MICROSCOPE

THE microscope is an optical instrument for the examination of minute objects or parts of objects, which enlarges the visual pictures formed upon the retina of the observer by the rays proceeding from them.

Microscopes are distinguished as *simple* or *compound.* In the former, the rays which enter the eye of the observer come from an object brought near to it after refraction through either a single lens or a combination of lenses acting as a single lens,—its action as a "magnifier" depending on its enabling the eye to form a distinct image of the object at a much shorter distance than would otherwise be possible. The latter consists of at least two lenses, so placed relatively to the object, to the eye, and to one another that an enlarged image of the object, formed by the lens placed nearest to it (the "object-glass"), is looked at through the lens nearest the eye (the "eye-glass"), which acts as a simple microscope in "magnifying" it; so that the compound microscope may be described as a simple microscope used to look at an enlarged image of the object, instead of at the object itself.

History of the Simple Microscope.—Any solid or liquid transparent medium of lenticular form, having either one convex and one flat surface or two convex surfaces whose axes are coincident, may serve as a "magnifier,"—what is essential being that it shall have the power of so refracting the rays which pass through it as to cause widely diverging rays to become either parallel or but slightly divergent. Thus if a minute object be placed on a slip of glass, and a single drop of water be carefully placed upon it, the drop will act as a magnifier in virtue of the convexity of its upper surface; so that when the eye is brought sufficiently near it (the glass being of course held horizontally, so as not to distort the spherical curvature of the drop) the object will be seen much enlarged. And if a small hole be made in a thin plate of metal, and a minute drop of water be inserted in it, this drop, having two convex surfaces, will serve as a still more powerful magnifier. There is reason to believe that the magnifying power of transparent media with convex surfaces was very early known. A convex lens of rock-crystal was found by Layard among the ruins of the palace of Nimrud. And it is pretty certain that, after the invention of glass, hollow spheres blown of that material and filled with water were commonly used as magnifiers (comp. vol. xiv. p. 577). The perfection of gem-cutting shown in ancient gems, especially in those of very minute size, could not have been attained without the use of such aids to the visual power; and there can be little doubt that the artificers who could execute these wonderful works could also shape and polish the magnifiers best suited for their own or others' use. Though it is impossible to say when convex lenses of glass were first made by grinding, it is quite certain that they were first generally used to assist ordinary vision as "spectacles," the use of which can be traced back nearly six centuries; and not only were spectacle-makers the first to produce glass magnifiers (or simple microscopes), but by them also the telescope and the compound microscope were first invented. There seems no reason to believe, however, that lenses of very high magnifying power (or short focus) were produced until a demand for them had been created by the introduction of the compound microscope, in which such lenses are required as "object-glasses"; and the difficulty of working lenses of high curvature with the requisite accuracy led in the first instance to the employment of globules made by fusing the ends of threads of spun glass. It was in this way that Robert Hooke shaped the minutest of the lenses with which he made many of the numerous discoveries recorded in his *Micrographia*; and the same method was employed by the Italian microscopist Father Di Torre. It seems to have been Leeuwenhoek that first succeeded in grinding and polishing lenses of such short focus and perfect figure as to render the simple microscope a better instrument for most purposes than any compound microscope then constructed,—its inferiority in magnifying power being more than counterbalanced by the superior clearness of the retinal picture. And, in despair of any such modification in the compound form as should remove the optical defects which seemed inherent in its plan of construction, scientific opticians and microscopic observers alike gave their chief attention for a considerable period to the improvement of the simple microscope. In order that the nature of these improvements may be understood, the principle of its action must be first explained.

The normal human eye has a considerable power of self-adjustment, by which its focal length is so varied that it forms equally distinct pictures of objects brought within ordinary reading distance (say 10 inches) and of objects whose distance is many times that length,—the size of the visual picture of any object diminishing, however, with the increase in the distance to which it is removed, and the amount of detail distinguishable in it following the same proportion. Thus a man who looks across the street at a placard posted on the opposite wall may very distinctly see its general form and the arrangement of its heading, and may be able to read what is set forth in its largest type, whilst unable to separate the lines, still more to read the words, of what is set forth below. But by crossing the street so as to bring his eye nearer the picture he finds himself able to read the smaller type as easily as he before read the larger,—the visual picture on his retina having been magnified, say 10 times in linear dimension, by the reduction of the distance of his eye from 40 feet to 4. Similarly, if he holds a page of excessively minute type at arm's length (say 40 inches) from his eye, he may be unable to read it, not because his eye does not form a distinct retinal picture of the page at that distance, but because the details of that picture are too minute for him to distinguish them. But if he brings the page from 40 inches to 10 inches distance, he may be able to read it without difficulty,—the retinal picture being enlarged four times linear (or sixteen times superficial) by this approximation. Now the rays that enter the eye from each point of a remote object diverge so little as to be virtually parallel; but the divergence increases with the approximation of the object to the eye, and at 10 inches the angle of their divergence is as wide as permits the ordinary eye to bring them to a focus on the retina. When the object is approximated more closely, an automatic contraction of the pupil takes place, so that the most diverging rays of each pencil are cut off, and a distinct picture may be formed (though not without a feeling of strain) when the object is (say) from 5 to 8 inches distant,—giving still greater minuteness of visual detail in conformity with the increase of size. A further magnifying power may be obtained without the interposition of any lens, by looking at an object, at 2 or 3 inches distance, through a pin-hole in a card; for by thus cutting off the more divergent rays of each pencil, so as to admit only those which can be made to converge to a focus on the retina at that distance, a distinct and detailed picture may be obtained, though at the expense of a great loss of light. Moreover,

although an ordinary eye does not form a distinct picture of an object at less than from 10 to 6 inches distance, a "myopic" or "short-sighted" eye (whose greater refractive power enables it to bring rays of wider divergence to a focus on the retina) may form an equally distinct picture of an object at from 5 to 3 inches distance; and, as the linear dimensions of that picture will be double that of the preceding, the object will be "magnified" in that proportion, and its details more clearly seen.

The effect of the interposition of a convex lens between the eye and an object nearly approximated to it primarily consists in its reduction in the divergence of the rays of the pencils which issue from its several points, so that they enter the eye at the moderate divergence which they would have if the object were at the ordinary nearest limit of distinct vision. And, since the shorter the focus of the lens the more closely may the object be approximated to the eye, the retinal picture is enlarged, causing the object to appear magnified in the same proportion. Not only, however, are the component rays of each pencil brought from divergence into convergence, but the course of the pencils themselves is changed, so that they enter the eye under an angle corresponding to that under which they would have arrived from a larger object situated at a greater distance; and thus, as the picture formed upon the retina by the small object *ab*, fig. 1, corresponds in all respects with that which would have been made by the same object AB of several times its linear dimension viewed at the nearest ordinary limit of distinct vision, the object is seen (by the formation of a "virtual image") on a magnified scale.

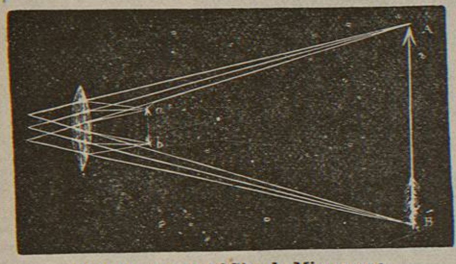

FIG. 1.—Action of Simple Microscope.

It is obvious that the "magnifying power" of any convex lens so used is measured by the ratio between the dimensions of the retinal picture formed with its assistance and those of the picture formed by the unaided eye. Thus, if by the use of a convex lens having 1 inch focal length we can form a distinct retinal image of an object at only an inch distance, this image will have ten times the linear dimensions of that formed by the same object at a distance of 10 inches, but will be only eight times as large as the picture formed when the object can be seen by ordinary vision at 8 inches distance, and only four times as large as the picture of the same object formed by a myopic eye at a distance of 4 inches. It is usual to estimate the magnifying power of single lenses (or of combinations that are used as such) by the number of times that their focal length is contained in 10 inches,—that of 1 inch focus being thus taken as ten times, that of $\frac{1}{10}$ inch as one hundred times, and so on. But the rule is obviously arbitrary, as the actual magnifying power varies in each individual with the nearest limit of distinct vision. Thus for the myopic who can see an object clearly at 4 inches distance, the magnifying powers of a 1 inch and $\frac{1}{10}$ inch lens will be only 4 and 40 respectively. The amplifying power of every single convex lens, however, is impaired (1) by that inability to bring to the same focus the rays which fall upon the central and the marginal parts of its surface which is called "spherical aberration," and (2) by that dispersion of the rays of different wave-lengths, in virtue of their different refrangibilities, which produces coloured fringes around the points and lines of the visual picture, and is therefore called "chromatic aberration" (see LIGHT). These aberrations increase with the "angle of aperture" given to the lens, that is, with the proportion between the diameter of its actual "opening" and the focal distance of the object; and thus, when a single lens of very short focus is used in order to gain a high magnifying power, such a reduction of its aperture by a perforated diaphragm or "stop" becomes necessary (in order, by excluding the peripheral rays, to obtain tolerable "definition" with freedom from false colour) that the amount of light admitted to the eye is so small as only to allow the most transparent objects to be thus viewed, and these only very imperfectly. In order to remedy this drawback, it was proposed by Sir D. Brewster to use instead of glass, in the construction of simple microscopes, such transparent minerals as have high refractive with low dispersive power; in which case the same optical effect could be obtained with lenses of much lower curvature, and the aperture might be proportionately enlarged. This combination of qualities is found in the diamond, whose index of refraction bears such a proportion to that of glass that a diamond lens having a radius of curvature of 8 would give the same magnifying power as a glass lens whose radius of curvature is 3, while the "longitudinal aberration" (or distance between the foci of central and of marginal rays) would be in a diamond lens only one-ninth of that of a glass lens having the same power and aperture. Putting aside, however, the costliness of the material and the difficulty of working it, a source of imperfection arises from a frequent want of homogeneousness in the diamond crystal, which has proved sufficient to make a lens worked from it give a double or even a triple image. Similar attempts made by Mr Pritchard with sapphire proved more successful; and, as a sapphire lens having a radius of curvature of 5 has the same focus and gives the same magnifying power as a crown-glass lens having a radius of 3, it was found to bear a much larger aperture without serious impairment by either spherical or chromatic aberration. As the sapphire, however, possesses the property of double refraction, the duplication of the markings of the object in their retinal image constitutes a very serious drawback to the utility of lenses constructed of this mineral; for, though the double refraction may be reduced almost to nothing by turning the convex side of the lens towards the object, yet, as this is the worst position in regard to spherical aberration, more is lost than is gained. Fortunately, however, for biological investigators working with simple microscopes, the introduction of the Wollaston doublet superseded the necessity of any further attempts at turning costly jewels to account as high-power magnifiers.

Wollaston Doublet.—This consists of a combination of two plano-convex lenses, whose focal lengths (as directed by Dr Wollaston) should be as 3 to 1, with their plane sides turned towards the object,—the smaller lens being placed lowest, and the upper lens at a distance of one and a half times its focal length above it. This construction, however, has been subsequently improved—(1) by the introduction of a perforated diaphragm between the lenses; (2) by a more effective adjustment of the distance between the two lenses, which seems to be most satisfactory when it equals the difference of their respective focal lengths, allowance being made for their thickness; and (3) by the division of the power of the lower lens (when a shorter focus than $\frac{1}{10}$ inch is required) into two, so as to form a "triplet." When combinations of this kind are well constructed, spherical aberration is almost wholly got rid of, and chromatic dispersion is so slight that the angle of aperture may be considerably enlarged without much sacrifice of distinctness. Such "doublets" and "triplets," having been brought into use in England while the compound microscope still retained its original imperfections, proved very serviceable to such as were at that time prosecuting minute biological investigations: for example, the admirable researches of Dr Sharpey on ciliary action in animals (1830–35) and Mr Henry Slack's beautiful dissections of the elementary tissues of plants, as well as his excellent observations on vegetable cyclosis (1831), were made by their means. No one, however, would now use Wollaston "doublets" or "triplets" of high power in place of a compound achromatic microscope; and for the simple microscopes of low power that are useful either for dissecting or for picking out minute specimens (such as diatoms) other constructions are preferable, as giving a larger field and more light. As a hand-magnifier the "Coddington" lens—which is a sphere of glass with a deep groove ground out of its equatorial portion—has many advantages.[1] By making this groove sufficiently deep, both spherical and chromatic aberrations can be rendered almost insensible; and, as the rays falling on any part of the spherical surface can only pass to the eye either through or near the centre, the action of every part of that surface is the same, so that the image of the object will be equally distinct (when properly focussed) whether its parts lie nearer to the axis of the sphere or more remote from it, or the axis be itself turned to one side or the other. Again, it was mathematically shown by Sir John Herschel in 1821 that by the combination of a meniscus with a double convex lens—the four surfaces of these lenses having certain proportionate curvatures—spherical aberration could be entirely extinguished for rays parallel to the axis, the combination being thus an "aplanatic" doublet, while another combination, which he termed a "periscopic" doublet, gives a remarkable range of oblique vision with low powers, and almost entirely extinguishes chromatic aberration, although at the expense of residual spherical aberration. These combinations have been mounted both as hand-magnifiers and as single microscopes, for both which purposes they are much superior to single lenses of the same magnifying power. But such combinations have been greatly improved by the introduction of concaves of flint glass, so as to render them achromatic as well as aplanatic; and nothing, according to the writer's experience, can now be used with greater advantage for all the purposes answered either by the simple microscope or the hand-magnifier than Browning's "platyscopic" lenses or the "achromatic doublets" of Steinheil of Munich. Each of these combinations gives a large flat field, with plenty of light, admirable definition, and freedom from false colour.

At the period when "doublets" of very short focus were used in order to obtain high magnifying power, it was requisite to mount these on such a stand as would enable the focal adjustment to be made, and would admit the use of a special illuminating apparatus with great exactness. But now that comparatively low powers only are employed the ordinary rack-and-pinion movement is quite sufficient for their focal adjustment, and nothing more is required for the illumination of the object than a concave mirror beneath the stage when it is transparent, and a condensing lens above when it is opaque The various patterns of simple microscope now made by different makers vary in their construction, chiefly in regard to portability, the size of their stages, and the mode in which "rests" or supports to the hands are provided. These, in Continental instruments, are very commonly attached to the stage; but, unless the stage itself and the pillar to which it is fixed are extremely massive, the resting of the hands on the supports is apt to depress the stage in a degree that affects the focal adjustment; and where portability is not an object it seems better that the hand-supports should be independent of the stage. For a laboratory microscope, the pattern represented in fig. 2 has been found very convenient,—the framework being of mahogany or other hard wood the stage being large enough to admit a dissection or carry a water-trough of considerable size, and the bent arm that carries the "powers" being made capable of reversion, so as to permit the use of lenses of very long as well as of very short focus. As it is desirable that the stage should not be acted on chemically by sea-water, acids, or other reagents, it may be made either of a square of plate-glass or of a plate of ebonite with an aperture in the middle; and either of these may be made to slide in grooves in the side supports, so that one may be substituted for the other. The arm may be easily made (if desired) to carry the body of a compound microscope, so as to apply it to the examination of objects dissected or otherwise prepared under the simple microscope, without transferring them to another instrument. A portable form of simple microscope is shown in fig. 30.

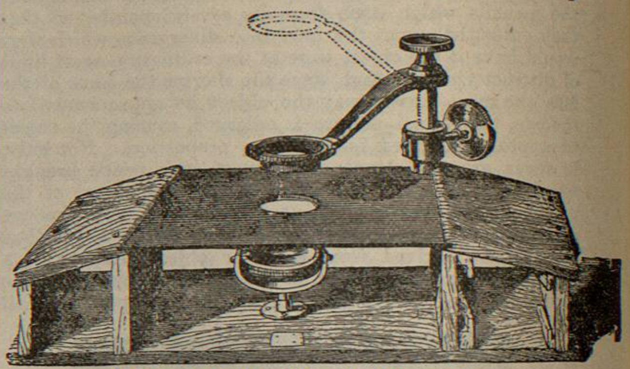

FIG. 2.—Laboratory Dissecting Microscope.

Compound Microscope.—The placing of two convex lenses in such relative positions that one should magnify an enlarged image of a small near object formed by the other naturally soon followed the invention of the telescope, and seems to have first occurred to Hans Zansz or his son Zacharias Zansz, spectacle-makers at Middelburg in Holland, about 1590. One of their compound microscopes, which they presented to Prince Maurice, was in the year 1617 in the possession of Cornelius Drebell of Alkmaar, who then resided in London as mathematician to king James I. In order to make clear the successive stages by which the rude and imperfect microscope of that period has, after remaining for two centuries unimproved in any essential particular, been developed within the last half-century into one of the most important instruments of scientific research that the combination of theoretical acumen and manipulative skill has ever produced, it is necessary to explain the principle of its construction, and to show wherein lay the imperfection of its earlier form.

In its simplest construction, as already stated, the compound microscope consists of only two lenses,—the "object-glass" CD, fig. 3, which receives the light-rays direct from the object AB placed near it, and forms an enlarged but reversed image A′B′ at a greater distance on the other side, and the "eye-glass" LM, which receives the rays that diverge from the several points of this image as if they proceeded from the points of an actual object occupying the position and enlarged to the dimensions A′B′, and brings these to the eye at E, so altering their course as to act as a simple microscope in magnifying that image to the observer. It was early found useful, however, to interpose another lens FF, fig. 4 (the "field-glass"), between the object-glass and the image formed by it, for the purpose of giving such a slight convergence to the pencil of rays as shall reduce the dimensions of the image, and thus allow a larger part of it to come within the range of the eye-glass, so that more of the object can be seen at once. And it was soon perceived that the eye-glass and the field-glass might be advantageously combined into an "eye-piece," in which a perforated diaphragm might be inserted at the focal plane of the image (*i.e.*, in the focus of the eye-glass), so as, by cutting off the peripheral portion of the field of view, to limit it to what can be seen with tolerable distinctness.

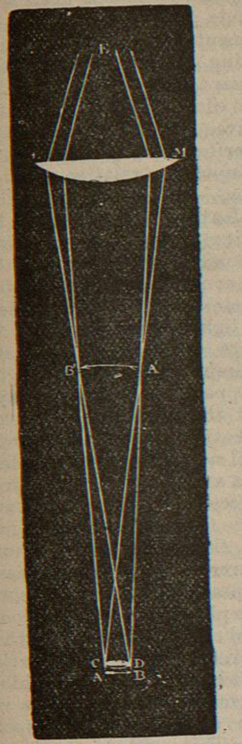

FIG. 3.—Diagram of Simplest Form of Compound Microscope.

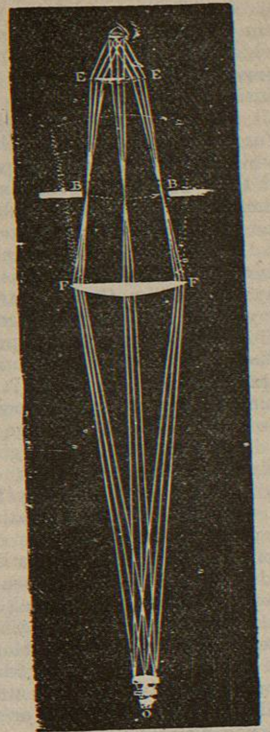

FIG. 4.—Diagram of Complete Compound Microscope.

It is obvious that the magnifying power of such an instrument would depend (1) on the proportion between the size of the image formed at BB and that of the actual object, and (2) upon the magnifying power of the eye-glass. And further the proportion which the size of the image bears to that of the object depends upon two factors,—(1) the focal length of the object-glass, and (2) the distance between the object-glass and the plane BB occupied by the image it forms. If we diminish the focal length of the object-glass, the object must be brought nearer to it, so that, while the distance of the image on the other side remains unchanged, that distance comes to bear a larger proportion to the distance of the object, and the size of the image is augmented in a corresponding ratio. On the other hand, the object-glass remaining unchanged, the distance at which it forms the image of the object can be increased by a lengthening of the tube of the microscope; and, as this involves a shortening of the distance between the object-glass and the object, the proportion which the former bears to the latter is augmented, and the image is correspondingly enlarged. Thus an increase in the magnifying power of the compound microscope may be gained in three modes, which may be used either separately or in double or triple combination,—viz., (1) shortening the focus of the object-glass, (2) lengthening the tube of the microscope, and (3) increasing the magnifying power of the eye-glass by shortening its focus. This, it may be remarked, also lengthens the distance of the image from the object-glass, by bringing the focal plane BB nearer the eye-glass. The second of these methods was not unfrequently used in the older microscopes, which were sometimes made to draw out like telescopes, so as to increase the amplifying power of their object-glasses. But, whilst very inconvenient to the observer, such a lengthening of the one distance involved such a shortening of the other as greatly impaired the distinctness of the image by increasing the aberrations of the object-glass, so that this method came to be generally abandoned for one of the other two.

When lenses of from 1 to 4 inches focus were used as object-glasses, and their apertures were restricted by a stop to the central part of each, tolerably distinct images were given of the larger structural arrangements of such objects as sections of wood or the more transparent wings of insects,—which images would bear a further moderate enlargement by the eye-glass without any serious deterioration either by want of definition or the introduction of colour-fringes. But when lenses of less than 1 inch focus were employed in order to obtain a higher magnifying power, the greater obliquity of the rays so greatly increased their aberrations that defective definition and the introduction of false colours went far to nullify any advantage obtainable from the higher amplification, while the limitation of the aperture required to keep these aberrations within even moderate limits occasioned such a loss of light as most seriously to detract from the value of the picture. On the other hand, the use of deeper eye-pieces to enlarge the images formed by the object-glasses not only brought out more strongly all the defects of those images, but introduced a new set of errors of their own, so that very little was gained by that mode of amplification. Hence many of the best of the older microscopists (notably LEEUWENHOEK, *q.v.*) made some of their most valuable discoveries by the use of the simple microscope; and the amount of excellent work thus done surprises every one who studies the history of microscopic inquiry. This was still more the case, as already stated, when the use of single lenses of very short focus was superseded by the introduction of the Wollaston doublet. And the substitution of these doublets for the single lenses of object-glasses, while the single lens of the eye-glass was replaced by a Herschel's aplanatic doublet, and the field-glass was a convex lens whose two curves had the proportion of 1:6 (the form of least spherical aberration), constituted the greatest improvement of which the instrument seemed capable in pre-achromatic times.[1]

It has been only within the last sixty years (1820–30) that the microscope has undergone the important improvement which had been worked out by Dollond in the refracting telescope more than sixty years previously,—namely, the correction of the chromatic aberration of its objectives by the combination of concave lenses of flint-

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[1] It is difficult to understand how the name of Coddington came to be attached to the grooved sphere, seeing that he neither was nor claimed to be the inventor of it. Dr Wollaston's first "doublet" consisted of a pair of plano-convex lenses with their plane surfaces opposed to each other, and a diaphragm with central aperture placed between them. Sir D. Brewster showed that this construction is most advantageous when the two lenses are hemispheres, and the central aperture between their two plane surfaces is filled up by a transparent cement having the same refractive index as glass. And from this the transition is obvious to the grooved sphere, which had been made for Sir D. Brewster long before the high commendation it received from Mr Coddington brought it into general repute.

[1] This combination was made in the first microscope of which the writer became possessed, about the year 1830; and he well recollects the great superiority to any compound microscope of the old construction which was proved by its power of separating the lines on the *Menelaus* scale, and of bringing into view the details of the structure of animalcules, with a clearness that only an achromatized object-glass could surpass.

glass with convex lenses of crown, while their spherical aberration is corrected by the combination (as in Herschel's aplanatic doublet) of convex and concave surfaces of different curvatures. The minute size and high curvature of the lenses required as microscopic objectives were long considered as altogether precluding the possibility of success in the production of such combinations, more especially as the conditions they would have to meet differ altogether from those under which telescopic object-glasses are employed. For the rays from distant objects fall upon the latter with virtual parallelism; and the higher the power required the longer is the focus given to them, and the smaller is the deflexion of the rays. In the microscope, on the other hand, the object is so closely approximated to the objective that the rays which proceed to it from the latter have always a very considerable divergence; and the deflexion to which they are subjected increases with that reduction of the focal length of the objective which is the necessary condition of the increase of its magnifying power. And thus, although the telescopic "triplet" worked out by Dollond (consisting of a double-concave of flint glass, interposed between two double-convex lenses of crown) can be so constructed as to be not only completely aplanatic (or free from spherical aberration) but almost completely achromatic (or free from chromatic aberration), this construction is only suitable for microscopic objectives of long focus and small angular aperture, the rays falling on which have but a very moderate divergence. And though, as will presently appear, some of the early attempts at the achromatization of the microscope were made in this direction, it was soon abandoned for other plans of construction, which were found to be alike theoretically and practically superior.

It seems to have been by Professor Amici, then of Modena, about 1812, that the first attempts were made at the achromatization of microscopic objectives; but, these attempts not proving successful, he turned his attention to the production of a reflecting microscope, which was a decided improvement upon the non-achromatized compound microscopes then in use. In the year 1820, however, the subject was taken up by Selligues and Chevalier of Paris, who adopted the plan of superposing three or four combinations, each consisting of a double-convex of crown cemented to a plano-concave of flint. The back combination (that nearest to the eye) was of somewhat lower power than those placed in front of it, but these last were all of the same focus, and no attempt was made by these opticians to vary the construction of the several pairs thus united, so as to make them correct each others' aberrations. Hence, although a considerable magnifying power could be thus obtained, with an almost complete extinction of chromatic aberration, the aperture of these objectives could not be greatly widened without the impairment of the distinctness of the image by a "coma" proceeding from uncorrected spherical aberration.

In ignorance, it would appear, of what was being done by the Paris opticians, and at the instigation of Dr Goring (a scientific amateur), Mr Tulley—well known in London as an able constructor of telescopic objectives—began, about the year 1824, to work object-glasses for the microscope on the telescopic plan. After many trials[1] he succeeded, in 1825, in producing a triplet of $\frac{9}{10}$ inch focus, admitting a pencil of 18°, which was so well corrected as to perform very satisfactorily with an eye-piece giving a magnifying power of 120 diameters. He afterwards made a similar triplet of shorter focus, which, when placed in front of the previous one, increased the angle of the transmitted pencil to 38°. and bore an eye-piece giving a magnifying power of 300 diameters. These triplets are said by Mr Ross to have never been exceeded by any similar combinations for accurate correction throughout the field.

Having come into possession, at the end of 1826, of an objective of Chevalier's construction, Mr J. J. Lister carefully examined its properties, and compared them with those of Tulley's triplets; and this comparison having led him to institute further experiments he obtained results which were at first so conflicting that they must have proved utterly bewildering to a less acute mind,[2] but which finally led him to the enunciation of the principle on which all the best microscopic objectives are now constructed. For he discovered that the performance of such composite objectives greatly depends upon the relative position of their component combinations,—the effect of the flint plano-concave upon the spherical aberration produced by the double-convex of crown varying remarkably according to the distance of the luminous point from the front of the objective. If the radiant is at a considerable distance, the rays proceeding from it have their spherical error under-corrected; but, as the source of light is brought nearer to the glass, the flint lens produces greater proportionate effect, and the under-correction diminishes, until at length a point is reached where it disappears entirely, the rays being all brought to one point at the conjugate focus of the lens. This, then, is one aplanatic focus. If, however, the luminous point is brought still nearer to the glass, the influence of the flint continues for a time to increase, and the opposite condition of over-correction shows itself. But, on still further approximation of the radiant, the flint comes to operate with less effect, the excess of correction diminishes and at a point still nearer to the glass vanishes, and a second aplanatic focus appears. From this point onwards under-correction takes the place of over-correction, and increases till the object touches the surface of the glass. As every such doublet, therefore, has two aplanatic foci for all points between which it is over-corrected, while for all points beyond it is under-corrected, the optician is enabled to combine two or more doublets with perfect security against spherical error. This will be entirely avoided if the rays be received by the front glass from its shorter aplanatic focus, and transmitted through the back glass in the direction of its longer aplanatic pencil. By the approximation of the two doublets over-correction will be reduced, while their separation will produce under-correction; and thus, by merely varying the distance between two such combinations, the correction of the spherical error may be either increased or diminished according to a definite rule. Slight defects in one glass may thus be remedied by simply altering its position in relation to the other,—an alteration which may be made with very little disturbance of the colour-correction. This important principle was developed and illustrated by Mr Lister in a memoir read to the Royal Society on January 21, 1830, *On some Properties in Achromatic Object-glasses, applicable to the Improvement of the Microscope*; and it was by working on the lines there laid down that the three London opticians Ross,[3] Powell, and James Smith soon produced microscopic objectives that surpassed any then constructed on the Continent, while the subsequent adoption of the same principles by French and German opticians, as also by Professor Amici of Florence, soon raised their objectives to a corresponding level.

It has proved more advantageous in practice to make the several components of an achromatic objective correct each others' aberrations than to attempt to render each perfect in itself; and the mode in which this is accomplished will vary with the focus and angular aperture given to each combination. Thus, while a single "telescopic triplet" answers very well for the lowest power usually made (4 inches focus), and the same plan may be used—though at the sacrifice of angular aperture—for objectives of 3 inches, 2 inches, and even 1 inch focus, the best performance of these powers requires the combination of two doublets. And, while this last system also serves for objectives of $\frac{2}{3}$ inch and $\frac{1}{2}$ inch of low angle, a third component is required for giving to these objectives the aperture that renders them most serviceable, as well as for all higher powers. Instead of combining three achromatic doublets, however, many makers prefer placing in front a plano-convex of crown, and adding a third lens of crown to the doublet at the back, still using a doublet in the middle,—the whole combination thus consisting of six lenses, four of crown and two of flint. Further, Mr Wenham has shown that the whole colour-correction may be effected in the middle by interposing a double concave of dense flint between two double-convex lenses of crown,—the back lens, as well as the front, being then a plano-convex of crown, making five lenses in all. This plan of construction, though suitable to objectives of moderate angular aperture, and advantageous in regard to comparative simplicity and economy of construction, does not seem so well adapted for objectives to which the largest attainable aperture is to be given,—these being usually constructed with a triplet in front, a doublet in the middle, and a triplet at the back, so as to consist of eight separate lenses. And the first-class constructors of achromatic objectives in the United States usually place in front of these, in their highest powers, a single plano-convex of crown, by the addition of which a greater working distance can be obtained. But, as every such addition increases the liability to error from imperfections in the centring and grinding of the lenses (as well as loss of light by the partial reflexion of oblique rays from their surfaces), it is obvious that the most exact workmanship, involving a proportionate costliness, is required to bring out the full effect of such complex construction. And where angular aperture is regarded as the quality of primary importance it will be usually found preferable to have recourse to objectives constructed on either the "water" or the "oil" immersion system, to be presently described.

The great increase thus attained in the perfection of the corrections of microscopic objectives for both spherical and chromatic aberration of course rendered it possible to make a corresponding increase in their angular aperture. The minute scales of the wings of butterflies and other insects were naturally among the objects much examined; and it was soon perceived that certain lines and other markings became clearly discernible on these scales with objectives of what was then considered large angle which were utterly undistinguishable with non-achromatized microscopes (however high their magnifying power), and very imperfectly shown under achromatic objectives of small angle. Hence these scales came to be used as "test-objects," for judging of the "definition" and "resolving power" of microscopic objectives,—the former property consisting in the clearness, sharpness, and freedom from false colour of the microscopic images of boundary lines, and depending on the accuracy with which the aberrations are corrected, while the latter term designates that power of separating very closely approximated markings which is now known to be a "function" of aperture. The insect-scales formerly most valued for these purposes were those of the *Morpho menelaus* (fig. 5) and the similarly lined scales of the *Polyommatus argus* (azure-blue), the "battledoor" scales of the same butterfly (fig. 6), the ribbed scales of the *Lepisma saccharina* (sugar-louse), and the minute and peculiarly marked scales of the *Lepidocyrtus curvicollis* (fig. 7), commonly known as the *Podura*. The writer recollects the time when the satisfactory "resolution" of the first three of these tests was considered a sufficient proof of the goodness of even high-power objectives, and when the *Podura*-markings, if visible at all, could only be distinguished as striæ. The further opening-out of the aperture, however, enabled these striæ to be resolved into rows of "exclamation marks"; and, while there is still some uncertainty as to the precise structure of which these markings are the optical expression, practical opticians are generally agreed that the *Podura*-scale is very useful as a test for definition, with even the highest objectives, though it only serves as a test for a very moderate degree of resolving power. For the latter purpose it has been completely superseded by the closely approximated markings of the silicified envelopes of certain diatoms (which, however, show themselves in very different aspects according to the conditions under which they are viewed, figs. 8–11), and also by lines artificially ruled on glass, as in Nobert's "test-plate," the number of lines in the nineteen bands of which is stated by M. Nobert to range from 1000 to 10,000 to a Paris line, while Dr Royston Pigott gives the numbers in an English inch as 11,529 to the inch in the first band, and 112,595 in the nineteenth. This last dimension (as will afterwards appear) approaches the minimum distance at which such markings are theoretically separable by any magnifying power of the microscope.

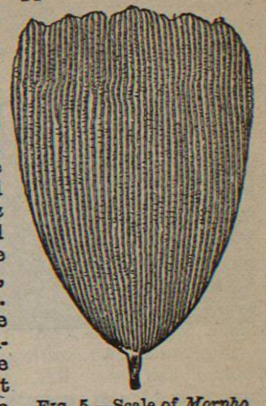

FIG. 5.—Scale of *Morpho menelaus.*

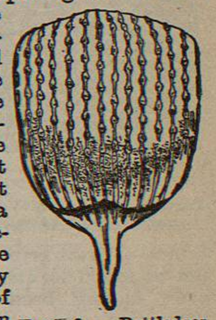

FIG. 6. — Battledoor Scale of *Polyommatus argus.*

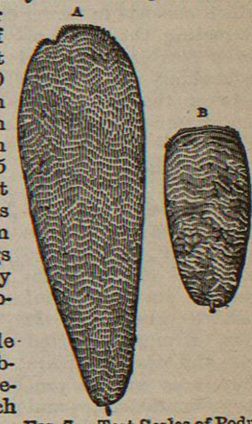

FIG. 7.—Test-Scales of Podura (*Lepidocyrtus curvicollis*). A, large, strongly marked scale; B, small scale, more faintly marked.

The enlargement of the angle of aperture of microscopic objectives and the greater completeness of their corrections, which were obtained in the first instance by the adoption of Mr Lister's principles, and were demonstrated by the resolution of the test-objects then in use, soon rendered sensible an imperfection in their performance under certain circumstances, which had previously passed unnoticed; and the

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[1] It is due to Mr Joseph J. Lister to mention that Tulley's final success with this low power seems to have been attained by working on a suggestion given him by that gentleman. See *Monthly Microscopical Journal*, vol. iii. (1870), p. 134.

[2] Thus he found that, while each of Chevalier's doublet combinations, when used singly, presented a "bur" or "coma" outwards, this coma, instead of being exaggerated by the combination of two of these doublets, was much diminished. On the other hand, while two of Tulley's triplets, each of which performed admirably by itself, were used together, the images of all objects not in the centre presented a strong bur inwards with an under-correction of colour.

[3] In 1837 Mr Lister gave Mr Ross a projection for an objective of $\frac{1}{8}$ inch focus, in which a triple front was combined with two doublets. The great superiority of this lens, admirably executed by Mr Ross, caused him to adopt its plan as the standard one for high powers; and it is still in general use,—the back lens also being sometimes made as a triplet.