XVII. *Continuation of Experiments for investigating the Cause of coloured concentric Rings, and other Appearances of a similar Nature.* *By* William Herschel, *LL. D. F. R. S.*

Read March 23, 1809.

In the first part of this paper, I have pointed out a variety of methods that will give us coloured concentric rings between two glasses of a proper figure applied to each other, and it has been proved that only two surfaces, namely, those that are in contact with each other, are essential to their formation; it will now be necessary to enlarge the field of prismatic phenomena, by showing that their appearance in the shape of rings has been owing to our having only used spherical curves to produce them.

35. *Cylindrical Curves produce Streaks.*

As soon as it occurred to me, that the cause of the figure of any certain prismatic appearance must be looked for in the nature of the curvature of one or both of the surfaces, that are essential to its production, I was prepared to expect that if a spherical curve, when applied to a plain surface of glass, produces coloured rings, a cylindrical one applied to the same would give coloured lines or streaks. To put this to the proof of an experiment, I ground one side of a plate of glass into a cylindrical curve, and after having given it a polish, I laid a slip of plain glass upon it, and soon perceived a beautiful set of coloured streaks. The broadest of them was at the line of contact, and on each side they were gradually narrower and less bright. The colours in the streaks were similar to those in the rings, and they were in the same manner changeable by pressure as in them. Their order was likewise the same, if we reckon from the line of contact, as with rings we do from the center; so that these streaks differed in no respect from rings, except in their linear instead of circular arrangement.

When the cylindrical surface was laid upon a plain slip of glass, the same streaks were seen as in the former experiment. They were of a lively red and green colour, and I saw at least ten, eleven, or twelve on each side of the line of contact.

Metalline surfaces had the same effect, for when the cylindrical surface of glass was laid on a plain metalline mirror, I had red, orange, yellow, green, and blue streaks. In the same manner a plain slip of glass placed upon a polished part of a brass cylinder of $3\frac{1}{2}$-inch in diameter, produced also coloured streaks.

The combination of two cylindrical surfaces has an effect on the streaks, which is similar to that which the contact of two spherical ones has on the rings; for when I placed the cylindrical surface of glass longitudinally upon the polished part of the brass cylinder, the streaks were contracted as rings would have been by the application of two spherical curves to each other.

36. *Cylindrical and spherical Surfaces combined produce coloured elliptical Rings.*

The theory which suggests to us that the particular figure of every prismatic appearance between glasses depends on the curvature of the surfaces which are in contact, is still farther confirmed when spherical and cylindrical curves are applied to each other; for these, accordingly, should give elliptical rings; and when I tried the experiment, by laying a 26-inch double convex lens upon the cylindrical surface of my plate of glass, it produced a coloured elliptical central part, encompassed with gradually vanishing rings of the same figure. By changing the focal length of the lens, I could alter the proportion of the conjugate to the transverse axes of these elliptical rings at pleasure. A lens of 55 inches gave ellipses that were much flattened, and one of 5 inches gave them nearly circular.

37. *Irregular Curves produce irregular Figures.*

The modifying power of surfaces may be further established by such as have no regular figure; for these ought to give irregular prismatic phenomena, and this was fully proved by the following experiment.

I took a large piece of mica which had a very glossy but irregular surface, and when a 34-inch double convex lens was placed upon a small ridge of it, several pretty straight streaks might be seen, but wherever the ridge was waving the streaks were following the same direction. In some places the mica gave irregular, coloured arcs, that were concave to some distant centre; and in others, the various contorted figures, that were to be seen, exceeded all the imaginary forms which the most inventive fancy can paint. The flexibility of mica also gave room for using different degrees of pressure, by which means a continual change of figure and succession of prismatic colours was produced.

When I laid a piece of this mica upon a cylinder, and placed a plain slip of glass or double convex lens upon it, all its irregularities were modified into disfigured streaks with the former, and distorted ellipses with the latter.

Experiments of a similar nature were made upon the irregular surface of Island crystal and other substances, which all gave the same result.

38. *Curved Surfaces are required for producing the coloured Appearances at present under Consideration.*

It has already been seen, in the first part of this paper, that spherical curves give circular rings, and I have now shown that cylindrical forms produce streaks; that a combination of spherical and cylindrical curvatures give elliptical rings, and that all sorts of variegated coloured phenomena are made visible by surfaces, which are irregularly and variously curved; these experiments prove in the fullest manner that the curvature of surfaces is the cause of the appearance, as well as of the shape of the coloured phenomena which are produced. For if we can invariably predict, from the nature of the curves we employ in an experiment, what will be the appearance and form of the colours that will be seen, it certainly must prove the efficacy of these curvatures in the production of such phenomena. This will receive additional confirmation in the following article, which shows that

39. *Coloured Appearances cannot be produced between the plain Surfaces of two parallel Pieces of Glass applied to one another.*

As the production and modification of the figure of the coloured appearances, that have hitherto been considered, has in the last article been ascribed to curved surfaces, it will be necessary to examine whether such phenomena may not also be seen between the plain surfaces of two parallel pieces of glass applied to each other directly in contact, or inclined towards each other in some certain extremely small angle.

The latter of these cases has already been considered in the 31st article of the first part of this paper, where I have shown that two plain surfaces, let the angle of the wedge of air between them be as small as you please, will not give coloured streaks. I have indeed seen two thin plain pieces of glass, with a slip of platina of an extraordinary thinness between them at one end tied together, which showed some streaks near the place where the glasses were in contact, but when I removed the thread that bound them together, the streaks vanished, which proves that the glasses had been constrained, and thus had probably assumed some curvature at the point of contact.

I have also tried two flat surfaces of glass, which were so perfect that no colour could be perceived unless they were by unequal pressure somewhat disfigured, and when that was the case large flashy coloured appearances became visible, and their configuration followed very evidently the stress which I laid upon the different parts of the glasses.

It is however unnecessary to dwell on proofs, that streaks cannot be seen when two plain parallel pieces of glass are applied to each other, as it will hereafter be shown that when the incumbent plain glass is not of a parallel thickness, coloured phenomena may be rendered visible between two perfectly plain surfaces, although no force or strain should be used to produce a fallacious, curved, contact.

40. *Of the Production of coloured Appearances.*

Hitherto I have only considered the coloured rings which Sir ISAAC NEWTON has pointed out, and have shown, at the end of the 28th article, that no more than two surfaces are essential to their formation. It has now also been proved, that the configuration of the coloured phenomena arises from the curvature of one or both of the two essential surfaces. From these principles it will be seen, that we are to distinguish between the production of the colours and that of their configuration when produced. By the experiments that have been given, the cause of the configuration is laid open to our view; but the production and arrangement of the colours remain to be investigated.

The leading feature of the arrangement of the colours of the rings is prismatic; that is to say their order is red, orange, yellow, green, blue, indigo, and violet; in order, therefore, to enter minutely into the subject, I shall have recourse to some prismatic experiments.

It will be necessary here to mention, that the proposed enumeration of the modifications of light, which was intended to have been given in this part of my paper, is grown to such an extent by the number of experiments I have made upon the subject, that its introduction would occasion a long interruption of the present subject; and although undoubtedly the action of bodies and surfaces on light would be better understood, if all the modifications wherein colours are produced had been before us, yet as the experiments I have to relate may be made plain, either by referring to modifications that are sufficiently known, or by explaining what is not already familiar, I shall postpone the intended enumeration to some future opportunity, and confine myself at present to a few remarks relating to them.

The colours contained in white light may be separated by reflection, as well as by refraction, and what is perfectly to my present purpose, the order, in which the colours thus produced are arranged, is the same in both cases; each of these principles therefore may cause coloured appearances, which the particular figure of the surfaces we use will mould into different configurations.

Sir ISAAC NEWTON, for instance, has shown that the rays of light will be separated, by what he calls a different reflexibility, when they fall on the base of a prism; the violet being reflected first, and the red last.* By this property of the differently coloured rays, he has explained a very remarkable phenomenon, which is that in a prism, when exposed in the open air, and when the eye is properly placed "the spectator will see a bow of a blue colour."† From the little the author has said of this bow, it may be supposed that he did not examine it farther than was required for his purpose; it will therefore be necessary to enter more fully into the subject.

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* See the illustration of the 9th experiment in the first book of NEWTON's Optics, page 46.

† See the 16th experiment in the second part of the first book, page 145.

41. *Particulars relating to the Newtonian prismatic blue Bow.*

The Newtonian blue bow may very conveniently be examined, when a right angled prism is laid down on a table before an open window. The eye being then brought to a convenient altitude, and pretty near the side of the prism, we see in it a bow, which from the predominant colour may be called blue. It contains some green followed by blue, indigo, and violet. A very faint red, orange, and yellow may also be perceived above the greenish colour; but these belong not to the blue bow, and have not been noticed by the author. Their appearance will hereafter be accounted for.

To analyse this blue bow more particularly, let us admit that the colours, which give it the general appearance of what may be called blue, consists of half the green, and of all the blue, indigo, and violet rays, which are reflected while the other half of the green, the yellow, orange, and red are transmitted. Then the angle of obliquity, at which this separation of the colours will happen, in consequence of the different refrangibility of the differently coloured rays assigned by NEWTON, will be $49^\circ\ 46'\ 12'',5$.

Let A B C D E, Plate XII. Fig. 1, be rays of light moving within glass in such directions, as to fall on the interior base F G upon the points $\alpha\,\beta\,\gamma\,\delta\,\varepsilon$. Then, if it be required that these rays after reflection from the base should meet in the point H, and form the blue bow, the angles $A\alpha G$, $B\beta G$, $C\gamma G$, $D\delta G$, and $E\varepsilon G$ must be respectively equal to $49^\circ\ 46'\ 12'',5$; $49^\circ\ 49'\ 20''$; $49^\circ\ 55'\ 33'',6$; $49^\circ\ 59'\ 41'',4$; and $50^\circ\ 7'\ 54''$; which will give the angles $\alpha H \beta$, $\beta H \gamma$, $\gamma H \delta$, $\delta H \varepsilon$, equal to $3'\ 7'',5$, $6'\ 13'',6$, $4'\ 7'',8$, and $8'\ 12'',6$, making in the whole the angle subtended by the bow $\alpha H \varepsilon$ 21′ 41″,5.[*] For in consequence of the different reflexibility of the differently coloured rays the violet, indigo, blue, and faintest half of the green rays will be reflected between α and β, if they fall on that space in any angle between the above mentioned ones contained between $A \alpha G$ and $B \beta G$; and will therefore meet at H, and form the greenish blue part of the bow. The red, orange, yellow, and the brightest half of the green rays, on the contrary being less reflexible, will be transmitted through the base between α and β, and by refraction pass in proper angles into the air. The letters $v\,i\,b\,\frac{1}{2}g$, which in the figure are placed within the space $\alpha H \beta$, denote the reflected colours, and $\frac{1}{2}g\,y\,o\,r$ put under the base between α and β are the initials of the transmitted colours; and in the same manner the reflections and transmissions which must happen between $\beta\gamma$, $\gamma\delta$, and $\delta\varepsilon$ are expressed by the letters over the base for the former, and under it for the latter. The order of the colours of the blue bow, when it is seen at H, is perfectly explained by the letters in the reflected part; and the eye must be placed, for seeing it, at the mean obliquity between the angles $A \alpha G$ and $E \varepsilon G$, which is 49° 57′ 3″,3.

In order to conform this account of the blue bow, to the manner in which it was viewed by NEWTON, I have preserved his way of ascribing the separation of the rays to their different reflexibility, which however is merely the effect of their

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[*] There is a mistake in one of the angles given by NEWTON, when in his Optics, page 145, he explains the blue bow; for 49 deg. $\frac{1}{28}$ taken from 50 deg. $\frac{1}{9}$, makes the breadth of the bow 1° 4′ 31″,4, which contradicts the refractions he has given, page 112. As he only takes in the blue, indigo, and violet colours, instead of $49\frac{1}{28}$ degrees, it should rather be $49\frac{23}{28}$.

different refrangibility. The angles at which the rays that constitute the blue bow are separated from the rest, may very properly be called *critical*, and the effect, which is the consequence of the oblique incidences that have been given, may with equal propriety be called a *critical separation* of the differently coloured rays of light.

42. *Account of a prismatic red Bow.*

I must now introduce a prismatic appearance, which on account of its similarity with the Newtonian blue bow, from which it only differs in colour, I have called, a prismatic red bow. It consists of red, orange, yellow, and some green rays; and the red colour being upon the whole very predominant, it may not improperly be called a red bow. It is not produced by the Newtonian different reflexibility of the differently coloured rays of light, but owes its origin to a modification which takes effect at the outside of the prism at very oblique angles of incidence, and may be called a different intromissibility; but this, like the Newtonian different reflexibility, is only the consequence of the different refrangibility of light.

To see the red bow, an observer should place himself in the open air, and standing with his back within a few feet of some wall or building, hold the side of an equilateral prism flat over his eyes, and look upwards to an altitude of about 30° at the heavens; he will then see a beautiful arch of a deep red colour, succeeded by a bright orange and yellow, with a considerable portion of green on the inside. The comparative darkness of the building behind will show the light in front to the best advantage. It is also to be observed, that all experiments on prismatic bows succeed best, when the heavens are totally overcast with an uniform cloudiness.

To analyze the production of this bow, let ABCDE, Fig. 2, Plate XII. be rays of light moving in air, in such directions as to fall on the exterior base FG, of a piece of glass, upon the points $\alpha\,\beta\,\gamma\,\delta\,\varepsilon$; then, if it be required that these rays, after their intromission into the glass should meet in the point H and form the red bow, the angles AαH, BβH, CγH, DδH, and EεH, must be respectively equal to 130° 29′ 33″,6; 133° 40′ 33″2; 134° 29′ 28″2; 135° 36′ 13″2; and 136° 10′ 38″,0; from which we have the angles AβB, AγC, AδD, and AεE, which a red ray would make were it to pass out of glass into air, equal to 3° 15′ 45″,5; 4° 7′ 30″5; 5° 19′ 17″5; and 5° 56′ 50″,5. Now by the laws of the different refrangibility of light, the red rays are intromissible at α, when by refraction they make the angle HαF = 49° 30′ 26″4; but the orange cannot be intromitted any where between α and β with any effect on the red bow, since it is only at β, where the angle HβF is 49° 35′ 12″3, that they can enter the glass so as to come to the eye at H. The yellow rays will, for the same reason, be efficiently intromitted only at γ, where they will make the angle HγF 49° 38′ 2″,3, and the brightest half of the green rays will find an efficient entrance from δ to ε, since the smallest angle of their intromission HδF is 49° 43′ 4″,3, and the angle HεF, which terminates the red bow, is 49° 46′ 12″5. The arrangement of the colours of this bow will be seen, as it was in the blue bow, from the letters placed above the base, which denote those that are intromitted so as to come to the eye; the rest of the colour-making rays, which cannot come in that direction, being marked by letters placed under the base. The whole angle of the red bow $\alpha H \varepsilon$ is 15′ 46″,1, and the mean obliquity of the eye at H is 49° 38′ 19″,5.

In the calculation of both the bows, the situation of the eye at H has been determined, as it would be, were the rays to remain in glass; but as they will be refracted by the side of a prism, when they come out of it, proper computations must be made not only of the place of the eye in air, but also of the angle which the bow will subtend; for this will be found to be considerably different in different prisms; those that have large refracting angles will magnify the bows more, and require the eye to be nearer than others that have smaller angles.

These bows may be examined at leisure, by projecting them upon a white ground in the following manner:

In a dark room, by a reflecting apparatus, I admitted a horizontal beam of the solar light through an opening of about an inch and a half in diameter. The formation of the bows requiring scattered light,* I covered the opening with a piece of glass evenly roughned on both sides. Then, with an intention to obtain a projection of the blue bow, I placed a prism having one angle of 91° and the other two nearly equal, close to the emeried surface, and turned it upon its axis till the angle of obliquity of the scattered rays, that fell on one side of the prism, was proper for the required critical separation of the coloured rays. The obliquity of the middle ray with the base, for this purpose, it has been shown, must be 49° 57′ 3″,3. In this position the interior critical separation of the prismatic colours taking place, the blue part, namely the violet, indigo, blue, and about one half of the green rays were

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* See the first paragraph of the 46th article of this paper.

reflected, and passing through the opposite side of the prism projected the blue bow upon the cieling of the room. The colours may there be conveniently seen; but as this bow is composed of the least luminous rays of the prismatic spectrum, it requires considerable attention to perceive the faintest of them. The green and blue are most visible, and by receiving the bow upon a screen of white paper held at the most favourable distance, the fainter colours, when the illumination is very bright may also be perceived.

In order then to project also the red bow, I turned the prism upon its axis till the scattered light fell with a proper obliquity on the base of it; the angle required for this purpose, it has been shown, must be from 0° 0′ 0″ to 5° 56′ 50″5; the side of the prism, which is turned towards the opening, should be covered with a slip of pasteboard to prevent any light from entering it. In this situation, I saw a very bright arch containing red, orange, and yellow projected at some distance backwards upon the cieling; that part of the green which no doubt was also transmitted, was lost in the brightness which is to be seen within the bow, for the same reason that the faint colours of the blue bow can only with great difficulty, if at all, be perceived; namely, that they join the dark inside of the bow. For NEWTON has proved that the space beyond the convex part of the blue bow must be bright, and that beyond the concave dark; but in the red bow, as my theory will show, we have that on the convex dark, and on the concave bright. This experiment therefore proves, that here, by the gradual intromission of the differently coloured rays, a critical separation takes place on the outside of the prism, similar to that which by reflection happens in the blue bow at the inside; and by which, in the present case, the red part of the prismatic spectrum, that is, the red, orange, yellow, and some of the green, can only reach the eye.

43. *Of a sudden Change of the Colours of the Bows.*

It has been shown that the red bow should be seen nearly in the same place where the Newtonian blue bow is visible. For in the 41st article the place of the eye, for seeing the blue bow in the prism of 100 degrees, was determined to be at an obliquity of 49° 57′ 3″,3; and with the red bow, and in the same prism, it has been shown that the eye must be placed at the obliquity of 49° 38′ 19″,5. The difference is only 18′ 43″,8, and by the following experiments it will be found, that both the bows may actually be seen nearly in the same part of every prism; and that the direction of the light, by which we see either the blue or the red bow, determines which of the two will be visible. To prove this, let a right angled prism be laid down on a sheet of white paper before a window, and when the eye is placed in the proper situation for seeing a reflected blue bow, we may instantly transform it into a transmitted red one, by covering the side of the prism which is towards the incident light with a slip of pasteboard; for by stopping the direct light, which before fell on the base of the prism, and was there reflected, we then see the bow by light intromitted from the paper through the base, which, as has been explained, will be red.

With proper management we may have the bow half red and half blue; blue in the middle with red sides, or red in the middle with blue sides; which appearances it will not be required to explain any farther, especially after what has already been said in the 18th article of the first part of this paper of the change of the colours of rings.

When we have before us a bow that is half blue and half red, it will be seen that both taken together contain all the prismatic colours in their regular order of refrangibility. It will now also appear that the faint red, orange, and yellow, which I have said are to be perceived above the blue bow* may arise either from an imperfectly transmitted red bow, which always lies concealed under the Newtonian blue one, or perhaps more probably from the partial reflection of the red, orange, and yellow rays, many of which will come to the eye notwithstanding they are also copiously transmitted.†

According to my account of the red bow, it ought to be seen in the prism a little above the blue one, and this is also further confirmed by any one of the experiments in which we have some part of each bow in view at the same time, for then the relative situation of the two bows will be visible.

Similar experiments may be made by candle light upon either of the bows; for when a sheet of white paper is pinned against a wall, that it may reflect the light of a candle placed upon a table about three or four inches from the paper, we may then see the blue bow in a prism placed upon a dark ground before the reflecting paper; and the green colour, which it is not very easy to perceive distinctly in daylight, will here be very visible, and the more so if we use an equilateral

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* See the first paragraph of the 41st article.

† In my modifications of light I have proved, by undeniable experiments, that within a prism as well as on the outside of it the rays of all the colours are equally reflexible, and that a critical separation of them only takes place at those angles where by refraction a ray cannot be transmitted.

prism instead of a right angled one. When the reflecting paper is removed from the wall and laid under the prism, that the light may then be thrown upwards and transmitted through the base, we see a bow of a lively red colour.

Before I can introduce more intricate phenomena, it will be necessary to advert to some other particulars relating to these bows.

44. *Of Streaks and other Phenomena produced from the prismatic blue and red Bows.*

It has been remarked in the 40th article, that the production of colours and their configuration when produced are owing to different causes; this will now be confirmed by an experiment.

Scattered rays, when they fall on a prism will by a critical separation of the colours, produce both the blue and the red bows, and these coloured appearances when produced may be modified into streaks, circular rings, and other forms, by the configurating power of surfaces. When a plain glass or metalline mirror is laid under the base of a right angled prism in which we see the blue bow, the contact of the two plain surfaces will immediately produce a great number of coloured streaks. They will be found to be parallel to the bow, most of them within and some just under it. They may be seen without any lens, merely by looking into the prism with the eye pretty close to the surface through which we see the blue bow. This experiment proves that plain surfaces, though they cannot produce colours, have a power of modifying and multiplying them when produced. As I shall have occasion hereafter to be more particular, I shall now only mention that when we lay a spherical surface, such as an object glass, under the prism it will immediately give us several sets of innumerable concentric coloured rings; and, as will now be readily expected, a cylindrical surface placed under the prism will give a number of lenticular appearances, such as are contained between the intersections of two circular arches drawn concave towards each other. The irregular surface of mica will in like manner produce multiplications of appearances, that may be seen much better than they can be described.

When the same surfaces are applied to the red bow, phenomena that are perfectly of the same form will be made visible within and just under the bow; and the streaks will also be in a parallel direction.

The side of the prism, to which a plain glass must be applied, is of singular use in the explanation of many appearances of the coloured phenomena, which are to be seen, and it is on this account that the formation of the generated colours into all sorts of configurations has been noticed before I come to that part of this paper, wherein this subject must find a further discussion; for by the application of a slip of plain glass, we can decisively ascertain the nature of any coloured appearance in the prism. Thus, when we see a common coloured red or blue arch, occasioned by the mere different refrangibility of light, the plain glass any how applied to the prism will give no streaks. If we apply the plain glass to a transmitting side, we can have no streaks from a critical blue bow, because it is occasioned by reflection; and for the same reason, when the plain glass is applied to a reflecting side, we can have no streaks that belong to a critical red bow, because it originates at the intromitting surface. With the assistance of this criterion I may now proceed to a review of more complicated phenomena.

45. *Explanation of various Appearances relating to prismatic Bows.*

If, in the open air, we look into the zenith with a right angled prism held across the eyes, we shall see two red bows convex towards each other. They are caused by the bright transmissions of the light of the heavens through the sides in which the bows appear; for when to either of these sides the criterion of the plain glass is applied, we shall have coloured streaks. The course of the rays which produce the two bows is delineated in Fig. 3, Plate XII. ABC represents the prism, and the rays that can enter the eye when they fall on AB within the limits *ab*A from 0° 0′ 0″ to 5° 56′ 50″,5, which are the red, orange, yellow, and the brightest part of the green, will form the red bow; and the situation of the eye at E will be had by the mean refrangibility of the rays which give the bow; for as the angle B*cd* must be 49° 38′ 19″,5, we have the obliquity B*dc* = 85° 21′ 40″,5 and the angle C*e*E that conveys the ray to the eye will be 82° 49′ 34″,2. The same thing will happen on the other side of the prism, where the rays *m n o p q* will come to the eye at E, in an equal but differently directed angle B*q*E, and cause an inverted red bow to be seen in the side AC.

When we look down into the side of an equilateral prism we see a blue bow, but on lifting the eye and prism gently up together towards the zenith, the bow, at a certain altitude, will be changed from blue to red; and by the application of the criterion, it is proved that we see the first by reflection, and the last by transmission. For, suppose *ab*, Fig. 4. Plate XII. to be a ray of a mean refrangibility between the violet, indigo, blue, and half the green; when this falls on the side A C of the equilateral prism A B C with an obliquity *ab*A of 57° 58′ 28″,5, it will be refracted so as to make the angle C*cd* 70° 2′ 56″,8 which gives 49° 57′ 3″,3 for the angle C*dc*; and consequently the ray *def*E will come to the eye by the same angles of reflection and refraction as it entered the prism, and make A*f*E equal to A*ba*. The eye at E will therefore see a blue bow. Then if a plain glass be applied to the transmitting side A C there can be no streaks; for blue bows being caused by the critical separation of the rays occasioned by the Newtonian reflexibility, the plain glass must be in contact with the reflecting side; and as soon as we hold it against B C, the coloured streaks will make their appearance. The change of the colour of the bow, on lifting the prism and eye together towards the zenith, is represented in figure 5; for the light from the sky, which will enter the prism on the side A B, will eclipse the blue bow which was seen before by light entering from the ground through the side A C in figure 4; then if *a b* fig. 5 is a ray of the mean refrangibility of the red bow, it will by refraction give the angle B*cd* 49° 38′ 19″,5, from which we obtain B*db* equal to 70° 21′ 40″,5, and the ray will, by a second refraction, come to the eye in an angle C*e*E of 58° 44′ 12″,4, where the red bow will be seen; but in order to produce coloured streaks, the plain glass must now be applied to the transmitting side A B.

When a right angled prism is held in the hand, so that the light of the sky through an open window may fall upon the base, if then an observer with his back to the light looks through the base into the side AC of the prism A B C fig. 6, he will see an erect blue bow by two reflections, only one of which however is the cause of the critical separation of the coloured rays, the other being a common one. For when a mean refrangible blue-bow-ray falls with an obliquity *a b* C of 82° 17′ 31″ on B C, it will by refraction give the angle B *c d* = 85° 2′ 56″,8, from which we obtain A *d e* = 49° 57′ 3″,3, which being the mean angle of the critically separated rays, they will by reflection pass to the side A C, where the angle of the common reflection C *e f* will be 40° 2′ 56″,8; this gives *e f* B 85° 2′ 56″,8, and by refraction the middle of the blue bow will be seen by an eye at E in an angle E *g* B equal to the angle *a b* C. From the construction of the figure, it is evident that the eye may be drawn from E towards *a*, and always keep the blue bow in view, which will still remain erect; for when the eye comes to *a*, the rays by which the bow is seen will then enter at E, and the critical reflection will still remain at *d*, as may be satisfactorily proved by an application of the plain glass to AC, which will cause no streaks, whereas they will immediately appear when it is held under the side A B.

When the eye looks into the side B C with the same obliquity of 82° 17′ 31″, but differently directed, so that in fig. 7 the angle may be *a b* B, instead of *a b* C a blue bow will again be seen, but in an inverted position. This also may be drawn over into the other side of the prism without an alteration of its appearance, the reason of which is sufficiently evident from the construction of the figure; but in this case the critical reflection will be a *e*, and the common one at *d*.

It will be proper to shew that like appearances of the red bow may be seen; for this purpose let the prism be laid with one side upon a sheet of white paper placed in a window, with the base towards the observer, as represented in fig. 8. In this position, the light from without reflected by the paper under the prism will be brighter than that from within the room, and the very oblique incident rays ab will be refracted by the horizontal side A B, so as to make the angle $\mathrm{B}cd$ equal to $49^\circ\, 38'\, 19'',5$, from which we have $\mathrm{B}dc = 85^\circ\, 21'\, 40'',5$, and by refraction $\mathrm{C}e\mathrm{E} = 82^\circ\, 49'\, 34''2$, the eye placed at E will therefore see an erect red bow in the horizontal side A B, which may be drawn over into the perpendicular side without change of position; for the scattered rays reflected from the paper will also enter the prism in the same oblique angle of incidence from the opposite direction ab fig. 9; where having caused the red bow by an intromissive critical separation at c, they will come to the eye after a common reflection from the side A C, in the same angle as before.

When an inverted red bow is to be seen the eye must be placed a little lower, and the calculation of the angles in the 10th and 11th figures, which represent the course of the rays, being similar though differently directed, will be sufficiently understood by an inspection of them; but as in fig. 8 and 9, the intromissive separation was produced by the horizontal side, so it is, in these figures, effected by the vertical one; all which may be proved by a proper application of the criterion.

There are many other phenomena attending the bows, but as they are more intricate, and not necessary for my present purpose, I leave them to the ingenuity of those who have entered into the preceding calculations, which are quite sufficient to point out the method that should be taken for explaining them.

46. *The first Surface of a Prism is not concerned in the Formation of the blue Bow, nor of the Streaks that are produced by a plain Glass applied to the efficient Surface.*

It has already been mentioned that the bows are formed by scattered light; but to have a direct experimental proof that such light, if not absolutely necessary to the formation of the bows, is at least equally efficient with regularly refracted light, I took a prism with one side of it roughened on emery, and receiving the light through it when the eye was in the situation required for seeing the blue bow, I saw it as completely formed by scattered light, as it could have been by light regularly refracted through a polished side.

A natural consequence of this experiment seems to be, that the form of the surface through which light enters can be of no consequence; this will however admit of a more convincing proof, as follows: upon the middle of the side of a right angled prism, through which the rays entered that caused the blue bow, I laid a plano convex lens of an inch and a half focus; the result was, that not the least alteration could be perceived either in the form or in the colour of the bow, both which remained as perfect under the place where the incident rays passed through the lens as they were on each side of it. When I changed the convex lens for a plano-concave glass of the same focus, appearances were still the same; and when by a critical application of a plain glass I produced coloured streaks from the base of the prism, the interposition of either the convex or concave glass was equally immaterial. A scattering glass applied to the incident ray, had no other effect than to diminish the brightness of the bow.

The same experiment may be repeated with the red bow; but as here the first surface is essential to the formation of the bow, the plain side of the convex lens or concave glass, when placed against the prism, as before, will produce streaks; neither the bow, nor its streaks however will be in the least affected by the convexity or concavity of the outward surface of the glass applied, through which the light is admitted. A scattering glass will have no effect to disturb the bow or its streaks, and when this glass is emeried on both sides, we have again the bow complete, but without streaks; and by this fact it is proved, that unless a polished plain reflecting surface is applied to the prism, streaks cannot be formed.

47. *The Streaks which may be seen in the blue Bow contain the Colours of both the Parts of the prismatic Spectrum, by the critical separation of which the Bow is formed.*

The moſt favourable way of observing the colours of the blue bow streaks that are formed when a plain glass is laid under the base of a right angled prism, is to place a screen of white paper, before an open window, and to let the direct solar light shine through it upon the side of the prism. This scattered light will be bright and uniform, and cause no adventitious colours to mix with the streaks. The eye should be within six or seven inches of the prism. A streak consists of a certain principal colour and the intermediate tint which separates it from the next; and in the following memorandum of fourteen streaks, which I saw in the manner above described, the principal colours are placed in front, and the dividing tints at the side between them.

1. Very faint blue, - - - - - - Pale red.
2. Faint blue, - - - - - - - Pale red.
3. Blue, - - - - - - - Pale red.
4. Bright blue, - - - - - - Faint red.
5. Purple blue, - - - - - - Whitish red.
6. Bluish red, - - - - - - Whitish red.
7. Deep red, - - - - - - - - Greenish white.
8. Red, - - - - - - - - Greenish white.
9. Red, - - - - - - - - Pale bluish green.
10. Red, - - - - - - - - Pale bluish green.
11. Pale red, - - - - - - - Pale bluish green.
12. Paler red, - - - - - - - Dirty white.
13. Dingy yellow, - - - - - - Dirty white.
14. Dingy yellow.

To ascertain whether the second surface of the subjacent glass, which by other experiments I know to have a multiplying power of at least six or seven reiterated interior reflections, all of which may be seen through the side of the prism, had any share in the production of these streaks, I fixed on one side of it a glass, of which the lowest surface was emeried, and on the other a metalline plain mirror, but found that the streaks were both in number and colour perfectly alike in them all.

By this account it is evident that the streaks derived from the blue bow contain not only the colours of the blue reflected, but also those of the red transmitted part of the spectrum. This fact is a clear indication of the office which is performed by the surface of the subjacent plain glass, which is simply that of reflecting back the rays of the transmitted red part of the spectrum, which being mixed with the blue part, both together, by their intersections, produce the observed streaks, as will be explained hereafter.

That the colours of the transmitted part of the spectrum are reflected back into the prism, is a point which I suppose will be admitted; but if it should be imagined that the red rays in the streaks of the blue bow might come into the prism by a scattered reflection of the light which falls on the plain glass under its base, then I say that a sheet of white paper or double emeried glass, ought to give the brightest streaks; whereas, on the contrary, neither of them produces any;* it is therefore evident, that a regular reflecting surface is necessary to their formation; but such a surface, be it glass or metal, can only reflect red rays when it receives them; and since we know that the red part of the spectrum is transmitted, and must fall on the reflecting surface, it is but fair to conclude that the

* See the last paragraph of the preceding article.

rays, of which that part is composed, are those which by reflection re-enter the prism.

48. *On the Formation of Streaks.*

As I have now ascertained that the streaks we see when a plain glass is laid under a prism, which shows the blue bow, are formed by the principle of reflection, which throws back the transmitted rays, it will be a considerable satisfaction if we can trace the course of these rays far enough to have some idea of the arrangement, whereby such appearances may be produced. To show, by calculation, the complete formation of the streaks in a case that is liable to such variation, on account of the different contact between the modifying surfaces, the position of the light and the inclination of the eye, would be a most laborious, if not endless, undertaking; it will therefore be sufficient, if I can make it appear, that streaks must unavoidably be produced by the rays which after transmission are reflected back again, and mix with those that form the bow; and this I believe will not be difficult. For instance, let F G, fig. 12, Plate XIII. be the base of a solid piece of glass, in which a compound ray of light is moving from A to α, with an obliquity A α G $= 49^\circ\, 46'\, 12,''5$; and let I K be the plain surface of a reflecting substance placed under the base; then will the violet, indigo, blue, and the faintest part of the green of this ray be reflected at α, and the remaining green, the yellow, orange, and red will be transmitted. Now, in order to understand the intention of this figure, it will be necessary to observe that on account of the minuteness of the operations of light, all the lines and distances are represented upon a scale one thousand times larger than what the calculation gives them. The real dimensions of several lines therefore cannot find room in the figure, and must be supplied by imagination. The distance of the eye from the base F G, for instance, which in the calculation has been assumed to be only three inches, will be 3000; the diameter of the pupil of the eye 200; the breadth of the base not less than 2160; and the subtense of the whole blue bow will be twenty-four inches eight tenths. The distance between the reflecting surface I K, and base F G, I have supposed to be the ten thousandth part of an inch; it is therefore in this figure represented by one tenth of an inch, and the space $\alpha\beta$, in which the colours that have been mentioned are transmitted, and which by calculation is ,003588 is expressed by 3,59 inches.

The rays of the different colours which are transmitted at α will be refracted in different angles, and when they come to the reflecting plane will be returned to the base in such a direction, as to come to it again in the same angle in which by refraction they left it; but their distance from the point α, when they reach the base, will differ considerably. If we call the angle of refraction φ, and the distance of the reflecting plane from the base x, then $2x \times \frac{\text{rad.}}{\text{tan. } \varphi}$ will be an expression for the intervals at which the several rays will re-enter the base, which for red will be $\alpha r =$,0019198, for orange $\alpha o =$,0022974, for yellow $\alpha y =$,0026675, and for green $\alpha g =$,0043053. At these places the rays will be a second time refracted, and rise towards the eye in parallel directions, and with an obliquity of 49° 46′ 12″,5 equal to that of their incidence A α G. Their course is represented in the figure by the letters $\alpha r r' r''$, $\alpha o o' o''$, $\alpha y y' y''$, and $\alpha g g' g''$.

These things being premised, I proceed to explain the consequences that must arise from the mixture of the transmitted with the originally reflected rays. The first is, that the rays which after transmission re-enter the prism at different points, and are the cause of the streaks, will not proceed in a parallel direction with those that by reflection from the same or neighbouring points form the blue bow. For instance, let $A \alpha \alpha'$, and $B \beta \beta'$, fig. 13, be two incident and reflected rays of the blue bow; then if the yellow ray transmitted at α after two refractions, and one reflection, not expressed in this figure, re-enters the prism at y, it will make the angle $y' y$ F equal to the angle $A \alpha G$. But from the construction of the blue bow, it has been shown that $B \beta G$ is greater than $A \alpha G$; $\beta' \beta F$ is therefore greater than $y' y$ F, and the rays $\beta \beta'$ and $y y'$ will meet somewhere in the line $\beta \beta'$ produced. If we call the greatest of the two angles m, the smallest n, and the distance of the angular points d, then $d \times \frac{\sin. n}{\sin. m - n}$ will give us the length of the line $\beta \beta'$, at which the two rays will meet and intersect each other, which according to the enlarged size of this figure, will be at 773 inches from β. For the same reason the orange ray $o o'$ will meet $\beta \beta'$ at 1084 inches, and the red ray $r r'$ at 1401 inches from β. It follows also from the same construction, that some of the transmitted rays will diverge from the reflected ones; for instance, the green ray transmitted at α, which re-enters the prism at g, will make the angle $g' g$ F less than the angle $\beta' \beta F$; the rays $\beta \beta'$ and $g' g$ will therefore diverge. To this may be added, that $g g'$ $y y'$ $o o'$ $r r'$ and $\alpha \alpha'$ will be parallel.

If such difference between the directions of the transmitted and reflected rays takes place, it will be seen that the rays transmitted through different points are among themselves subject to the same variety in the direction of their course; $r' r''$, $o' o''$, $y' y''$, $g' g''$, for instance, which passed through the point α, are parallel to each other; but all of them converge respectively to $r r'$, $o o'$, $y y'$, $g g'$ transmitted through c; and on the other hand $y' y''$, $o' o''$, $r' r''$, diverge from $g g'$.

Fig. 14, Plate XIV. is a general representation of the course of the rays of the blue bow, and of those that produce the streaks. The base of the bow is divided into twenty equal parts, and one ray of the bow reflected from each of the points of the division is marked by a line. Twenty-one sets of rays of the different colours transmitted through the same points re-enter the base at their calculated places, and are represented by dotted lines drawn at proper angles; but here it should be noticed, that the difference of the twenty angles being much too small to give any idea of their converging or diverging condition, the difference between each set has been expressed by one degree less towards the right, and one degree more towards the left; the angle of the middle ray being of its proper magnitude. The strong lines marked A α, B β, C γ, D δ, E ϵ, show the division of the colours, and are the same which in fig. 1 were used to explain the construction of the blue bow. The rays incident on the base FG, in the direction of these lines, which are reflected in the same angles, and are also marked with strong lines, meet at the point where the eye is supposed to be placed.

The figure has been drawn by the result of a strict calculation contained in the following table. In the first column are the angles of the obliquity of the incident rays; in the second we have the distances of the reflecting points on the base from α. The remaining columns contain the distances also reckoned from α, at which the transmitted rays of the several colours re-enter the base, after two refractions and one reflection.

Table of Calculations.

No.	Obliquity.	Distances.	Red.	Orange.	Yellow.	Green.	Blue.	Indigo.	Violet.
	° ′ ″								
1	α 49 46 12,50	,0000000	,0019198	,0022974	,0026675	,0043053			
2	49 47 17,58	,0012397	,0030962	,0034310	,0037464	,0049503			
3	49 48 22,65	,0024794	,0042782	,0045780	,0048491	,0057881			
	β 49 49 20,00	,0035880	- - -	- - -	- - -	- - -			
4	49 49 27,73	,0037191	,0054653	,0057356	,0059726	,0067327			
5	49 50 32,80	,0049588	,0066566	,0069021	,0071117	,0077443	,0118750		
6	49 51 37,88	,0061985	,0078517	,0080759	,0082630	,0088005	,0112212		
7	49 52 42,95	,0074382	,0090501	,0092559	,0094243	,0098887	,0115764		
8	49 53 48,03	,0086779	,0102514	,0104413	,0105938	,0110005	,0122780		
9	49 54 53,10	,0099176	,0114553	,0116311	,0117701	,0121302	,0131457		
	γ 49 55 34,00	,010721	- - -	- - -	- - -	- - -	- - -		
10	49 55 58,18	,0111573	,0126614	,0128249	,0129523	,0132741	,0141088		
11	49 57 3,25	,012397	,0138695	,0140221	,0141395	,0144294	,0151325	,0186142	
12	49 58 8,33	,0136367	,0150797	,0152224	,0153309	,0155939	,0161973	,0183685	
13	49 59 13,40	,0148764	,0162915	,0164254	,0165261	,0167661	,0172916	,0188450	
	δ 49 59 41,00	,0154406	- - -	- - -	- - -	- - -	- - -	- -	
14	50 0 18,48	,0161161	,0175048	,0176307	,0177246	,0179447	,0184081	,0196009	
15	50 1 23,55	,0173558	,0187194	,0188382	,0189259	,0191288	,0195415	,0204987	,0231720
16	50 2 28,63	,0185955	,0199354	,0200476	,0201299	,0203177	,0206884	,0214808	,02[illegible]1409
17	50 3 33,70	,0198352	,0211525	,0212588	,0213361	,0215106	,0218460	,0225168	,0236904
18	50 4 38,78	,0210749	,0223707	,0224715	,0225444	,0227070	,0230125	,0235906	,0244812
19	50 5 43,85	,0223146	,0235899	,0236857	,0237545	,0239066	,0241864	,0246915	,0253990
20	50 6 48,93	,0235543	,0248100	,0249013	,0249663	,0251090	,0253664	,0258130	,0263933
21	ε 50 7 54,00	,024794	,0260309	,0261180	,0261797	,0263138	,0265518	,0269504	,0274380

From the complex nature of this figure, it will immediately be seen that we cannot attempt an investigation of the particular streaks, that will be formed by the mixture of the transmitted with the reflected rays. An inspection of it, however, will be sufficient to show that streaky appearances must be produced. For instance, between α and the first red ray which re-enters the base, a narrow blue streak should be seen; this will be broken in upon by the mixture of two sets of red, orange, and yellow rays, which together with the reflected colours of the bow, the green being still wanting, must give a pale red division immediately joining the blue streak. When we advance farther into the figure, the great mixture of the colours and the different directions of the rays are so various, that nothing particular can be determined without entering into a very complicated calculation of the meeting and intersections of the rays; we see, however, that these mixtures will produce a condensation of rays in some parts, and vacancies in others, so that no uniform tinge can remain, and consequently streaky appearances must be seen. The same conclusion may be drawn from an inspection of the places where the transmitted colours re-enter the base; for the green, which is transmitted between α and β does not enter again till after the fourth division of the base; the blue which begins to be transmitted at β cannot find admittance again till after the tenth; the indigo transmitted from γ to δ does not re-enter into the composition till after the sixteenth division; and the violet transmitted between δ and ε will only come in again after the nineteenth. There will consequently be a considerable space without green, another without blue, a third without indigo, and a fourth without violet; from which it follows, that streaky appearances must every where be seen in the composition of the rays that come to the eye. We should also notice that towards δ all colours but violet will be transmitted, for which reason when they rise again a compound of them will produce streaks that approach to white, such as pale red, pale bluish green, dingy yellow, and dirty white; so that both at the beginning and end of the bow-streaks all observations * of them agree perfectly with what is pointed out by the foregoing remarks; and though we have not analysed the particular construction of the streaks in the middle of the bow, yet what has been said will sufficiently prove that various successive changes of the colours must also take place.

It will be understood that I have only attempted to give some idea of the action of surfaces, in giving configuration to colours that are already produced; but that the principle of reflection is the cause of streaks will remain evident, even if the method of its action should not have been explained so much to our satisfaction as we might wish. It will also remain to be proved, that streaks are only the effect of one of those modications which depend on the figure of the reflecting surface;† and having got thus far in this research, I may advance towards a final consideration of my subject.

49. *Prismatic Bows when seen at a Distance are straight Lines.*

The next point to be shown, in order to approach gradually to a solution of my problem, is that the apparently arched figure of the blue and red bows, which may be seen in a prism,

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* See the first paragraph of the last article.

† See the second paragraph of the 44th article.

is merely the consequence of the position of the eye, and the modifying power of the surface through which it sees them. For a proof of this, it would be sufficient to refer to the principles of the formation of the bows, from which it must be evident that the critical separation of the rays will be exerted in every direction, and that the extent of the bows we see would consequently be parallel to the sides and base of the prism, if the eye could receive the rays which form them, every where in the same angle from a line drawn parallel to that side of the prism through which they pass. An experimental confirmation of this we have by laying down a prism, and keeping either of the bows in view while we gradually draw the eye away; it will then be seen that the curvature, which the bows had assumed, will continually be diminished, and nearly vanish at a very moderate distance.

50. *The Colours of the Bow-streaks owe their Production to the Principle of the critical Separation of the different Parts of the prismatic Spectrum.*

That streaks will be produced when a plain glass is laid under the side of a prism which forms either of the coloured bows, has already been sufficiently shown; but that these streaks, as well as the rest of the phenomena which have been mentioned in the 44th article, are exclusively to be deduced from the same principle by which the bows have been explained will require some proof. With regard to streaks, the following experiment, I believe, will remove every doubt upon the subject.

Let a plain glass be laid under the base of a right angled prism; then, if the eye at first be placed very low, no streaks will be seen; but when afterwards the eye is gradually elevated, till by the appearance of the blue bow we find that the principle of the critical separation of colours is exerted, the streaks will become visible, and not before; nor will they remain in view when the eye is lifted higher than the situation in which the effects of the critical separation are visible. It is therefore evident, not only that the colours are furnished by the same cause which produces the bow, but also that they are modified into streaks by the plain surface under the prism.

In addition to this, it must be remarked that the criterion, which has been successfully used in the explanation of several prismatic phenomena, proves that no other colours, but those which arise from the same source, can be modified so as to give streaks. The following experiment will show the foundation on which this criterion is established.

Let there be an horizontal opening in the upper part of a window-shutter, of about three feet long and one foot high; then, if we look at it through one side of a right angled prism, we shall see a red bow from the highest margin of the opening, and a blue one from the lowest; but when a plain glass is applied to either of the sides of the prism through which we see these bows, neither of them will give any coloured streaks. The experimenter must carefully keep the critical bows out of the way; for should either of them fall upon those which are under examination, streaks must of course be seen to pass over them.

When a spherical surface is placed under the prism, it has likewise been shown that coloured rings will be seen; but these, like the streaks, will not be visible when the eye is below the place where the bows can be seen, which would not have happened had a plain glass been used instead of the prism; for with such an arrangement, coloured rings may be seen at the most oblique as well as perpendicular stations of the eye.—As soon as the blue bow is perceived, the rings begin to be formed, first partly, then half, and lastly, we see them completed; and what is remarkable, these coloured rings are of such a magnitude and brightness, that they cannot be a moment mistaken for those we see when a plain glass is laid upon the same spherical curve.—The eye being then gradually elevated above the range in which the bows may be seen, these rings will pretty suddenly shrink in their dimensions, and lose much of their brilliancy; till at last, when the eye comes to a perpendicular situation, we find them dwindled away to the size and appearance of such as may be seen when a plain glass is substituted for the prism.

Irregular surfaces are no less decisive in the phenomena they exhibit; for when an equilateral prism is laid upon red mica in a strong illumination of scattered light, we may see a most admirable variety of very minute coloured appearances, whenever the eye is brought to the blue bow place; but as soon as it is in the least elevated above, or depressed below that situation, these fantastical figures are sure to vanish.

51. *A Lens may be looked upon as a Prism bent round in a circular Form.*

Those who have followed me in the analysis of the blue and red bows, will readily enter into the application I shall make of this theory to the generation of coloured rings by lenses.

It has been proved, that the different refrangibility of the prismatic colours, at certain critical angles, will cause the violet; indigo, blue, and part of the green rays to be separately reflected, and that, according to what has been said in ths 49th article, this will produce an extended straight-lined appearance tinged with the abovementioned colours. It has also been shown that the same principle, at certain critical angles, will cause the red, orange, yellow, and part of the green rays to be exclusively intromitted, in such directions as will produce a similarly extended straight-lined appearance tinged with these latter colours. From the angle in which the eye must receive these appearances in a prism, they are converted into the blue and red bows; but, since they would appear to be straight lines, if they were seen in directions perpendicular to a line drawn parallel to the edges of the prism, it follows, that were a long prism bent round into a circular form so that its two ends might meet, these lines would then be changed into rings, one of which would be formed by reflection, the other by transmission.

A lens may be said to be such a prism, from which indeed it differs only in one respect, which is, that an angle contained between two lines applied as tangents to different parts of its surface is changeable, whereas the refracting angle of a given prism is constant.

If it should be remarked that in consequence of considering a lens in this light, a plano-convex one, for instance, ought to present us, in certain situations, with a ring of the colours of the blue bow, and in others with a similar ring containing those of the red one, I must observe that the reason why such rings or bows can never be seen by the eye, though the physical separation of the rays should actually take place, is owing to that particular circumstance in which, we have remarked, the lens differs from a prism, namely, the curvature of the refracting surface; for although it has been proved that the figure of the first surface of a prism is not concerned in the formation of the blue bow, yet that of the surface through which it is seen by the eye is of material consequence, as will appear by the following experiment.

An equilateral prism, one side of which I had made cylindrical, was exposed so as to receive the incident light through the convex surface. In this situation, the eye being about three or four inches from the prism, a bow was formed which in every respect was like one I saw in another equilateral prism, whose three sides were flat; but when the convexity of the first prism was turned towards the eye, the bow could no longer be seen, although the critical separation of the rays would undoubtedly form it in this, as well as in the other prism; the two sides and angles of each exposed to the light being perfectly equal. By much attention to what may be perceived when the eye is placed at various distances, I found that the curvature of the surface through which I tried to see the bow, produced a focal contraction and subsequent inversion of the rays in their passage to the eye, and thus occasioned a total change of appearances. Now, since a ring or bow would not be visible in a prism bent round, if the side through which it must be seen were curved, we cannot expect to see such appearances in a lens, which every where presents us with a spherical surface.

The effect upon the appearance of the bows, produced by the surface through which the rays must pass to come to the eye, may be still better examined by laying the plain side of a plano-convex glass of a short focus upon the flat side of a prism, through which we see either of the bows; for when the eye is near the focus of the lens, they will be entirely effaced as far as they are covered by the lens.

A consequence of great importance may be drawn from these experiments; for since the cause of the coloured appearances, which have been called bows when seen in a prism, is now perfectly understood to be the critical separation of the colours of the incident light, it must be admitted that such a separation will certainly take place whenever a beam of light can find an entrance into glass, so as to make the required angles either with an interior or exterior surface, be it in the shape of a prism, lens, or solid of any kind, although the figure of the last transmitting surface should not permit such coloured-appearance-making-rays to reach the eye. A plano-convex lens will consequently by its construction separate the rays of light which enter at the convex surface in such a manner, as by reflection to produce what, if it could be seen, would be called a blue bow, and by rays that come in at the plain side, separate them by intromission so as to produce a red one.

To remove all doubt about the truth of this theory, I ground a small part of a plano-convex lens flat, that I might look into it, as it were, through a window, to see what passed within. The flat made an angle with the base of about thirty-four degrees, and I saw through it very plainly, in different directions of the illumination, a blue bow by light entering at the convex surface, and a red bow by light coming in at the plain one.

With regard to a plain glass contained between parallel surfaces, it may be remembered that when in the last paragraph of the 39th article I said that streaks could not be seen by laying another plain glass under it, I intimated at the same time the formation of colours; this will now admit of a satisfactory explanation. Scattered rays will enter into a parallel piece of glass, and by reflection the critical separation of colours will take place on its interior surface, so that if this effect could be seen, a blue bow would appear; and in the same manner a red bow might be seen by rays intromitted through the lowest surface. In consequence of the course of these rays, streaks would also appear from each of the bows when another plain glass is laid under the parallel piece; but from a calculation made according to the principles that have been established in the preceding part of this paper, the reflection of a mean ray of the blue bow from the interior surface being at the angle 49° 57′ 3″,3; and this being also the oblique incidence on the upper surface, a ray which comes in that direction with the mean refrangibility of the rays of the blue bow cannot come out of glass. The angle of obliquity of the mean intromitted ray for the red bow is 49° 38′ 19″,5, and on computing its direction by the mean refrangibility of the red bow, it will also be found that it cannot clear the glass. I have seen the bows and their streaks when the upper surface of the glass was inclined only nine degrees to the lower one; and possibly a much smaller angle would have been sufficient to permit the emergence of the coloured rays. The strong reflection from the outside of the glass, and the contraction of the dimensions of the bows are however much against perceiving them at a great obliquity.

52. *The critical Separation of the Colours, which takes place at certain Angles of Incidence, is the primary Cause of the Newtonian coloured Rings between Object-glasses.*

It has been proved that streaks, concentric rings, lenticular figures, and all sorts of irregular coloured phenomena may be seen by means of the prism; and in the 35th, 36th, and 37th articles, it has already been sufficiently explained that the cause of the great variety of these appearances is to be found in the configurating power of surfaces. I have also remarked in the 40th article, that in order completely to account for the Newtonian rings, it remained only to be shown how the colours thus modified are produced.

The prismatic experiments contained in this paper have explained in what manner a critical separation of the colours, which takes place at certain angles of incidence, is the cause of the appearance of the blue and red bows; since the different reflexibility of the rays of light, by which NEWTON has accounted for the blue bow, brings on a critical separation of the blue colours, and since also the different intromissibility by which I have explained the red bow, occasions an equally critical separation of the red ones.

In the 50th article I have not only proved that all the above described various appearances, which in the first part of this paper were produced by convex glasses, may be equally well obtained by the use of a prism, but have also shown that the great simplicity of this valuable optical instrument has cleared up great difficulties, by pointing out to us that the colours which are modified into such various shapes, are in all prismatic experiments exclusively produced by the critical separation of the rays of light. Now, as this must be admitted; it will certainly not be philosophical to look for a different cause of the same or similar effects, when convex glasses, which have all the required prismatic properties are used to produce them.[*]

To show the great similarity, or rather the identity of these effects, let us examine them in different points of view, and since the variety of the configurations is no longer an object that wants explaining, I shall only take the most simple case of each, namely, the coloured rings, that are produced when a plano-convex lens is laid with its convex side upon a plain reflecting surface; and the coloured streaks which are produced when the base of a right angled prism is in the same manner placed upon such a surface.

The form of rings arises from the spherical figure of the lens.[†]

The right-lined appearance of the streaks is owing to the straight figure of the plain surface of the prism.[‡]

The colour of the rings may suddenly be changed.[§]

The colour of the blue bow-streak may as instantly be converted into those of the red bow.[||]

The cause of the sudden change of the rings has been shown to be that the sets of one colour are seen by reflection, and those of other by transmission.[¶]

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[*] By this it will be understood that if any case should occur, in which the critical separation cannot account for the observed phenomena, we are then authorised to look out for some other cause to explain them.

[†] See the first paragraph of this paper.

[‡] See the 49th article.

[§] See the 15th article of the first part of this paper.

[||] See the 43d article.

[¶] See the 8th article of the first part of this paper.

It has also been shown that the blue bow-streaks are seen by reflection, and those of the red bow by transmission.[*]

In a lens we may at the same time see, in half the set, the colours of the reflected, and in the other half, the colours of the transmitted rings.[†]

And in a prism held before an open window, when the eye is close to it, and when half the bow falls on the side of the room, we may see blue streaks by reflection from half the blue bow, and green streaks by transmission from half the red bow. [‡]

When deep convex, or concave glasses, are laid upon the first surface of a lens, the rings are not affected by it.[§]

And when the same glasses are laid upon the first surface of a prism the streaks remain unaltered. [||]

When the convexity of the lens, which is placed on the reflecting surface, is changed, the size of the rings is also changed.[¶]

And when the angle of the prism is increased or diminished, the distance of the streaks undergoes a proportional alteration.[**]

When the lens is pressed upon the plain glass, the rings increase in diameter.[††]

And by a pressure of the plain glass against the prism the distance of the streaks grows larger.

To form rings by a lens, scattered light is only required.[‡‡]

And the same light is best for the production of streaks by a prism.[§§]

Many other instances of similarity might be adduced, but

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[*] See the 43d article.

[†] See the second paragraph in the 18th article.

[‡] The experiment has been made, though not mentioned in this paper.

[§] See the sixth paragraph of the 24th article.

[||] See the second paragraph of the 46th article.

[¶] See the first paragraph of the 7th article.

[**] See the fourth paragraph of the 42d article.

[††] See the 8th article.

[‡‡] See the seventh paragraph of the 24th article.

[§§] See the third paragraph of the 46th article.

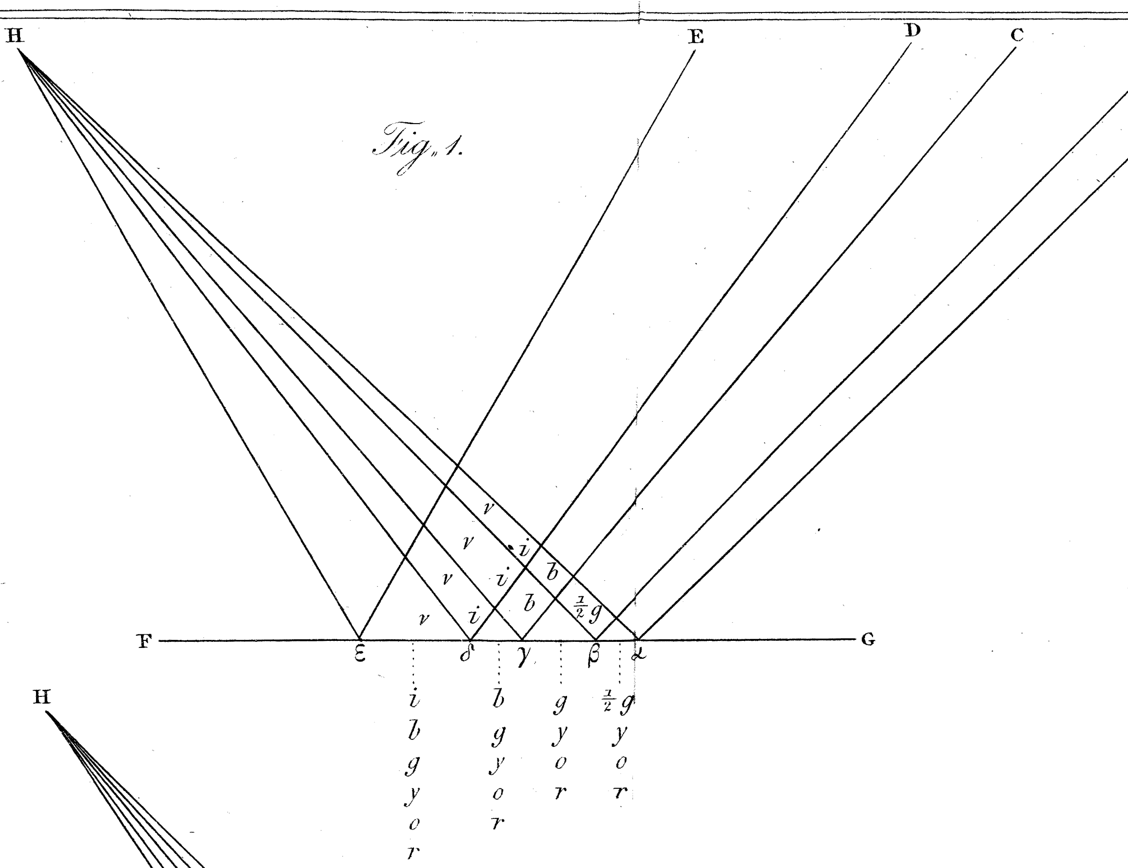
those that have been recited will surely be sufficient to show that the same operations, which will produce these prismatic phenomena, will equally account for those that are formed by the lens; now, as it has been clearly proved, that the critical separation of the colours, which takes place at certain angles of incidence, occasions all the phenomena of the blue and red bows, and of the streaks, rings, and other regular or irregular appearances, that may be seen in a prism, there cannot remain a doubt but that the Newtonian rings observed between object glasses, are owing to the same cause.

53. *Remarks relating to the Newtonian alternate Fits of easy Reflection and easy Transmission.*

In attempting to rescue the science of optics, from what has been so long considered as unsatisfactory for explaining the great question about the cause of the coloured rings, I have made use of a principle, the effects of which have so near a resemblance to those of the supposititious fits of easy reflection and easy transmission, that the author of them might easily be misled by appearances. But although the principle of a critical separation of the colours substituted for these fits, admits the reflection of some rays at the same angles of incidence at which others are transmitted, yet since the Newtonian different refrangibility of light will account for these critical reflections within glass, and the equally critical intromissions from without, we can have no longer any reason to ascribe original fits to the rays of light, which in the first part of this paper, they have already been proved not to possess, and which now, in all prismatic experiments, I have shown are not necessary for explaining appearances that may be accounted for without them.

Slough near Windsor,
Dec. 9, 1808.

Fig. 1.



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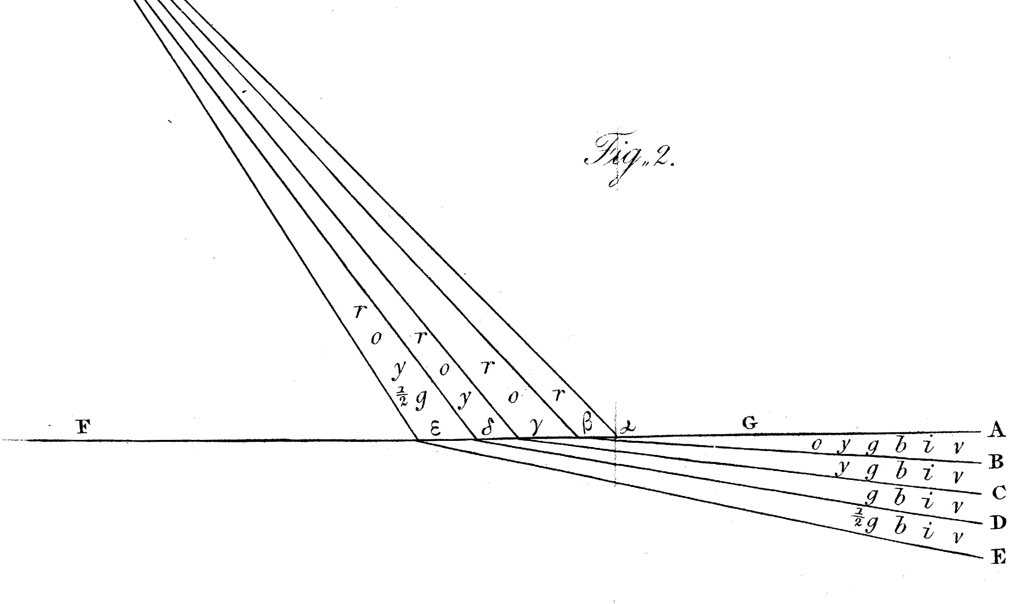

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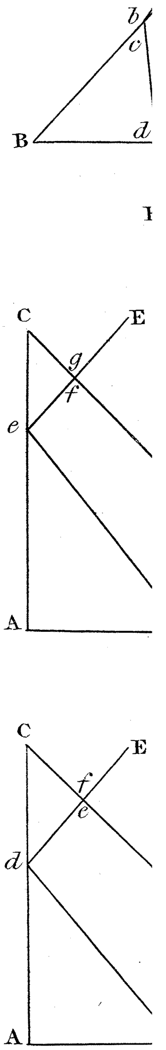

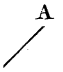

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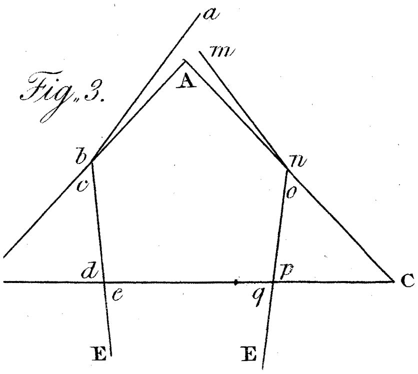

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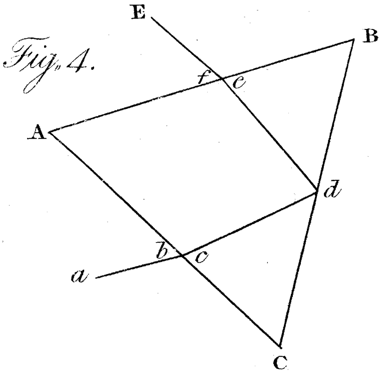

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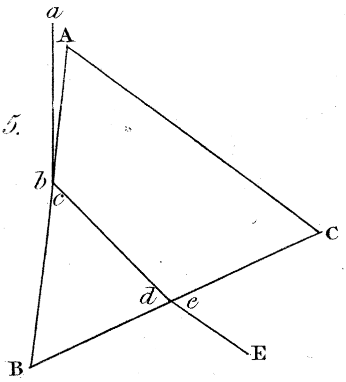

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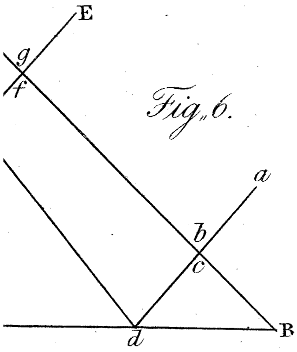

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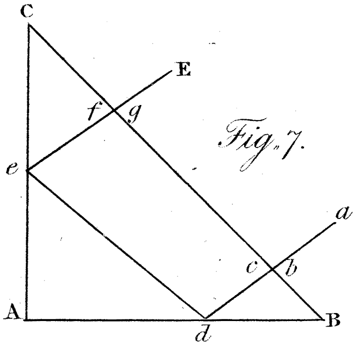

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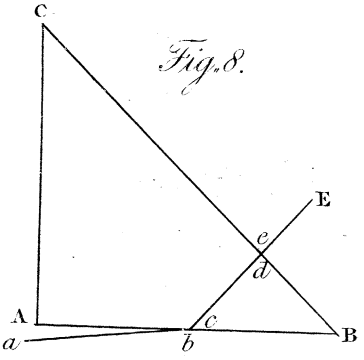

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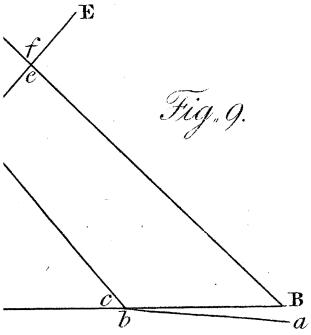

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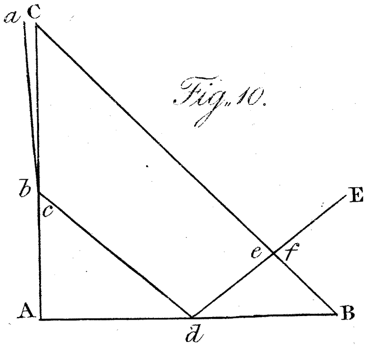

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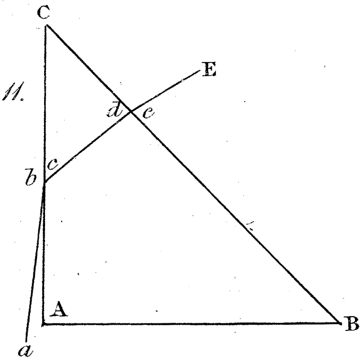

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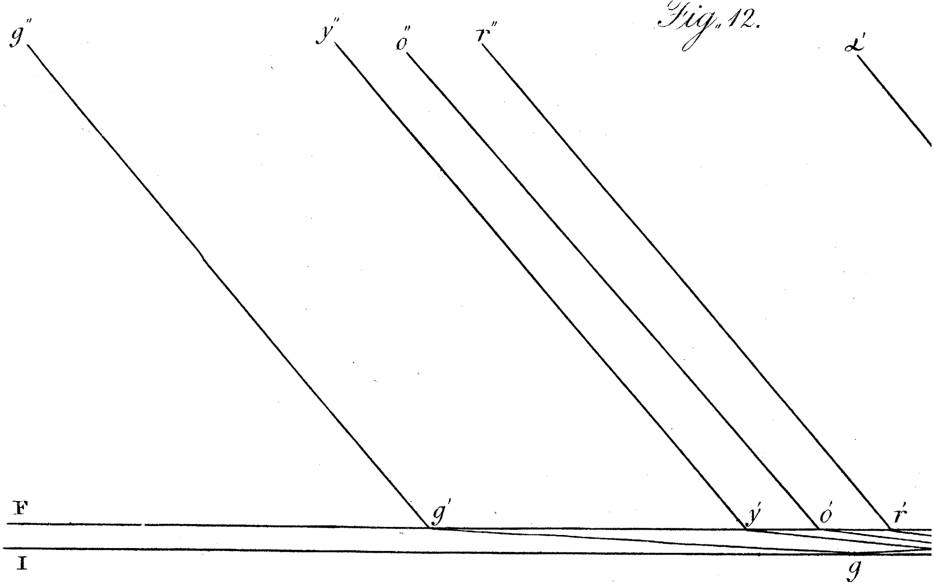

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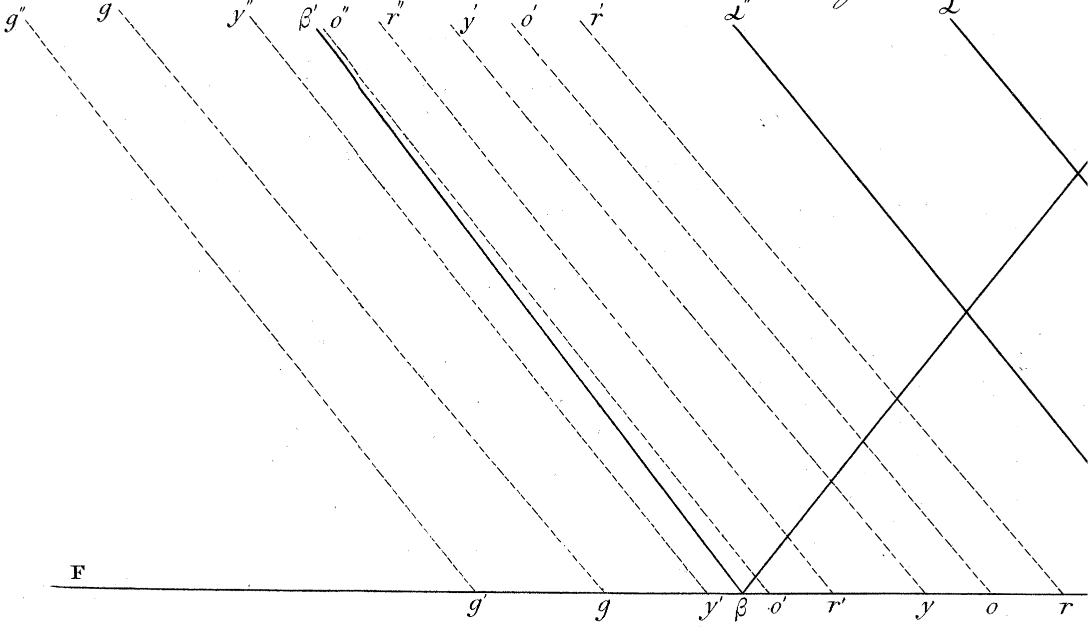

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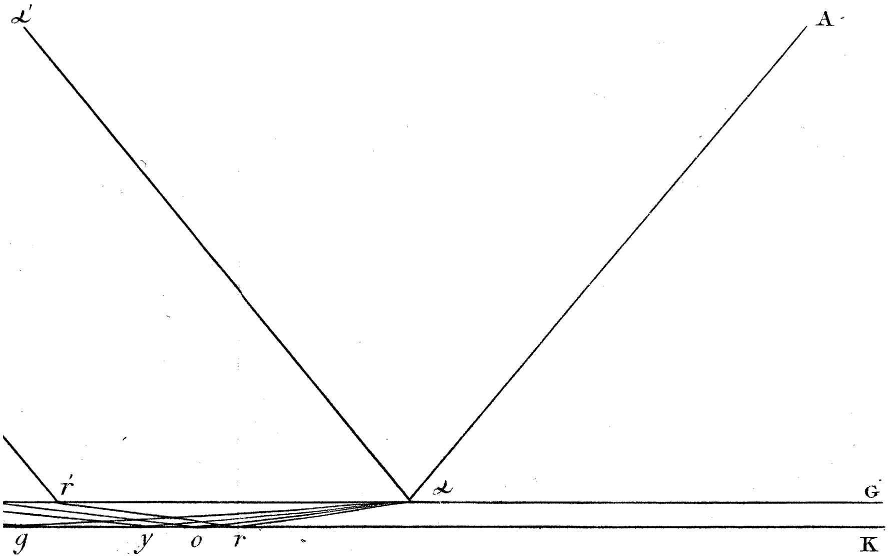

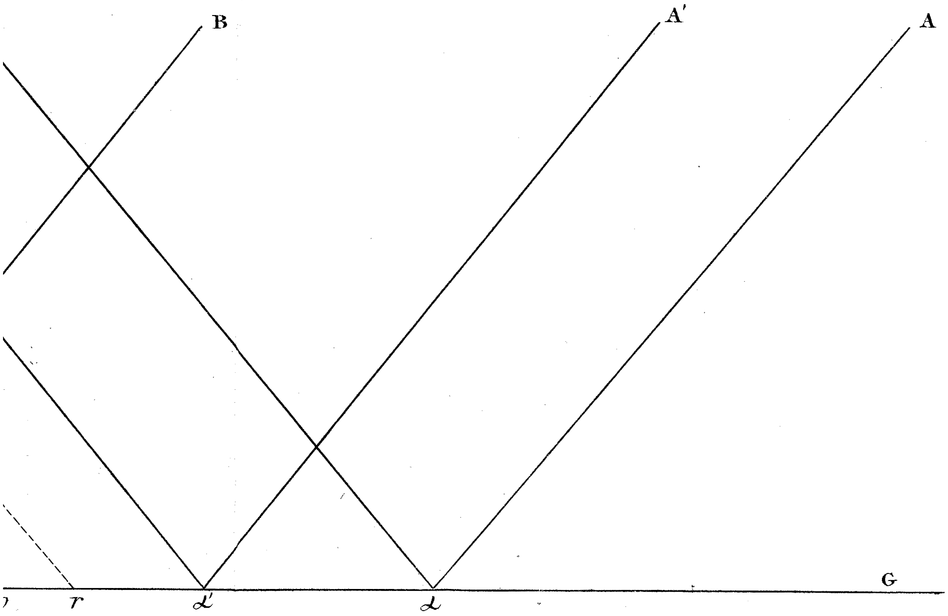

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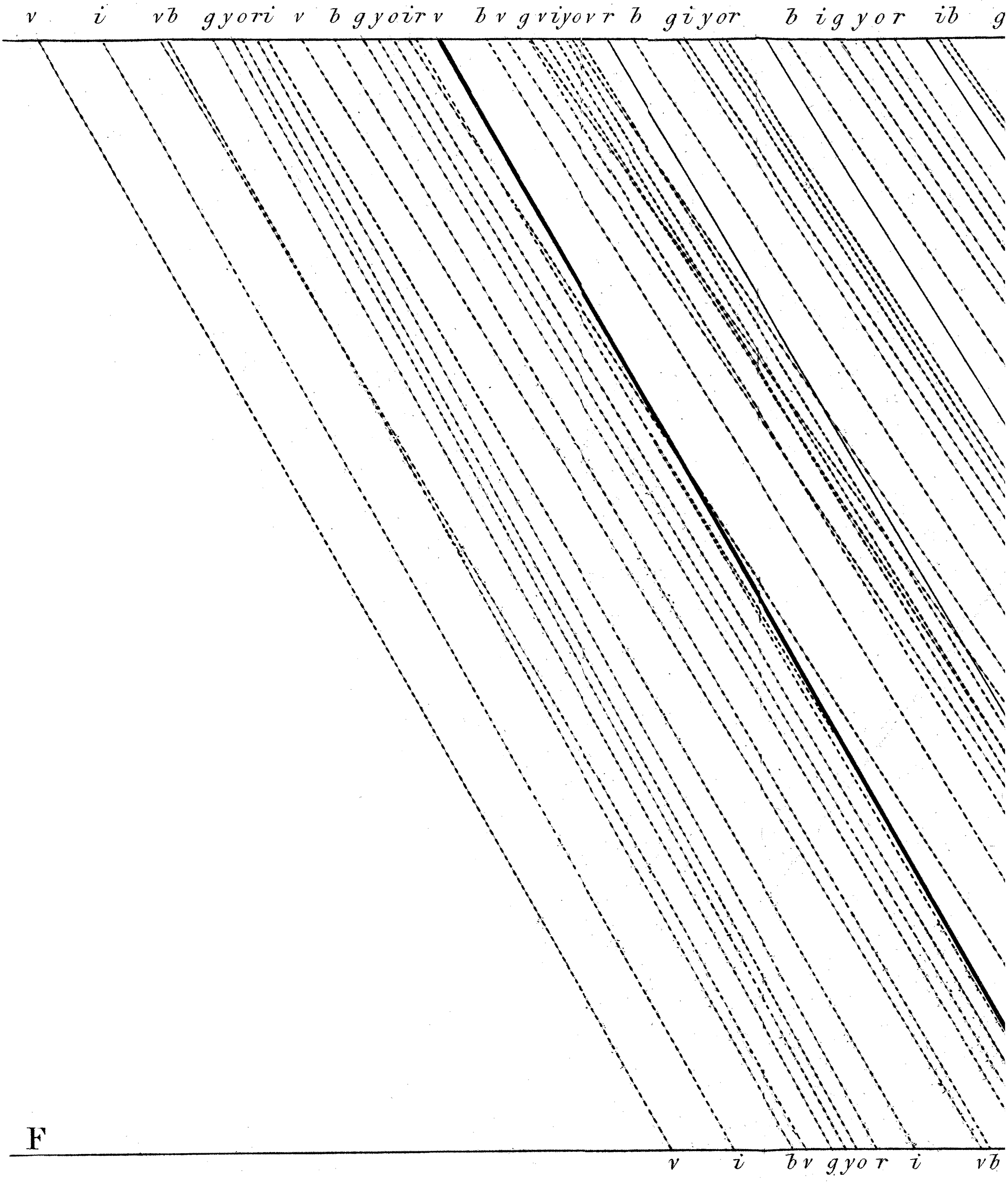
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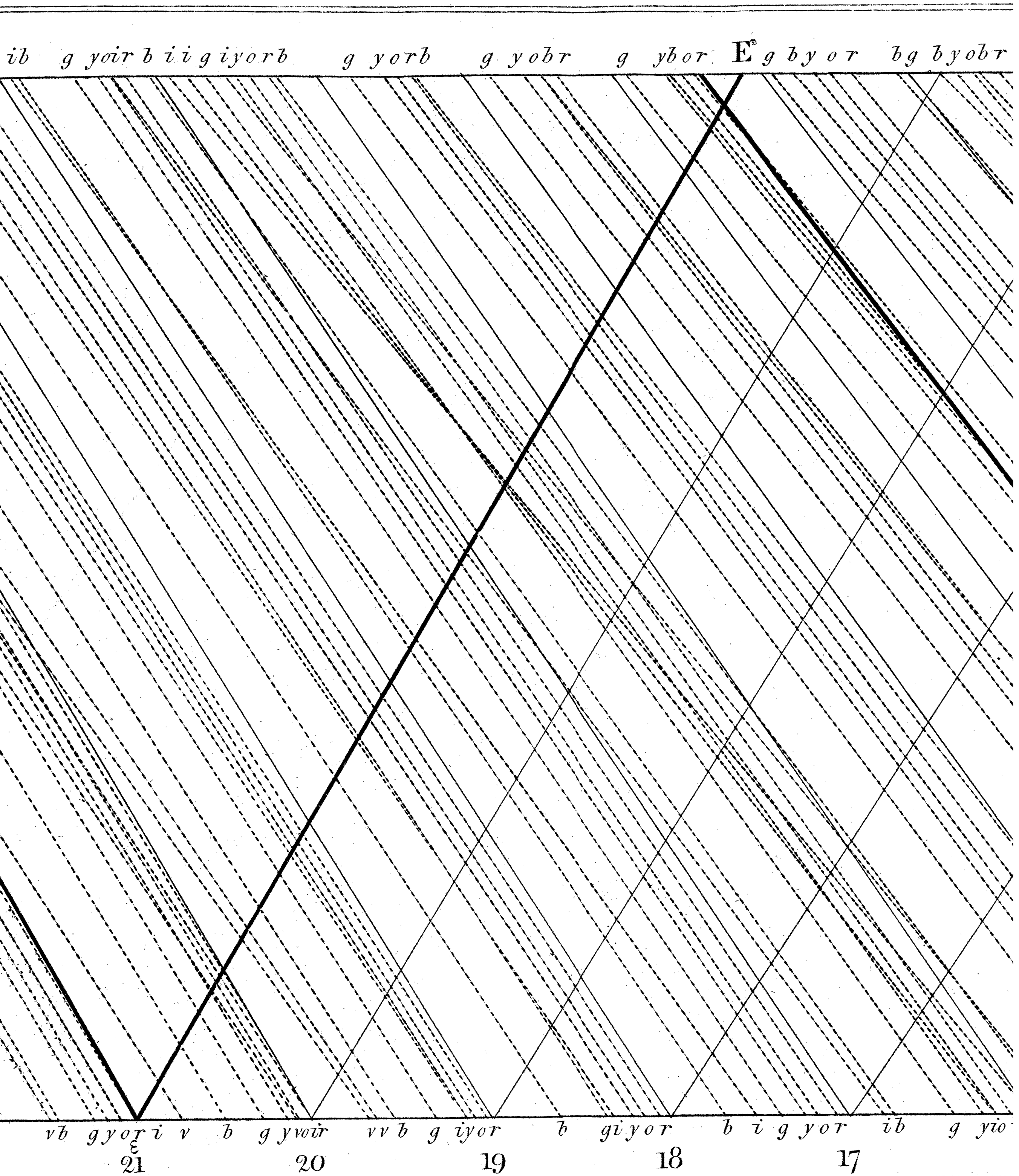
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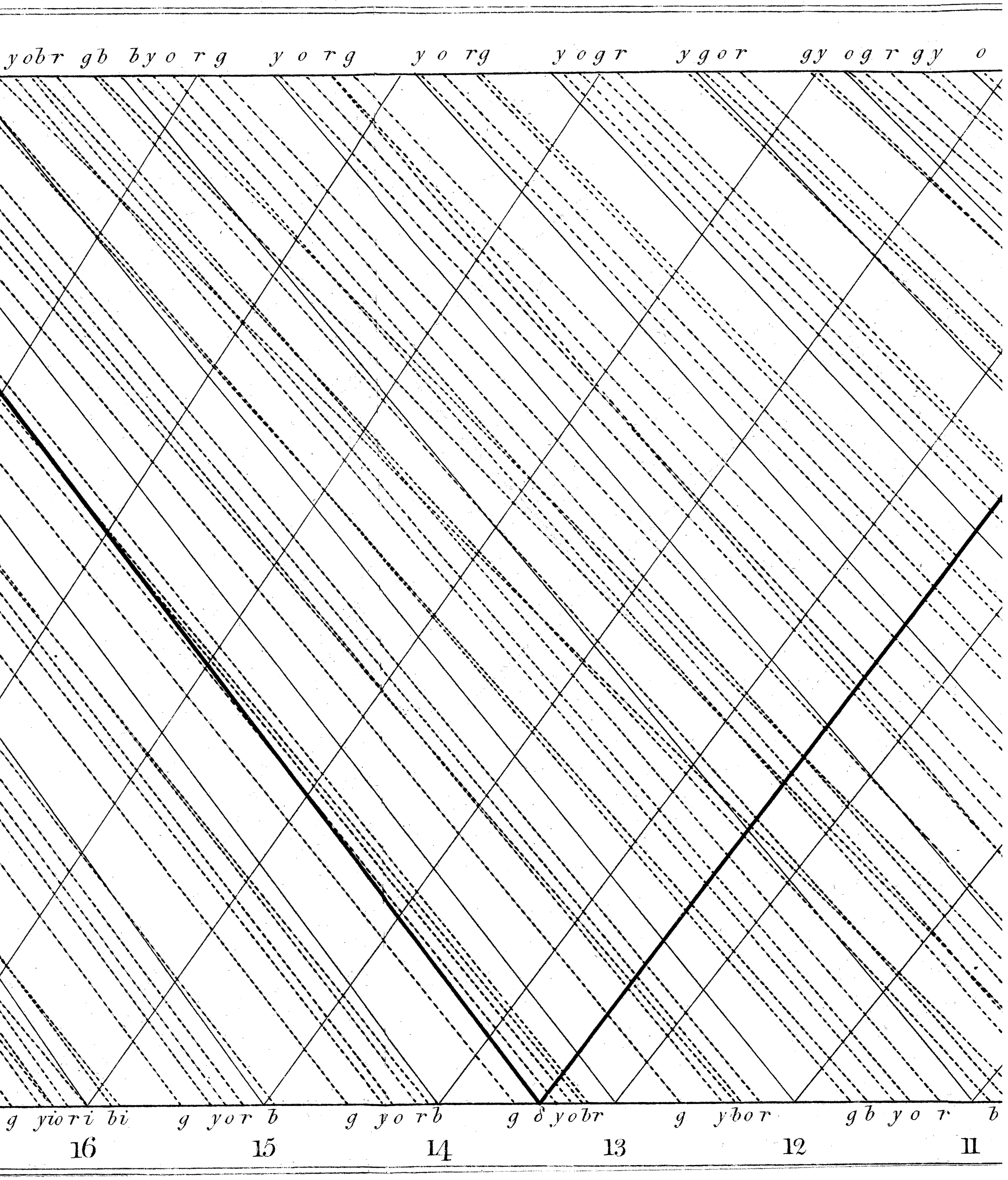
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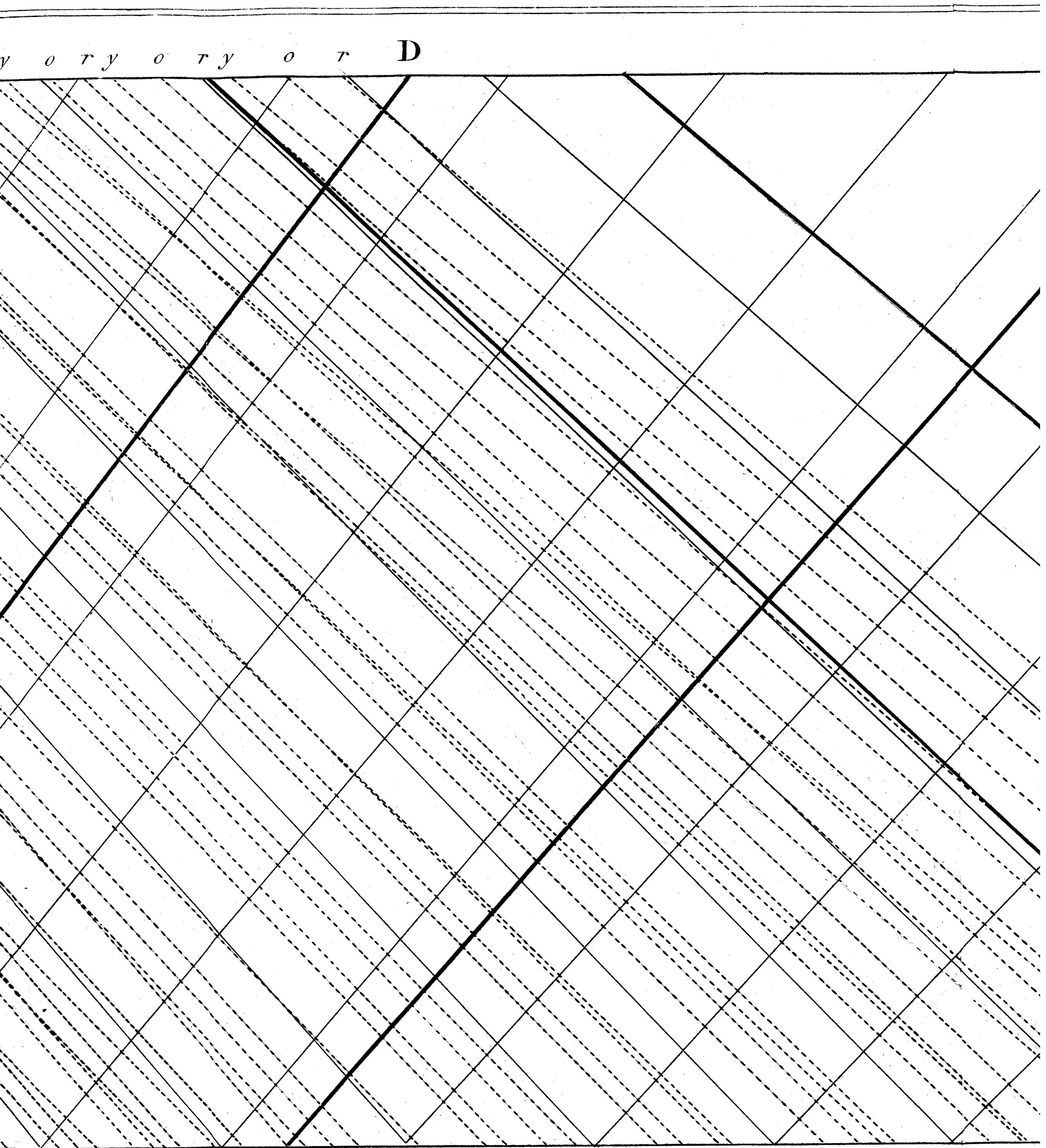
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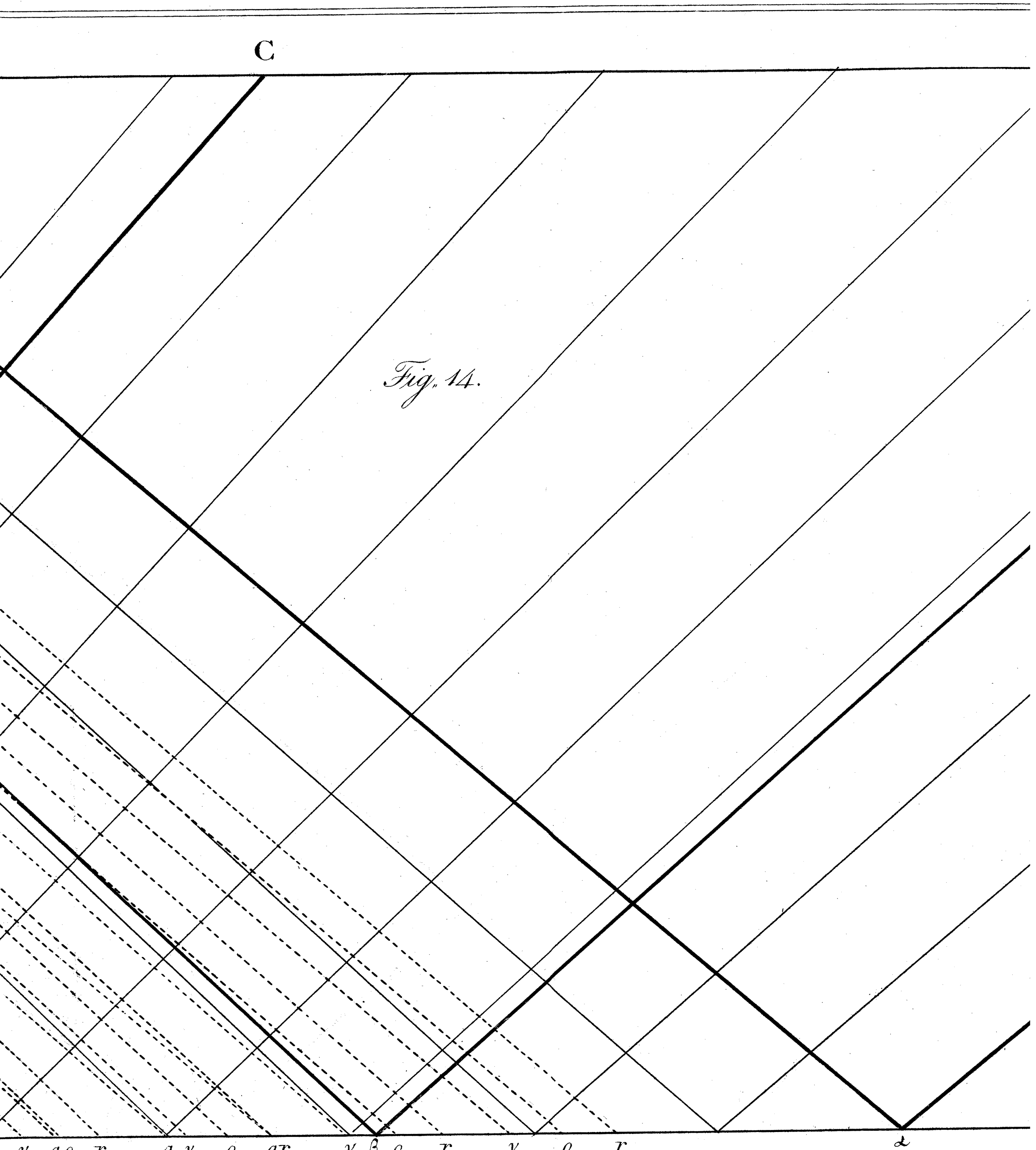
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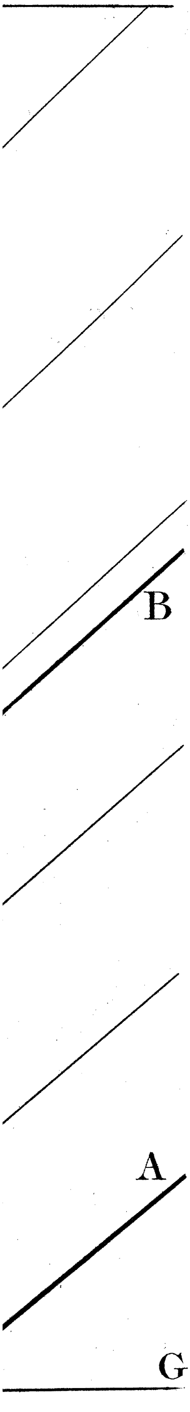
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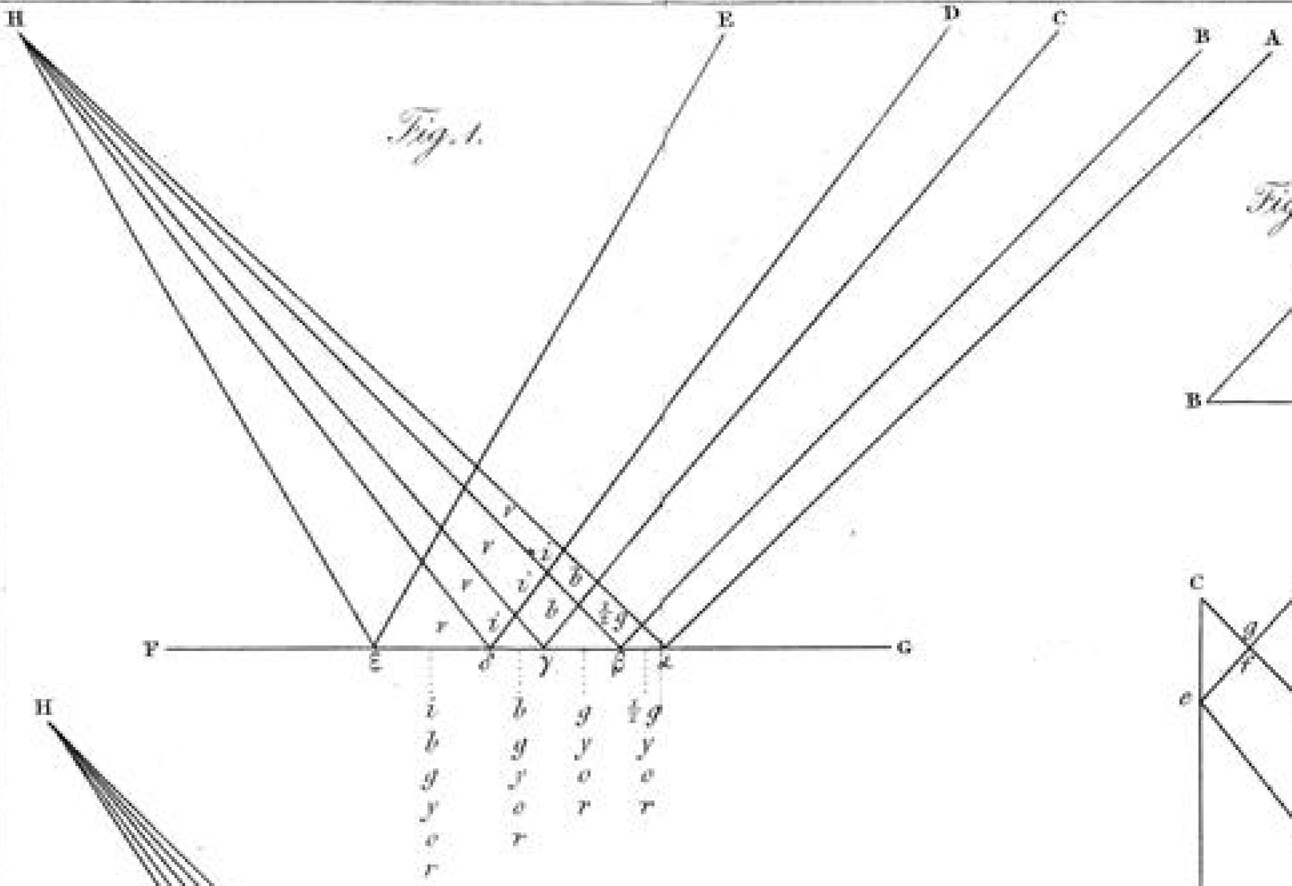

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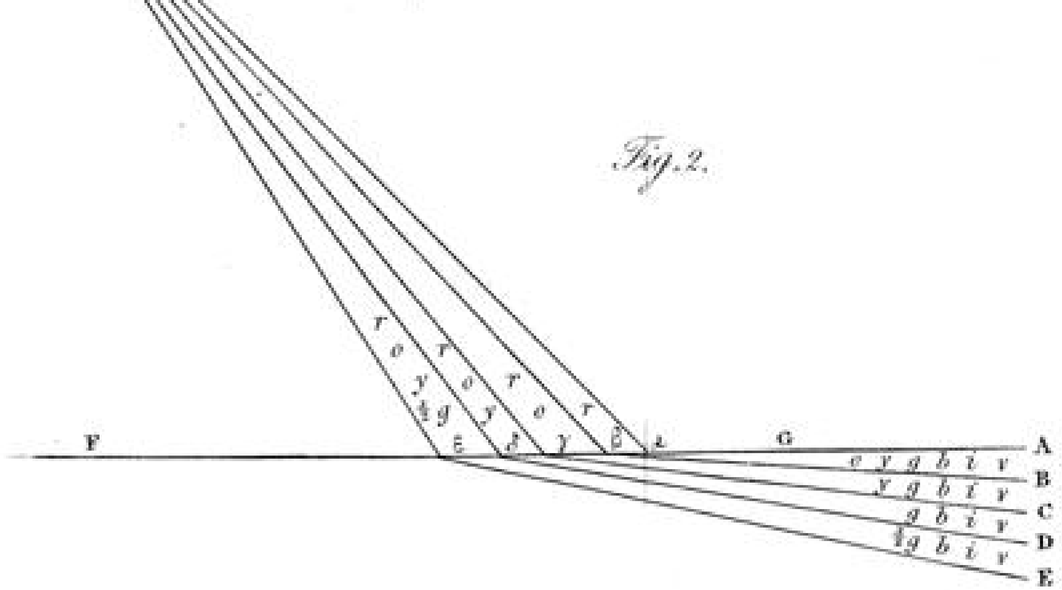

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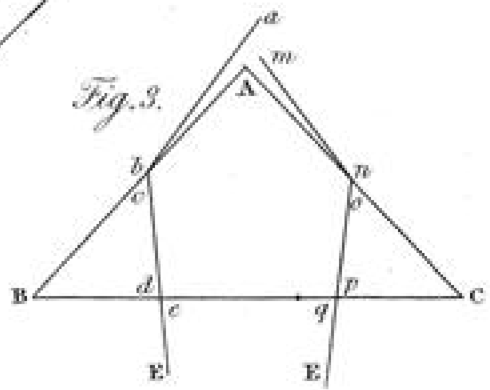

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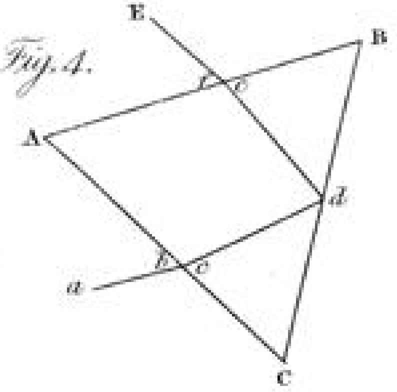

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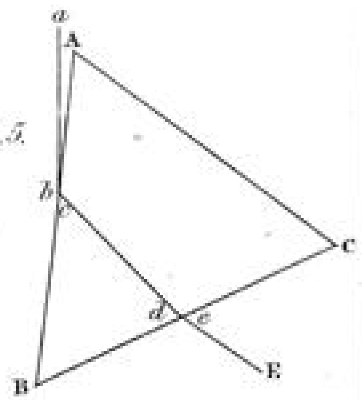

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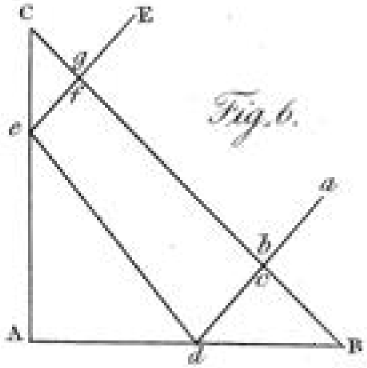

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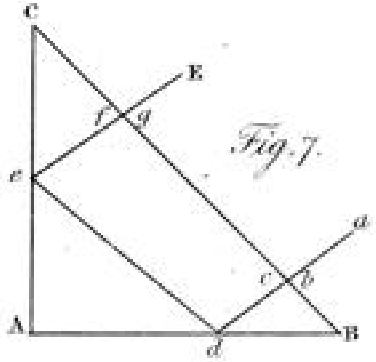

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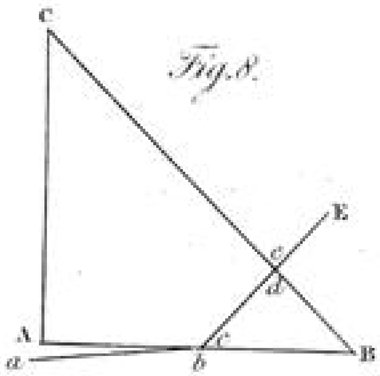

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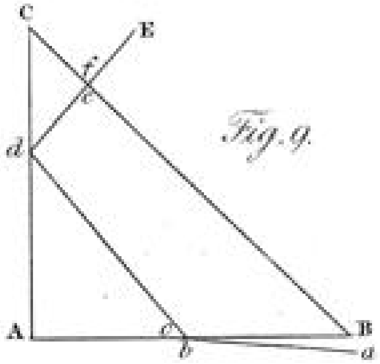

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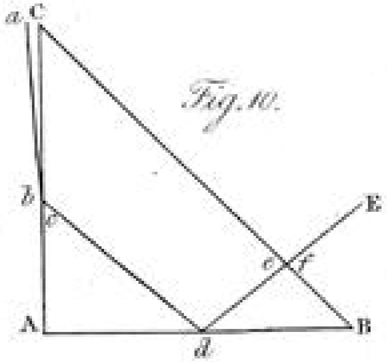

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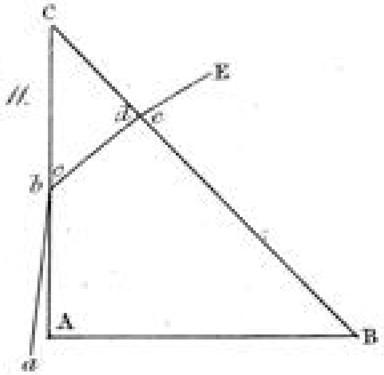

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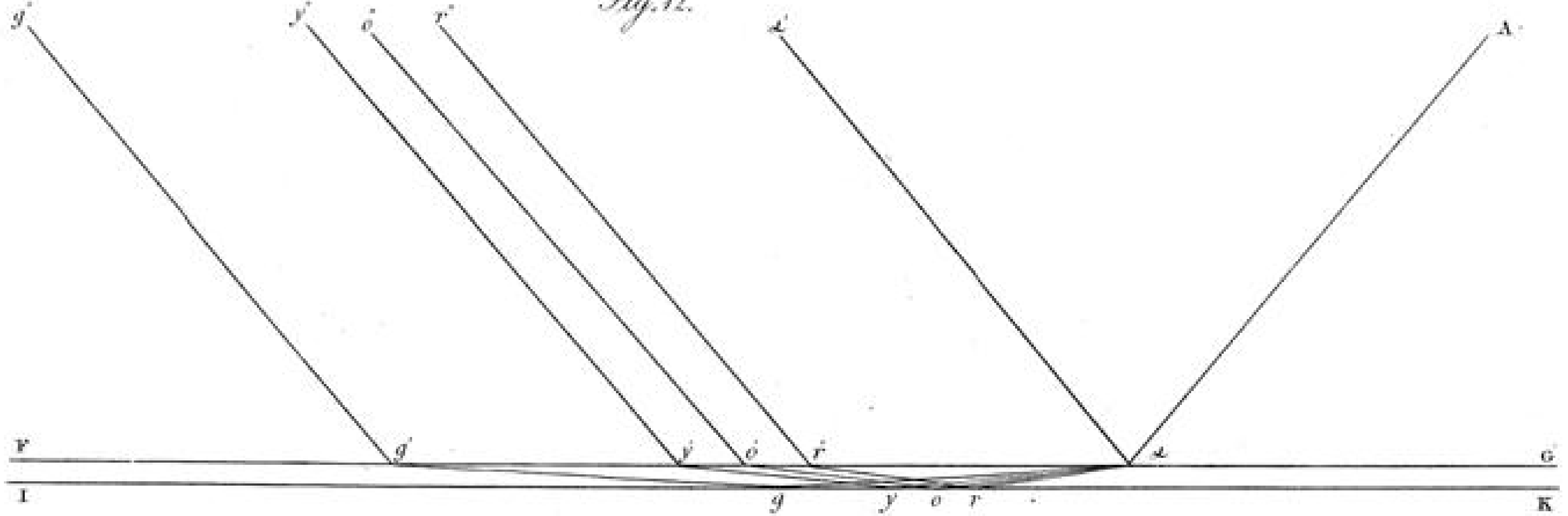

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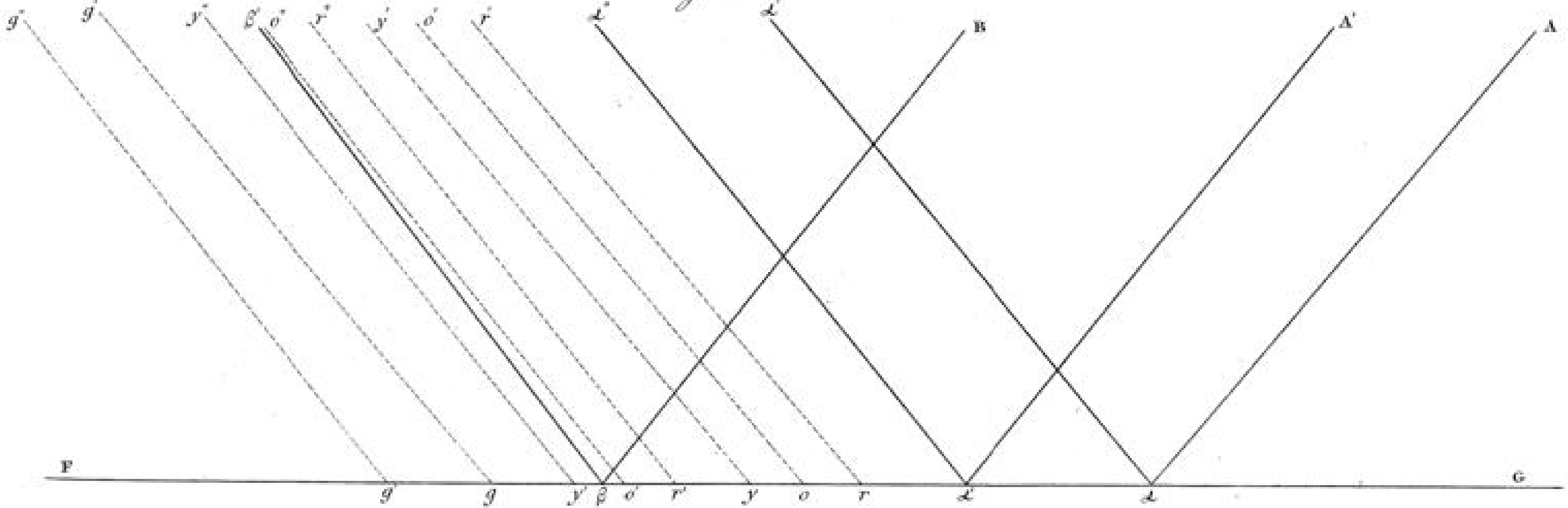

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Fig. 14.