XIII. *On some properties in achromatic object-glasses applicable to the improvement of the microscope.* *By* Joseph Jackson Lister, *Esq.* *Communicated by Dr.* Roget, *Secretary.*

Read January 21, 1830.

The improvement of the achromatic compound miscroscope having been an occasional object of my leisure for several years past, my attention has in consequence been attracted to some properties of object-glasses of short focus and large aperture, which, so far as I am aware, have not been before noticed, and which, I flatter myself, may be applied to increase its powers and the ease of its manufacture.

In offering these, accompanied by some other miscellaneous remarks, it may be explanatory to introduce them by a short notice of the several achromatic object-glasses for the microscope which have originated apparently independent of each other within a few years past.

The first produced in England were the triple ones constructed in 1824 and 1825 by Tulley, who had been incited to the undertaking by Dr. Goring: of these an account is already before the public. Tulley has since adopted for his triple object-glass to be used singly the focal length of 0.9 inch, applying another of not quite 0.5 inch focus before it when high magnifying power is required; and he obtains with these an image of great sharpness and perfection. His first glasses have all the merit of a new invention, having been executed without the knowledge that any thing of the kind previously existed, though other achromatic glasses had before been made in France by Selligue, by Fraunhofer at Munich, and by Amici at Modena.

The glasses of Selligue's microscope, of which a report was made by M. Fresnel to the Royal Academy of Sciences in 1824, were composed of a plano-concave lens of flint-glass, and a double convex of crown or plate, with their inner curves cemented together. Four of these, of from $1\frac{1}{2}$ to $1\frac{7}{8}$ inch

each in focal length, were made to screw before each other, so as to be used together or alone in the manner long practised with single lenses.

The chromatic aberration was thus in a considerable degree corrected, but the glasses were fixed in their cells with the convex side foremost, which is their worst position; and the spherical error was in consequence enormous, showing itself even through the contracted opening, to which it was necessary on that account to limit them.

Yet, inferior as was the instrument of SELLIGUE, the happy idea of combining achromatic object-glasses, now generally adopted and to which their present superiority is owing, seems to have occurred to no one else till put in practice by him; and the very simple structure of his glasses will be shortly seen not to be incompatible with the finest microscopic vision.

CHEVALIER of Paris having manufactured some of these instruments, appears to have observed the great error in the position of SELLIGUE's glasses; he retained their construction, but turned their plane sides foremost; and making them of shorter focal length and more correctly achromatic, produced in 1825 a microscope far superior to the former. His deepest glasses are not more than 0.4 inch in focal length, and two of these were united in his earlier instruments for his highest power; but this was the only combination retained in them, and all his glasses were restricted to apertures too small to show difficult test objects.

He has since increased the number of his glasses to be used together, and otherwise improved their performance; but if I may judge from microscopes of his which I have recently seen in this country, he does not yet derive from the construction that he has adopted, all the advantage which it may afford.

I am unacquainted with the date of the first production of FRAUNHOFER'S glasses; they resemble the French in having their flint lens plano-concave, but they are not cemented, and the inner surfaces are not in contact, each object-glass being adapted by the curves of its convex lens for being used alone. My friend Mr. BROWN has kindly lent me a series of five glasses of this description, purchased by him at Munich a few months ago from the establishment of UTZSCHNEIDER and FRAUNHOFER, which range from 1.8 to 0.43 inch in focal length, and are of excellent workmanship: they screw before one another in the manner of SELLIGUE'S. It appears from an account of the microscope of

those artists, printed in 1829, that it is only lately the glasses have been combined together, and that of the shortest focus added to the former series of four; and also that they are intended to be used in the order of their focal lengths, the shorter towards the object. Each of these glasses singly admits but a small pencil of from 8° to 15° of light, and when so used, their defining power is necessarily not very great; but their combinations have much more, and the different effects of these will be again adverted to.

The eminent professor of Modena, besides inventing his well-known reflecting microscope, was engaged about the year 1815 with achromatic object-glasses; but as they did not equal his reflector, he laid the work aside, till he was induced to resume it in 1824, from reading the report already mentioned on the microscope of SELLIGUE: from this AMICI took the thought of combining his object-glasses, and pursued it with great success, making them double, with the curves of the two lenses of each planned for the place it is to occupy, and for obtaining a good image either with the back glass alone, or with a second or a third in front.

He brought with him, when he visited London in 1827, some glasses of this description of very fine performance; and I have been informed by him that he has since executed a combination of "2.7 lines in focal length and 2.7 lines in aperture," which considerably excels them.

The glasses which have been enumerated possess very different degrees of merit, chiefly dependent on the extent to which they are divested of chromatic and spherical aberration, and particularly, in connection with this, on the focal angle of their aperture; for it has been well established, that a large pencil from the object is absolutely essential to that brilliancy and distinctness of image which characterize a fine achromatic.

When the rays received by the most perfect object-glass from any indefinitely small bright portion of an object in the centre of its field are brought together at its conjugate focus, the image formed by them, though it appears a sharply defined point if moderately magnified, is really a spot or small circle, and will show as such if the microscope is sufficiently overcharged with power in the eye-glass. These circles bear a considerable analogy to the spurious disks of stars; and like them they will be found to be much enlarged by diminishing the aperture of the object-glass.

They are enlarged also, without contracting the aperture of the glass, by

increasing the intensity of the illumination, whereas by darkening the object beyond a certain point they may be rendered ill defined, and be at length dissolved.

These peculiarities are most observable on some opaque objects, (the reflection from a very small microscopic globule of quicksilver* offers perhaps the best example,) but the same effects are produced on the light received from transparent ones; and the consequent blunting and mingling together of their minute details when the object-glass admits but a small pencil of light, gives rise to various fallacious appearances. One of the most remarkable is the spottiness which some surfaces assume, not unfrequently so much resembling small globules as to have been mistaken for them; an optical illusion having thus been the basis of some ingenious speculations on organic matter.

Such appearances have little place with the finer achromatics, the large angle of whose pencil and its accurate correction enable us to magnify their image greatly, still discovering something new in our object, before we are checked by the circles of diffusion of the effective rays; but these at last, whether proceeding from the causes mentioned or from others to be hereafter noticed, form in every microscope the boundary to defining power, except where faulty materials or workmanship give it an earlier limit.

It is the marginal rays which contribute especially to render visible close and delicate lines, such as those on the scales of lepidopterous insects, and some of the most difficult of these are even best seen when the central light is intercepted†.

A glass that is far from correct in its figure will sometimes show lines of this description sharply, while the outline of the scale is indistinct, and the

* To obtain such, I have always placed a globule on a piece of black glass, and scattered it into many by a smart stroke, some of which will be extremely minute.

† The blue down of the Menelaus and the white of the Cabbage Butterfly (Morpho Menelaus and Pieris Brassicæ) well deserve the place they have acquired as standard tests, especially on account of the respective characters of their transverse tracings. Some of the small oval scales from the body of the Twenty-plumed Moth (Alucita hexadactyla) are among the closest and most elegant in their lines that I have seen; others are very easily resolvable, and the down has such diversity of form as often to afford within a short space a ready variety of excellent tests. The same is to be said of the scales of Podura plumbea, of which all are difficult, and some seem to defy all powers of definition.

It may be observed, that with most objects there is such difference between individual specimens of the same kind, that in general the only safe way to determine between two good microscopes, is to apply the same specimen to both under the same circumstances of power and light.

contrary; but one in which both aberrations are destroyed should give the outline and the lines distinct together. Even some good glasses, however, have a defect, against which we should be on our guard; that in certain directions of the light they are liable to show lines on an object which do not really exist.

It is observable, that provided the aperture of the glass remains open, the central pencil of light admitted behind many transparent objects may be limited to a very small one without greatly impairing their sharpness; parallel lines or spots spread closely over a flat surface often remaining plainly visible in this case, which at a far less amount of contraction by a stop behind the object-glass cannot by any management be made to appear. The reason of this seems to be, that both reflection and refraction of a part of the rays take place at such objects, by which the pencil is spread out on leaving them to a much increased angle in its progress to the glass.

The relation between the aperture of microscopic object-glasses, even of the same focal length, and the pencil of light admitted by them, will vary much, according to differences in their thickness, their combination &c.; and as aperture is valuable only in proportion to the pencil it admits, the latter would seem to be the circumstance the more deserving attention of the two. It is so often erroneously estimated, that I will mention a simple mode of ascertaining it, which will be found pretty accurate.

Fix a piece of paper on a table, and on it place the microscope with its body horizontal, and one of the eye-pieces on; set a candle on a level with it a few yards distant; then having directed the body of the instrument so far on one side of the candle, as that the light from it shall bisect the field vertically, leaving half of it dark, trace on the paper a line corresponding to the side of one of the legs. Now, taking the focus of the object-glass as a pivot, turn the microscope horizontally to the other side of the candle till the opposite half of the field only is illuminated, and mark again on the paper the position of the side of the leg. The measure of the angle traversed shown by the two lines is that of the pencil of light.

In the remarks which follow, the term correction is used to imply the effect produced by the denser concave lens of a compound object-glass upon the aberration of its convex. Thus as in a simple convex lens, the rays which pass through it near the circumference have their foci shorter than the more

central rays, and the colours of the violet side of the spectrum into which each ray is refracted have also their foci shorter than those of the red side; if either of these errors is but partially removed by the concave lens, the glass is said to be under-corrected as to that aberration, and over-corrected if the opposite error is produced by it.

A large focal pencil free from all aberration is evidently the great requisite for the object-glass of the compound microscope; a second point desirable to be attained is, that the field should be flat and well defined throughout; and a third, that the light admitted should as much as possible be only such as goes to form the picture, and should not be intercepted or diffused over the field by too many reflections.

The prominent obstacle to obtaining a sufficient pencil for high powers by one object-glass of large aperture and deep curves, is that the correction for the spherical figure by the concave lens is greater for the rays of the circumference than its due proportion to that for the more central ones; so that when such a glass is corrected for the mean of the pencil, if we suppose its disk divided into a central space and three rings surrounding it, the rays which pass through the central space and those of the second ring from it will arrive at their focus when those of the first ring will have just crossed the axis, and those of the marginal ring will not quite have reached it. The injury resulting to the defining power is in similar glasses inversely as the squares of their focal lengths, as far as regards this cause of error, as well as those which arise from incorrigible colour and defects of workmanship. The effects upon the pencil which have been before described, must not be included under the same law. This excess of correction in the marginal rays increases after a certain point so rapidly with a small enlargement of the aperture of the glass, as soon to prescribe a limit, beyond which it cannot be carried without injury to the picture.

With glasses of more contracted aperture and at the several surfaces of which the marginal refraction is moderate, the effect alluded to is comparatively inconsiderable; and consequently by dividing the refraction among two or more such glasses corrected for the rays that pass through them, the pencil received may be enlarged without impediment, and the light and distinctness greatly increased, thus constituting the important advantage of combination.

The triple object-glass is thus very superior to a double one when each is used singly, and the union of two triple ones has been already proved in England to be eminently effective. TULLEY's 0.9 inch glass singly admits a pencil of near 20°, and his combination, one of 38°.

These triple glasses and the double ones of Professor AMICI are adapted by the form of their curves each to its respective place; but the foreign double glasses which have their flint lens plano-concave, and particularly those of UTZSCHNEIDER before mentioned, are made much on one model, and intended to be each good alone. It might seem but reasonable to infer from this, that they would be unfit to be combined; and accordingly when screwed together, most of the numerous practicable changes of his series of five glasses, of which as many as four may be united for use, have much indistinctness from spherical error; and this is I think the case with all those combinations which the maker contemplated. Some peculiarities, however, observed two years ago in CHEVALIER's object-glasses, led me to undertake a close examination of these, which were liberally placed at my disposal for the purpose, in the hope of discovering the cause for a discrepancy which appeared in their effects.

I found that with a part of the combinations, the image of any bright point that was at some distance from the centre of the field had a faint light or coma stretching outwards from it; with others the coma was as much inwards.

The spherical aberration was in general much over-corrected, but in some triple and quadruple combinations the opposite error showed itself; and out of the whole number one triple and one quadruple were remarkably beautiful and distinct.

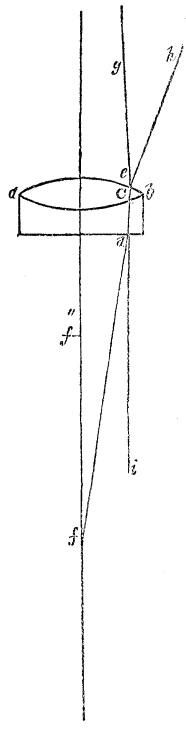
The result of this investigation was to disclose or confirm to me the existence of some properties of the double object-glass, which have not I believe been hitherto recorded, and which it is now my purpose to describe only in connection with the subject before us,—the improvement of the microscope.

With this in view I would premise that the plano-concave form for the correcting flint lens, which was probably adopted at first for its simplicity, has in that quality a strong recommendation; particularly as it obviates the danger of error which otherwise exists in centering the two curves, and thereby admits of correct workmanship for a shorter focus. To cement together also the two lenses of the glass, diminishes by very nearly half, the loss of light from reflexion,

which is considerable at the numerous surfaces of a combination. I have thought the clearness of the field and brightness of the picture evidently increased by doing this; it prevents any dewiness or vegetation from forming on the inner surfaces; and I see no disadvantage to be anticipated from it, if they are of identical curves and pressed closely together, and the cementing medium permanently homogeneous.

These two conditions then, that the flint lens shall be plano-concave, and that it shall be joined by some cement to the convex, seem desirable to be taken as a basis for the microscopic object-glass, provided they can be reconciled with the destruction of the spherical and chromatic aberrations of a large pencil.

Now in every such glass that has been tried by me, which has had its correcting lens of either Swiss or English flint glass, with a double convex of plate, and has been made achromatic by the form given to the outer curve of the convex, the proportion has been such between the refractive and dispersive powers of its lenses, that its figure has been correct for rays issuing from some point in its axis not far from its principal focus on its plane side, and either tending to a conjugate focus within the tube of a microscope, or emerging nearly parallel.



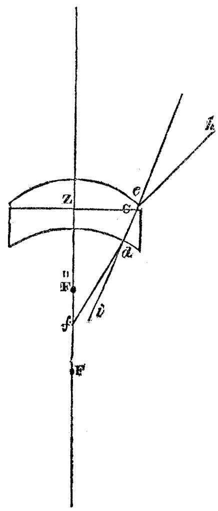
Let *a b* be supposed such an object-glass, and let it be roughly considered as a plano-convex lens, with a curve *a c b* running through it, at which the spherical and chromatic errors are corrected, which are generated at the two outer surfaces; and let the glass be thus free from aberration for rays *f d e g* issuing from the radiant point *f*; *h e* being a perpendicular to the convex surface, and *i d* to the plane one. Under these circumstances the angle of emergence *g e h* much exceeds that of incidence *f d i*, being probably almost three times as great.

If the radiant is now made to approach the glass so that the course of the ray *f d e g* shall be more divergent from the axis, as the angles of incidence and emergence become more nearly equal to each other, the spherical aberration produced by the two will be found to bear a less proportion to the opposing error of the single correcting curve *a c b*; for such a focus therefore the rays will be over-corrected.

But if f still approaches the glass, the angle of incidence continues to increase with the increasing divergence of the ray, till it will exceed that of emergence which has in the mean while been diminishing, and at length the spherical error produced by them will recover its original proportion to the opposite error of the curve of correction. When f has reached this point f'', (at which the angle of incidence does not exceed that of emergence so much as it had at first come short of it,) the rays again pass the glass free from spherical aberration.

If f be carried from hence towards the glass, or outwards from its original place, the angle of incidence in the former case, or of emergence in the latter, becomes disproportionately effective; and either way the aberration exceeds the correction.

These facts have been established by careful experiment: they accord with every appearance in such combinations of the plano-convex glasses as have come under my notice, and may I believe be extended to this rule;—that in general an achromatic object-glass, of which the inner surfaces are in contact, or nearly so, will have on one side of it two foci in its axis, for the rays proceeding from which it will be truly corrected at a moderate aperture; that for the space between these two points, its spherical aberration will be over-corrected, and beyond them either way under-corrected.



I am not aware that an exception is to be made for any quality of glass or curves that are likely to be used for the microscope: but I apprehend a case may occur, if the flint glass is convexo-concave and the convex lens united to its concave side, that neither of the aplanatic pencils may converge after traversing the glass, and that their foci for a radiant may be on opposite sides of it, the principle however of the two foci remaining unaltered.

To try this principle under a great change of circumstances, and to prove in what manner it was applicable to another most simple form of the object-glass, having made a magnified tracing of the curves of one of Utzschneider's*, and drawn a ray through it from its longer aplanatic focus,

* See Figure p. 194.

which was ascertained after cementing the lenses; I laid down a figure of the flint lens inverted, and by means of the angles of the other diagram projected a plano-convex *z* to be joined to its flat side. The new glass proved as achromatic as the original, though the single radius of the plano-convex was more than one-third longer than corresponded with the curves of the former double convex lens: the two aplanatic foci showed themselves as before; the longer, however, not in the place indicated by the ray drawn: but at a point F, about two-thirds more distant from the glass, and from which both surfaces of the flint lens bent the pencil outwards; the shorter focus F'' too becoming about half the length of the other, and the angle of incidence of its rays not equalling that of their emergence.

The longer aplanatic focus may be found when one of the plano-convex object-glasses is placed in a microscope, by shortening the tube if the glass shows over-correction, if under-correction by lengthening it, or by bringing the rays together should they be parallel or divergent, by a very small good telescope. The shorter focus is got at by sliding the glass before another of sufficient length and large aperture that is finely corrected, and bringing it forwards till it gives the reflexion of a bright point from a globule of quicksilver, sharp and free from mist, when the distance can be taken between the glass and the object.

The longer focus is the place at which to ascertain the utmost aperture that may be given to the glass, and where, in the absence of spherical error, its exact state of correction as to colour is seen most distinctly.

The correction of the chromatic aberration, like that of the spherical, tends to excess in the marginal rays; so that if a glass, which is achromatic with a moderate aperture, has its cell opened wider, the circle of rays thus added to the pencil will be rather over-corrected as to colour.

The same tendency to over-correction is produced, if, without varying the aperture, the divergence of the incident rays is much augmented; as in an object-glass placed in front of another: but, generally, in this position a part only of its aperture comes into use; so that the two properties mentioned neutralize each other, and its chromatic state remains unaltered. If, for example, the outstanding colours were observed at the longer focus to be green and claret, which show that the nearest practicable approach is made to the

union of the spectrum, they usually continue nearly the same for the whole space between the foci, and for some distance beyond them either way.

The places of these two foci and their proportions to each other, depend on a variety of circumstances. In several object-glasses that I have had made for trial,—plano-convex, with their inner surfaces cemented, their diameters the radius of the flint lens, and their colour pretty well corrected,—those composed of dense flint and light plate have had the rays from the longer focus emerging nearly parallel; and this focus has been not quite three times the distance of the shorter from the glass: with English flint the rays have had more convergence, and the shorter focus has borne a rather less proportion to the longer.

If the inner surfaces are not cemented, a striking effect is produced by minute differences in their curves. It may give some idea of this, that in a glass of which almost the whole disk was covered with colour from contact of the lenses, the addition of a film of varnish so thin that this colour was not destroyed by it, caused a sensible change in the spherical correction.

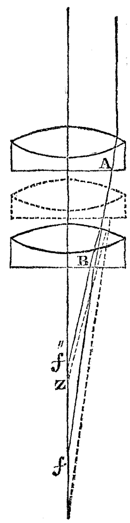
I have found that whatever extended the longer aplanatic focus, and increased the convergence of its rays, diminished the relative length of the shorter. Thus by turning to the concave lens the flatter instead of the deeper side of a convex lens, whose radii were to each other as 31 to 35, the pencil of the longer aplanatic focus, from being greatly divergent, was brought to converge at a very small distance behind the glass; and the length of the shorter focus which had been one-half that of the longer, became but one-sixth of it.

The direction of the aplanatic pencils appears to be scarcely affected by differences in the thickness of glasses, if their state as to colour is the same.

One other property of the double object-glass remains to be mentioned; which is, that when the longer aplanatic focus is used, the marginal rays of a pencil not coincident with the axis of the glass are distorted, so that a coma is thrown outwards; while the contrary effect of a coma directed towards the centre of the field is produced by the rays from the shorter focus. These peculiarities of the coma seem inseparable attendants on the two foci, and are as conspicuous in the achromatic meniscus, as in the plano-convex object-glass.

Of several purposes to which the particulars just given seem applicable, I must at present confine myself to the most obvious one. They furnish the

means of destroying with the utmost ease both aberrations in a large focal pencil, and of thus surmounting what has been hitherto the chief obstacle to the perfection of the microscope. And when it is considered that the curves of its diminutive object-glasses have required to be at least as exactly proportioned as those of a large telescope, to give the image of a bright point equally sharp and colourless, and that any change made to correct one aberration was liable to disturb the other, some idea may be formed of what the amount of that obstacle must have been. It will however be evident, that if any object-glass is but made achromatic, with its lenses truly worked and cemented so that their axes coincide, it may with certainty be connected with another possessing the same requisites and of suitable focus, so that the combination shall be free from spherical error also in the centre of its field. For this the rays have only to be received by the front glass B, from its shorter aplanatic focus *f*, and transmitted in the direction of the longer correct pencil *f* A of the other glass A. It is desirable that the latter pencil should neither converge to a very short focus, nor be more than very slightly, if at all, divergent; and a little attention at first to the kind of glass used will keep it within this range, the denser flint being suited to the glasses of shorter focus and larger angle of aperture.



The adjustment for the microscope is then perfected, if necessary, by slightly varying the distance between the object-glasses; and after that is done, the length of the tube which carries the eye-pieces may be altered greatly without disturbing the correction; opposite errors which balance each other being produced by the change.

If the two glasses, which in the diagram are drawn as at some distance apart, are brought nearer together, (if the place of A for instance, is carried to the dotted figure,) the rays transmitted by B in the direction of the longer aplanatic pencil of A, will plainly be derived from some point (z) more distant than f'', and lying between the aplanatic foci of B; therefore (according to what has been stated) this glass, and consequently the combination, will then be spherically over-corrected. If on the other hand the distance between A and B is increased, the opposite effects are of course produced.

In combining several glasses together, it is often convenient to transmit an

under-corrected pencil from the front glass, and to counteract its error by over-correction in the middle one.

Slight errors in colour may in the same manner be destroyed by opposite ones; and on the principles described, we not only acquire fine correction for the central ray, but by the opposite effects at the two foci on the transverse pencil, all coma can be destroyed, and the whole field rendered beautifully flat and distinct.

The occurrence of two good combinations among the numerous ones of UTZSCHNEIDER's glasses will now appear only what might be expected; and more are to be obtained from them by varying the distance of the glasses from each other.

I have very lately seen one of CHEVALIER's combinations of three glasses, each about 0.4 inch in focus, inferior indeed to these, and of contracted aperture, but which I ought to notice because its image is pretty well corrected with the glasses in the order given to them by the maker. At the same time, I do not suppose him to be acquainted with the principle which constitutes the key to the effect; otherwise he would hardly have failed to apply it more effectually.

The achromatic meniscus that has been described enters well into combination, and may perhaps be useful as the front glass of three, but its power is small in proportion to its curves. It admits too of being cemented at the back of an achromatic plano-convex; and they may make together a powerful compound glass to go before another.

Though the plano-concave form has been proposed for the flint lens, in the larger glasses it might perhaps occasionally be relinquished with benefit.

Some attention has yet to be given to obtain the best effect from combination; so that with the largest pencil that may be found desirable, and sufficient clear space before the front of the glass, the field may be aplanatic, and the focus short. Already, however, the three first plano-convex glasses that have been made for me by TULLEY, only for preliminary experiments, the shortest of them of 0.7 inch focus, have produced at an aperture of 50° the most distinct microscopic vision that I have yet met with; and I anticipate no serious impediment to the carrying defining power much further.

These statements are intended only as a notice, for practical purposes and

wholly detached from theory, of facts that have been in part very recently ascertained. In investigating them I have depended chiefly on magnified measurements and diagrams, which, though not strictly correct, may perhaps be as well adapted as other far more exact but difficult methods, for constructing the minute and complex object-glass of a microscope. It is to this that the observations made particularly apply; and should they bring more within reach than previously, the requisites which have been enumerated, I trust they may not be unacceptable to the enlightened optician; especially if in this department he unite, like Tulley, the zeal of the amateur with the skill of the superior artist.

I intend soon to put to the test of experiment, whether or not the principle of the two aplanatic pencils may be applied to telescopes, in cases in which it is requisite to restrict their length, so as to enlarge their aperture with a corresponding increase of light and distinctness. In the mean time, it would give me pleasure to see that principle demonstrated, if it deserve it, by some abler hand than mine, and treated in a more rigorous manner than my own limited acquaintance with mathematical science qualifies me to undertake.