}^2$, which agrees also with the first case, where *m* being $= 1$, $\underline{a^{m-1}}$, may be esteemed the hyperbolic logarithm of *a*.”

H. BROUGHAM.

Edinburgh,
July 2, 1796.

Fig. 1.

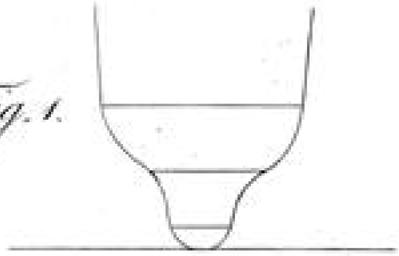


Fig. 2.

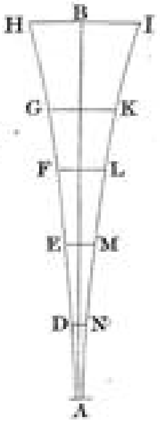


Fig. 3.

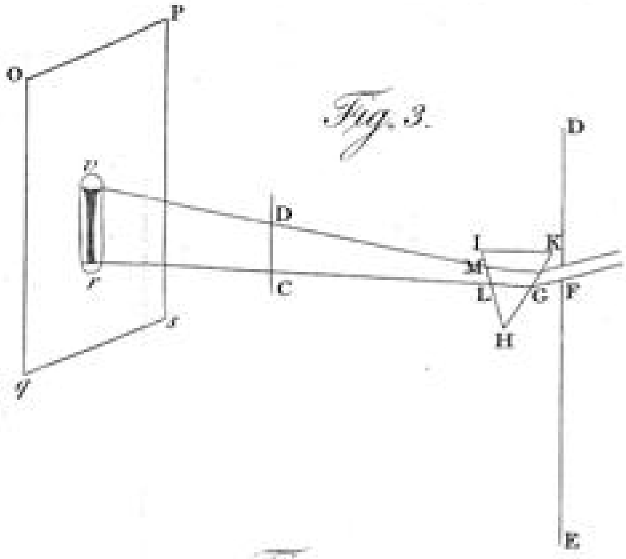


Fig. 4.

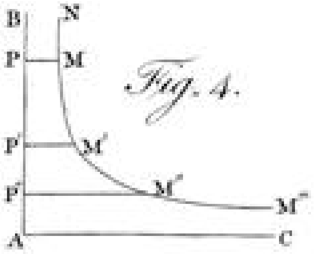


Fig. 5.

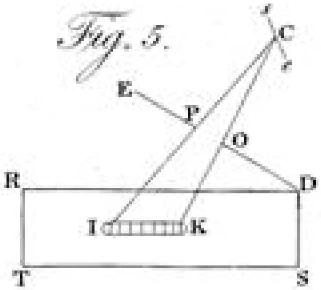


Fig. 6.

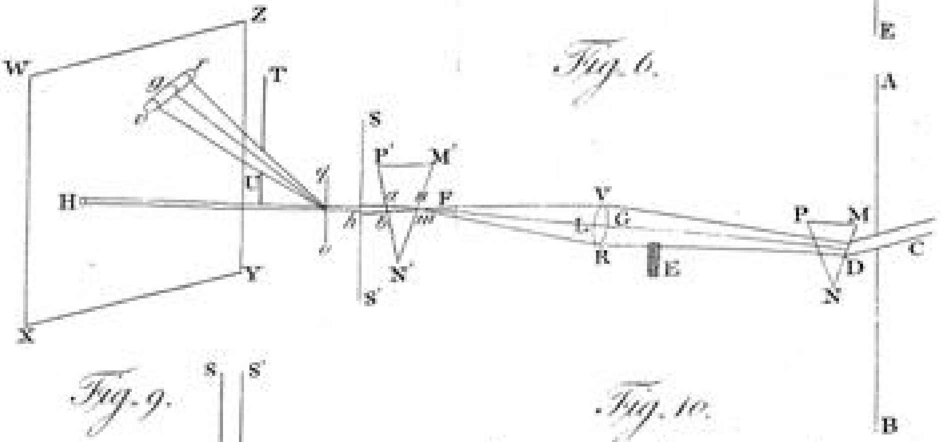


Fig. 7.

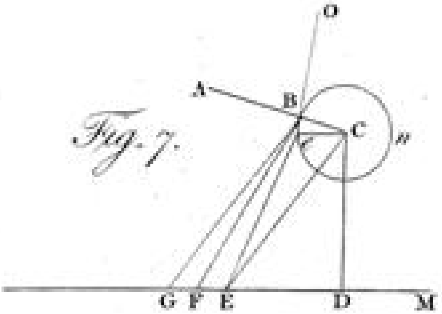
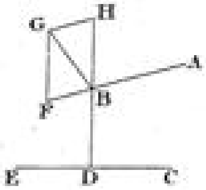


Fig. 8.



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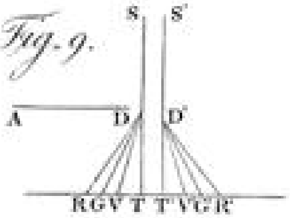

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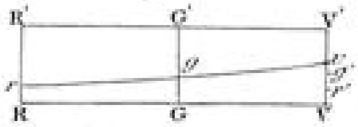

Fig. 11.

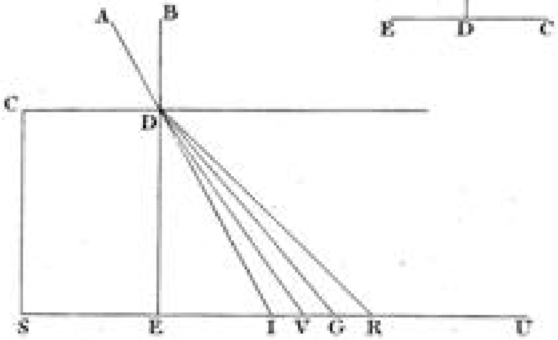

Fig. 12.

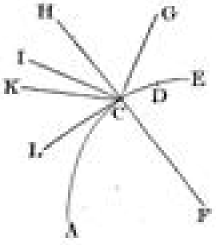

Fig. 13.