the object at an obliquity corresponding to that at which the most divergent rays enter the objective. Now, although in the case of objects whose markings are only superficial such obliquity may not be productive of false appearances (though even this is scarcely conceivable), it must have that effect when the object is thick enough to have an internal structure; and the experience of all biological observers who have carried out the most delicate and difficult investigations is in accord, not only as to the advantage of direct illumination, but as to the deceptiveness of the appearances given by oblique, and the consequent danger of error in any inferences drawn from the latter. Thus, for example, the admirable researches of Strassburger, Fleming, Klein, and others upon the changes which take place in cell-nuclei during their subdivision can only be followed and verified (as the writer can personally testify) by examination of these objects under axial illumination, with objectives of an angle so moderate as to possess focal depth enough to follow the wonderful differentiation of component parts brought out by staining processes through their whole thickness.

The most perfect objectives for the ordinary purposes of scientific research, therefore, will be obviously those which combine exact definition and flatness of field with the widest aperture that can be given without an inconvenient reduction of working distance and loss of the degree of focal depth suitable to the work on which they are respectively to be employed. These last attributes are especially needed in the study of living and moving objects; and, in the case of these, dry objectives are decidedly preferable to immersion, since the shifting of the slide which is requisite to enable the movement of the object to be followed is very apt to produce disarrangement of the interposed drop. And, owing to the solvent power which the essential oils employed for homogeneous immersion have for the ordinary cements and varnishes, such care is necessary in the use of objectives constructed to work with them as can only be given when the observer desires to make a verv minute and critical examination of a securely-mounted object.

The following table expresses the magnifying powers of objectives constructed on the English scale of inches and parts of an inch, with the 10 inch body and the A and B eye-pieces usually supplied by English makers, and also specifies the angle of aperture which, in the writer's judgment, is most suitable for each. He has the satisfaction of finding that his opinions on this latter point, which are based on long experience in the microscopic study of a wider range of animal and vegetable objects than has fallen within the purview of most of his contemporaries, are in accordance with the conclusions drawn by Professor Abbe from his profound investigations into the theory of microscopic vision,[1] which have been carried into practical accomplishment in the excellent productions of Mr Zeiss.

Focal Length.	Angular Aperture.	Magnifying Power.		Focal Length.	Angular Aperture.	Magnifying Power.	
		A Eye-piece.	B Eye-piece.			A Eye-piece.	B Eye-piece.
	°				°		
4 inches	9	12	18	¼ inch.	50–80	200	300
3 "	12	18	27	⅕ "	95	250	375
2 "	15	25	37	⅙ "	110	300	450
1½ "	20	36	54	⅛ "	140	400	600
1 "	30	50	75	$\frac{1}{10}$ "	150	500	750
⅔ "	40	75	112	$\frac{1}{12}$ "	160	600	900
½ "	45	100	150	$\frac{1}{16}$ "	170	800	1200
$\frac{4}{10}$ "	70	125	187				

For ordinary biological work, the ⅛, $\frac{1}{10}$, and $\frac{1}{12}$ objectives, with angles of from 100° to 120°, will be found to answer extremely well if constructed on the water-immersion system.

Each of these powers should be tested upon objects most suited to determine its capacity for the particular kind of work on which it is to be employed; and, in such testing, the application of deeper eye-pieces than can be habitually employed with advantage will often serve to bring out marked differences between two objectives which seem to work almost equally well under those ordinarily used,—defects in definition or colour-correction, and want of light, which might otherwise have escaped notice, being thus made apparent. No single object is of such general utility for these purposes as a large well-marked *Podura* scale; for the eye which has been trained to the use of a particular specimen of it will soon learn to recognize by its means the qualities of any objective between 1 inch and ⅛ inch focus; and it may be safely asserted that the objective which most clearly and sharply exhibits its characteristic markings is the best for the ordinary work of the histologist.

For the special attribute of resolving power, on the other hand, tests of an entirely different order are required; and these are furnished, as already stated, either by the more "difficult" diatoms, or by the highest numbers of Nobert's ruled test-plate. The diatom-valve at present most in use as a test for resolving power is the *Amphipleura pellucida*, the lines on which were long supposed to be more closely approximated than those of Nobert's nineteenth band, being affirmed by Mr Sollitt to range from 120 to 130 in $\frac{1}{1000}$ of an inch. But the admirable photographs of this valve obtained by Colonel Dr Woodward have confirmed the conclusion long previously expressed by the writer, that this estimate was far too high, being based on the "spurious lineation" produced by diffraction, and show that the striæ on the largest valves do not exceed 91, while those on the smallest are never more numerous than 100, in $\frac{1}{1000}$ of an inch. The same admirable manipulator has also obtained excellent photographs of another very difficult test-diatom, *Surirella gemma*, from which it appears that its transverse striæ count longitudinally at the rate of 72,000 to the inch, whilst the beaded appearances into which these may be resolved count transversely at the rate of 84,000 to the inch. Thus it appears that the complete resolution of these "vexatious' diatoms does not require by any means the maximum of aperture, but is probably dependent at least as much on the perfection of the corrections and the effectiveness of the illumination.

It must be understood that there is no intention in these remarks to undervalue the efforts which have been perseveringly made by the ablest constructors of microscopic objectives in the direction of enlargement of aperture. For these efforts, besides increasing the resolving power of the instrument, have done the great service of producing a vast improvement in the quality of those objectives of moderate aperture which are most valuable to the scientific biologist; and the microscopist who wishes his *armamentum* to be complete will provide himself with objectives of those different qualities, as well as different powers, which shall best suit his particular requirements.[2]

ILLUMINATING APPARATUS.

Every improvement in the optical performance of the compound achromatic microscope has called forth a corresponding improvement in the illumination of the objects viewed by it, since it soon came to be apparent that without such improvement the full advantage of the increased defining and resolving powers of the objectives could not be obtained. For the illumination of transparent objects examined by light transmitted through them under low powers of moderate angle a converging pencil of rays reflected upon their under surface by a concave mirror is generally sufficient,—a "condenser" being only needed when the imperfect transparency of the object requires the transmission of more light through it. And the microscopist engaged in ordinary biological studies, who works on very transparent objects with objectives of ⅙ or ⅛ inch focus, or $\frac{1}{10}$ inch immersion, will find that the small concave mirror of short focus with which the Continental models are furnished (see fig. 28) will generally prove sufficient for his needs. This mirror is usually hung at such a distance beneath the stage that parallel rays falling on it are brought to a focus in the object as it lies on a slip of glass resting on the stage; and thus, when the instrument is used by day, the light of a bright cloud (which is preferable to any other) gives a well-illuminated field, even with the powers last-mentioned. But when lamplight is used its divergent rays are not brought to a focus in the object by a mirror that is fixed as just stated; and the distance of the mirror beneath the stage should be made capable of increase (which is easily done by attaching it to a lengthening bar), so as to obtain the requisite focal convergence. Still the best effects of objectives of less than ¼ inch focus cannot be secured without the aid of an achromatic condenser, interposed between the mirror and the object, so as to bring a larger body of rays to a more exact convergence.

When objectives of still higher power are employed, the employment of such a condenser becomes indispensable; and when the highest powers are being used by lamplight, it is desirable to dispense with the mirror altogether, and to place the flame exactly in the optic axis of the microscope. The condenser should be an achromatic combination, corrected for the ordinary thickness of the glass slip on which the object lies, and capable of being so adjusted as to focus the illuminating pencil in the object.

As it is often found desirable that an object should be illuminated by central rays alone, or that the quantity of light transmitted through it should be reduced (for bringing into view delicate details of structure which are invisible when the object is flooded with light), every microscope should be provided with some means of cutting off the outer rays of the illuminating cone. The "diaphragm-plate" ordinarily used for this purpose is a disk of black metal, pivoted to the under side of the stage, and perforated with a graduated series of apertures of different diameters, any one of which can be brought, by the rotation of the disk, exactly into the optic axis of the microscope. But the required effect can be much more advantageously obtained by the "iris-diaphragm," in which a number of converging plates of metal are made so to slide over each other by the motion of a lever or screw that the aperture is either enlarged or diminished, while always remaining practically circular as well as central; and in this manner a continuous

view of the object is obtained, with a gradational modification of the light. Another method, commonly adopted in German microscopes, is to place a draw-tube in the optic axis between the stage and the mirror, and to drop into the top of this tube one of a set of "stops" perforated with apertures of different sizes; this allows a gradational effect to be obtained by raising or lowering the tube, so as to place the stop nearer to or more remote from the object; but it is not nearly so convenient as the iris-diaphragm; and the effect of the stop is not nearly so good when it is removed to some distance beneath the object as when it is very near to the under surface of the glass object-slide. When an achromatic condenser is used, either a diaphragm-plate or an iris-diaphragm should be placed below its back lens, so as to cut off any required proportion of the outer rays that form its illuminating cone.

Such an arrangement, while suiting all the ordinary requirements of the microscopist who uses the highest powers of his instrument for the purposes of biological investigation (as, for example, in the study of *Bacteria* or of the reproduction of the *Monadina*), does not serve to bring into effective use the special resolving power possessed by objectives of large aperture. It has long been known that for the discernment of very closely approximated markings oblique illumination is advantageous,—an objective which exhibits such a diatom-valve as *Pleurosigma angulatum* with a smooth unmarked surface when illuminated by the central rays of the achromatic condenser making its characteristic markings (figs. 8–11) distinctly visible when the central rays of the condenser are kept back by a stop, and the object is illuminated by its convergent marginal rays only. And it has also been practically known for some time that the resolution of lined or dotted tests can be often effected by mirror illumination alone, if the mirror be so mounted as to be able to reflect rays through the object at such obliquity to the optic axis of the microscope as to reach the margin of a wide-angled objective. But it has only been since Professor Abbe's researches have given the true theory of "resolution" that the special advantage of oblique illumination has been fully comprehended, and that the best means have been devised for using it effectively. Two different systems have now come into use, each of which has its special advantages.

One consists in the attachment of the illuminating apparatus (mirror and achromatic condenser) to a "swinging tail-piece" (see fig. 32), which, moving radially upon a pivot whose axis intersects the optic axis at right angles in the plane of the object, can transmit the illuminating pencil through it at any degree of obliquity that the construction of the stage allows. The direction of this pencil being of course limited to one azimuth, it is requisite, in order to bring out its full resolving effect, that the object should be made to rotate, by making the stage that carries it revolve round the optic axis, so that the oblique pencil may impinge upon the lines or other markings of the object in every direction successively. It will then be found that the appearances presented by the same object often vary considerably,—one set of lines being shown when the object lies in one azimuth, and another when its azimuth has been changed by rotation through 60°, 90°, or some other angle. Various contrivances have also been devised for throwing very oblique illuminating pencils on the object by means of prisms placed beneath the stage.

Illumination of at least equal obliquity to that afforded by the swinging tail-piece may now, however, be obtained by the use of condensers specially constructed to give a divergence of 170° to the rays which they transmit when used immersionally, by bringing their flat tops into approximation to the under side of the glass slide on which the object is mounted, with the interposition of a film of water or (preferably) of glycerin. By using a central stop, marginal rays alone may be allowed to pass; and these will be transmitted through the object in every azimuth at the same time. But diaphragms with apertures limiting the transmitted rays to one part of the periphery may be so fixed in a tube beneath the condenser as to be easily made to rotate, thus sending its oblique pencils through the object in every azimuth in succession. And where this rotation of the diaphragm brings out two sets of lines at a certain angular interval a diaphragm with two marginal openings at a corresponding angular distance will enable both to be seen at once. Numerous arrangements of this kind have been devised by those who devote their special attention to the resolution of difficult diatom-tests; but they are of little or no use to those who use the microscope for biological research.

For the illumination of the surfaces of opaque objects which must be seen by reflected light the means employed will vary with the focal length of the objective employed. For large bright objects viewed under a low magnifying power good ordinary daylight is sufficient; but if the surface of the object is dull, reflecting but little light, the aid of a bull's-eye or large bi-convex lens must be employed in order to give it sufficient brilliance. This aid will always be required by lamplight; and by a proper adjustment of the relative distances of the lamp and the object the rays from the lamp may be made either to spread themselves over a wide area or to converge upon a small spot. The former is the method suitable to large objects viewed under a low magnifying power; the latter to the illumination of small objects which are to be examined under objectives of (say) 1 inch or ⅔ inch focus. Another method which may be conveniently had recourse to when the microscope is provided with a swinging tail-piece is to turn this on its pivot until the concave mirror is brought above the stage, so that rays which it gathers either from natural or artificial sources may be reflected downwards upon the surface of the object.

The illumination of an opaque object to be seen with a higher power than the ⅔ or ½ inch objectives was formerly provided for by a concave speculum (termed a Lieberkühn after its inventor), with a perforation in the centre for the passage of the rays to the objective to which it is fitted,—the curvature of the speculum being so adapted to the focus of the objective which carries it that, when the latter is duly adjusted, the rays reflected upwards around the object from the mirror to the speculum shall converge strongly on the object. The various disadvantages of this mode of illumination, however, have caused it to be now generally superseded by other arrangements. For powers between 1½ inch and $\frac{4}{10}$ inch, and even for a ¼ or ⅕ inch of small angle and good working distance, nothing is so convenient as the parabolic speculum or side-illuminator (F, fig. 17) invented by the late Richard Beck. This is attached to a spring-clip that slides on the tubes of low-power objectives, so that its distance from the object and the direction of its reflected pencil are readily adjusted; and for use with higher powers it may be either mounted on a separate arm attached to some part of the stand of the microscope, or may be hung in the manner shown in fig. 17 from an "adapter" A interposed between the objective and the body. By rotating the collar B and making use of the joints C, C, the lengthening rod D, and the ball and socket E, any position may be given to the speculum F that may best suit the objective with which it is used.

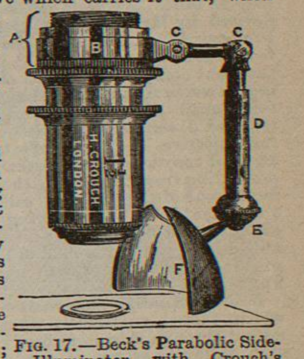


FIG. 17.—Beck's Parabolic Side-Illuminator, with Crouch's Adapter.

When, however, it is desired to illuminate objects to be seen under objectives of high power and very short working distance, side illumination of any kind becomes difficult, though not absolutely impossible;[1] and various modes have been devised for the illumination of the object by means of light sent down upon it, through the objective, from above. This is done in the vertical illuminator of Messrs Beck (fig. 18)—the original idea of which was first given by the American Professor H. L. Smith—by a disk of thin glass B, *b*, attached to a milled head by which its angular position may be adjusted, and introduced by a slot A, *e* into the interior of an adapter that is interposed between the objective C, *d* and the nose *c* of the body. The light which enters at the lateral aperture A, *a*, falling upon the oblique surface of the disk C, *b*, is reflected downwards, and is concentrated by the lenses of the objective upon the object beneath. The lateral aperture may be provided with a diaphragm, with openings of different sizes, for diminishing the false light to which this method is liable; or a screen with a small aperture may be placed between the lamp and the

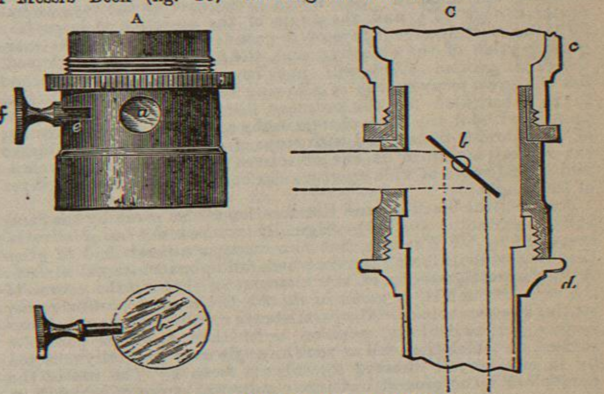


FIG. 18.—Beck's Vertical Illuminator.

---

[1] See his paper on "The Relation of Aperture and Power in the Microscope," in *Jour. Roy. Micros. Soc.*. 1882, pp. 300, 460.

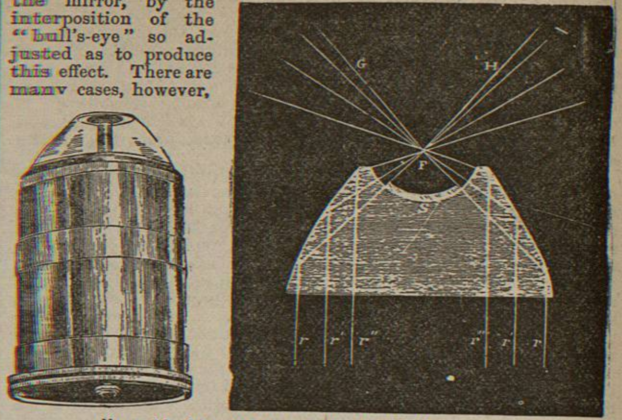
[2] See the remarks of Mr Dallinger,—whose experience in the application of the highest powers to the study of the minutest living objects is probably greater than that of any living observer,—in *Jour. Roy. Micros. Soc.*, December 1882, p. 853.

[1] See a method devised by Mr James Smith, in *Jour. Roy. Micros. Soc.*, vol. iii. N. S., 1880, p. 398.

illuminator, at any distance that is found to produce the best effects. In using this illuminator, the lamp should be placed at a distance of about 8 inches from the aperture; and, when the proper adjustments have been made, the image of the flame should be seen upon the object. The illumination of the entire field, or the direction of the light more or less to either side of it, can easily be managed by the interposition of a small condensing lens placed at about the distance of its own focus from the lamp. The objects viewed by this mode of illumination with dry-front objectives are best uncovered, since, if they are covered with thin glass, so large a proportion of the light sent down upon them is reflected from the cover (especially when objectives of large angle of aperture are employed) that very little is seen of the objects beneath, unless their reflective power is very high. With immersion objectives, however, covered objects may be used. Another method of vertical illumination long since devised by Mr Tolles has recently been brought into notice by Professor W. A. Rogers of Boston (U. S.). It consists in the introduction of a small rectangular prism at a short distance behind the front combination of the objective, so that parallel rays entering its vertical surface pass on between its parallel horizontal surfaces until they meet the inclined surface, by which they are reflected downwards. In passing through the front combination of the objective, they are deflected towards its axis; but, as their angle of convergence is less than the angle of divergence of the rays proceeding from the object, the reflected rays will not meet in the focal point of the lens, but will be so distributed as to illuminate a sufficient area. By altering the extent to which the prism is pushed in, or by lifting or depressing its outer end by means of a milled-head screw, the field of illumination can be regulated. The working of this prism with immersion-objectives is stated by Mr Tolles to be peculiarly satisfactory.

Black-Ground Illumination.—There are certain classes of objects which, though sufficiently transparent to be seen with light transmitted through them, are best viewed when illuminated by rays of such obliquity as not to pass directly into the objective,—such a proportion of these rays being retained by the object as to render it self-luminous, when, all direct light being cut off, the general field is perfectly dark. This method is particularly effective in the case of such delicate mineral structures as the siliceous tests of *Polycystina* and the "frustules" of *Diatomaceæ*. And it is one advantage of this kind of illumination that it brings out with considerable effect the solid forms of objects suited to it, even when they are viewed monocularly. Two modes of providing this illumination are in use, each of which has its special advantages. One consists in placing a central stop either upon or immediately beneath a condenser of wide aperture, which shall cut off all rays save those that, after passing through the object (as in fig. 20), diverge at an angle greater than that of the objective used; so that, while the ground is darkened, the object is seen brightly standing out upon it. But if the divergence of the rays is but moderate (say 60°), and the angle of the objective is large (say 90°), the most divergent rays of the condenser will enter the marginal portion of the objective, and, the field not being darkened, the black ground effect will not be produced. This method has the great convenience of allowing black-ground illumination to be substituted for the ordinary illumination under different powers, without any other change in the apparatus than the turning of a diaphragm-plate fitted with stops of different sizes suitable to the several apertures of the objectives; and the modern achromatic condensers of wide aperture can be thus used with objectives of 120° angle.

An excellent black-ground illumination is also given by the parabolic illuminator (fig. 19), originally worked out as a silvered speculum by Mr Wenham, but now made as a paraboloid of glass that reflects to its focus the rays which fall upon its internal surface. A diagrammatic section of this instrument, showing the course of the rays through it, is given in fig. 20, the shaded portion representing the paraboloid. The parallel rays r, r', r'', entering its lower surface perpendicularly, pass on until they meet its parabolic surface, on which they fall at such an angle as to be totally reflected by it, and are all directed towards its focus F. The top of the paraboloid being ground out into a spherical curve of which F is the centre, the rays in emerging from it undergo no refraction, since each falls perpendicularly upon the part of the surface through which it passes. A stop placed at S prevents any of the rays reflected upwards by the mirror from passing to the object, which, being placed at F, is illuminated by the rays reflected into it from all sides of the paraboloid. Those rays which pass through it diverge again at various angles; and if the least of these, GFH, be greater than the angle of aperture of the object-glass, none of them can enter it. The stop is attached to a stem of wire, which passes vertically through the paraboloid and terminates in a knob beneath, as shown in fig. 19; and by means of this it may be pushed upwards, so as to cut off the less divergent rays in their passage towards the object, thus giving a black-ground illumination with objectives of an angle of aperture much wider than GFH. In using the paraboloid for delicate objects, the rays which are made to enter it should be parallel; consequently the plane mirror should always be employed; and when, instead of the parallel rays of daylight, we are obliged to use the diverging rays of a lamp, these should be rendered as parallel as possible, previously to their reflexion from the mirror, by the interposition of the "bull's-eye" so adjusted as to produce this effect. There are many cases, however, in which the stronger light of the concave mirror is preferable. When it is desired that the light should fall on the object from one side only, the circular opening at the bottom of the wide tube that carries the paraboloid may be fitted with a diaphragm adapted to cover all but a certain portion of it; and, by giving rotation to this diaphragm, rays of great obliquity may be made to fall upon the object from every azimuth in succession.



FIGS. 19, 20.—Wenham's Parabolic Illuminator.

In order to adapt this paraboloid to objectives of very wide angle of aperture, a special modification of it, originally devised by Mr Wenham, has been latterly reintroduced under the designation of "immersion-paraboloid," with most excellent effect. This consists in making the top of the paraboloid flat instead of concave, and in interposing a film of glycerin between its surface and the under surface of the glass slide carrying the object. Only rays of such extreme obliquity are allowed to pass into the slide as would be totally reflected from its under surface if they fell upon it through air; and, as these illuminate the object without passing into the objective, it can be thus examined under even the highest powers.

BINOCULAR MICROSCOPES.

Stereoscopic Binoculars.—The admirable invention of the stereoscope by Professor Wheatstone has led to a general appreciation of the value of the conjoint use of both eyes, in conveying to the mind a conception of the solid forms of objects such as the use of either eye singly does not generate with the like certainty or effectiveness (see STEREOSCOPE). This conception is the product of the mental combination of the dissimilar perspective projections which our right and left retinæ receive of any object that is sufficiently near the eyes for the formation of two images that are sensibly dissimilar. Now it is obvious that a similar difference must exist between the two perspective projections of any object in relief that are formed by the right and left halves of a microscopic objective and that this difference must increase with the angular aperture of the objective. And the fact of this difference may be easily made apparent experimentally, by adapting a semicircular "stop" to any objective of from 20° to 30° angle in such a manner that it can be turned so as to cover either its right or its left half; for not only will the two images of any projecting object formed by the rays transmitted through the two uncovered halves be found sensibly different, but if they be photographed or accurately drawn, the "pairing" of their pictures in the stereoscope will bring out the form of the object in vivid relief. What is needed, therefore, to give the true stereoscopic effect to a binocular microscope is a means of so bisecting the cone of rays transmitted by the objective that its two lateral halves shall be transmitted the one to the right and the other to the left eye, and that the two images shall be crossed (the image formed by the right half of the objective being sent to the left eye, and that formed by the left half of the objective being sent to the right eye) in order to neutralize the reversing effect of the microscope itself. If this crossing does not take place, the effect will be rendered "pseudoscopic," not "orthoscopic,"—its projections becoming depressions, and its depressions being brought out as prominences. It was from a want of due appreciation of this fact that the earlier attempts at constructing a stereoscopic binocular gave representations of objects placed under it, not in their true orthoscopic, but in their pseudoscopic aspect. This was the case, for example, with the binocular microscope first devised by Professor Riddell of New Orleans in 1851, which separated the cone of rays by a pair of rectangular prisms so placed edge to edge above the objective that the rays passing through its right half were reflected horizontally to the right side, to be changed to the vertical direction and sent to the right eye by a lateral rectangular prism, while the rays from the left half of the objective were sent to the left eye in a similar manner. Professor Riddell describes the "conversion of relief" produced by this arrangement with the ordinary eye-piece as making a metal spherule appear "as a glass ball silvered on the under side, and a crystal of galena like an empty box." And to render the images "normal and natural" he found himself obliged to use erecting eye-pieces, which should produce a second reversal of the images that had been reversed in their first formation.[1] Subsequently, however, Professor Riddell devised and perfected another arrangement giving a true orthoscopic effect, which, after being long disregarded, has been latterly taken up and brought into use by Mr Stephenson. The cone of rays passing upwards from the objective meets a pair of prisms (A, A fig. 21) fixed immediately above its back lens, which divides it into two halves; each of these is subjected to internal reflexion from the inner side of the prism through which it passes; and the slight separation of the two prisms at their upper end gives to the two pencils B, B, on their emergence from the upper surfaces of the prisms, a divergence which directs them through two obliquely-placed bodies to their respective eye-pieces. By this internal reflexion a lateral reversal is produced, which neutralizes that of the ordinary microscopic image, so that, while each eye receives the image formed by its own half of the objective, the pairing of the two pictures produces a true orthoscopic effect.[2]

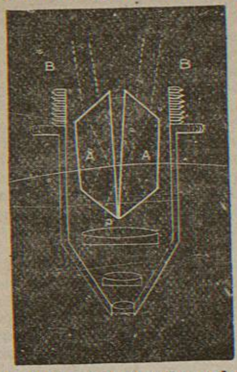


FIG. 21.—Riddell's Binocular Prisms.

About the same date MM. Nachet of Paris succeeded in devising a binocular that should give a true orthoscopic image, by placing above the object-glass an equiangular prism (P. fig. 22) with one of its surfaces parallel to its back lens, which, receiving the pencils *ab* forming the right half of the cone, internally reflects them obliquely upwards to the left, and in like manner reflects the pencils *a′b′* from the left half of the cone obliquely upwards to the right. These pencils, passing out of the left and right oblique faces of the prism at right angles (so as not to undergo either refraction or dispersion), enter right and left lateral prisms, also at right angles, and, after being internally reflected by these, pass out vertically, at right angles to their upper surfaces, through two parallel bodies (fig. 23), whose eye-pieces bring them to a focus in the right and left eyes respectively. The distance between these bodies may be adjusted to the varying distances between the axes of individual pairs of eyes, by adjusting screws at their base, which vary the distance of the lateral prisms from the central. This instrument gives a theoretically perfect representation of a microscopic object in relief, as it would appear if enlarged to the size of its image, and brought to within about 10 inches of the eye; and its chief practical defect is that, as the two bodies are parallel, instead of being slightly convergent, it cannot be continuously used without an uncomfortable strain. But, as its performance depends upon the accuracy of the seven plane surfaces of the three prisms, and on the correctness of their relations to each other, it is liable to considerable error from imperfections in its construction; and, as the instrument can only be used for its own special purpose, the observer must be provided with an ordinary single-bodied microscope for the examination of objects unsuited to the powers of the binocular. This last objection applies also to Professor Riddell's model.

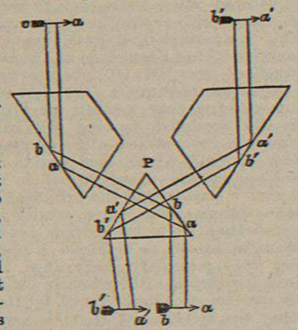


FIG. 22.—Nachet's Binocular Prisms.

It was for these reasons that Mr Wenham, fully impressed with the advantages of stereoscopic vision to the microscopist, set himself to devise a construction by which it might be obtained without the drawbacks inevitable in the working of Riddell's and Nachet's instruments; and he soon succeeded in accomplishing this on a plan which has proved not only convenient but practically satisfactory, notwithstanding its theoretical imperfection. Only the right half of the cone of rays proceeding upwards from the right half of the objective (*a*, fig. 24) is intercepted by a prism placed immediately over that half of its back lens, which, by two internal reflexions (as shown in fig. 25), sends its pencils obliquely upwards into the left-hand or secondary body L, whilst the pencils of the left half-cone pass uninterruptedly into the right-hand body R, and form an image that suffers no other deterioration than that which results from the halving of the angular aperture and the consequent loss of light. The moderate convergence of the two bodies (which, by varying the angles of the prism, may be made greater or less, so as to accord with the ordinary convergence of the optic axes in the individual observer) is much more generally suitable than the parallelism of MM. Nachet's earlier instrument; and the adjustment requisite for variation of distance between the eyes can be made by simply lengthening or shortening the bodies by drawing out or pushing in the diverging eye-pieces.

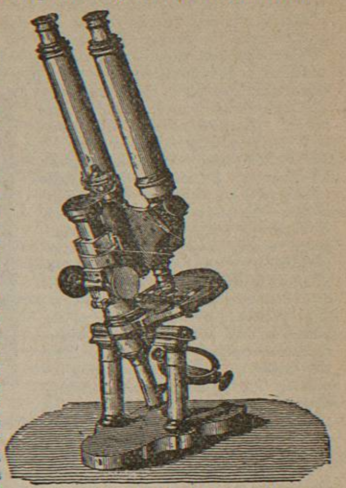


FIG. 23.—Nachet's Binocular Microscope.

It may be fairly objected to Mr Wenham's method (1) that, as the rays which pass through the prism and are obliquely reflected into the secondary body traverse a longer distance than those which pass on uninterruptedly into the principal body, the image formed by them will be somewhat larger than that which is formed by the other set, and (2) that the image formed by the rays which have been subjected to the action of the prism must be inferior in distinctness to that formed by the uninterrupted half of the cone of rays. But these objections are found to have no practical weight. For it is well known to those who have experimented upon the phenomena of stereoscopic vision (1) that a slight difference in the size of the two pictures is no bar to their perfect combination, and (2) that, if one of the pictures be good, the full effect of relief is given to the image, even though the other picture be faint and imperfect, provided that the outlines of the latter are sufficiently distinct to represent its perspective projection. Hence if, instead of the two equally half-good pictures which are obtainable by MM. Nachet's original construction, we had in Mr Wenham's one good and one indifferent picture, the latter would be decidedly preferable. But, in point of fact, the deterioration of the second picture in Mr Wenham's arrangement is less considerable than that of both pictures in the original arrangement of MM. Nachet; so that the optical performance of the Wenham binocular is in every way superior. It has, in addition, these further advantages over the preceding:—first, the greater comfort in using it (especially for some length of time together) which results from the convergence of the axes of the eyes at their usual angle for moderately near objects; second, that this binocular arrangement does not necessitate a special instrument but may be applied to any microscope which is capable of carrying the weight of the secondary body,—the prism being so fixed in a movable frame that it may in a moment be taken out of the tube or replaced therein, so that when it has been removed the principal body acts in every respect as an ordinary microscope, the entire cone of rays passing uninterruptedly into it; and, third, that the simplicity of its construction renders its derangement almost impossible. Hence it is the one most generally preferred by microscopists who use the long-bodied English model.

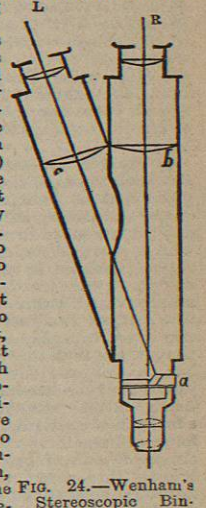


FIG. 24.—Wenham's Stereoscopic Binocular Microscope.

For short-bodied Continental microscopes, however, MM. Nachet

---

[1] See Silliman's *Journal*, vol. xv., 1853, p. 68; and *Quart. Jour. of Micros. Sci.*, vol. i., 1853, p. 236.

[2] *Quart. Jour. of Micros. Sci.*, vol. ii., 1854, p. 18.

have devised an arrangement of two prisms, based on Mr Wenham's fundamental idea of deflecting one half of the cone of rays into a secondary body, whilst the other half proceeds onwards without change of direction into the principal body. And it is an interesting feature in this construction that, by a simple change in the position of the dividing prism, the true "orthoscopic" image may be made, by a "conversion of relief," to become "pseudoscopic."[1]

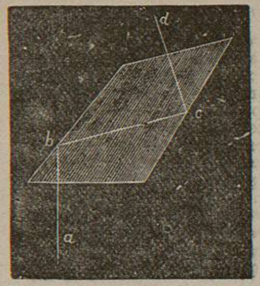


Fig. 25.—Wenham's Binocular Prism.

The effect of stereoscopic projection may be attained, however, without a double body, by the insertion of a suitably constructed binocular eye-piece into the body of any ordinary monocular microscope. A plan of this kind was first successfully worked out by Mr Tolles (the very able optician of Boston, United States), who interposed a system of prisms similar to that devised by MM. Nachet (fig. 22), but on a much larger scale, between an "erector" (resembling that used in the eye-piece of a day telescope) and a pair of ordinary Huygenian eye-pieces, the central or dividing prism being placed at or near the plane of the secondary image formed by the erector, while the two eye-pieces are placed immediately above the lateral prisms,—the combination thus making that division in the pencils forming the secondary (erected) image which it makes in the Nachet binocular in the pencils emerging from the objective.

A stereoscopic eye-piece of a very different construction has been recently devised by Professor Abbe, who, making use, for the division between the two eye-pieces of the rays going to form the first image, of an arrangement of prisms essentially similar to that devised by Mr Wenham for his non-stereoscopic binocular (fig. 27), obtains either an orthoscopic or a pseudoscopic effect by placing on each eye-piece a cap with a semicircular diaphragm, so as to extinguish half of each of the cones of rays that form the two retinal images. While in one position of the diaphragms true stereoscopic or orthoscopic relief is given, it is sufficient to turn the diaphragms into the opposite position to obtain a pseudoscopic conversion.[2] It appears, however, that this arrangement, though possessing points of great interest in relation to the theory of binocular vision, is not likely to supersede the ordinary Wenham prism.

It must be obvious to every one who studies with sufficient attention the conditions under which true stereoscopic relief can be given that no combination of two dissimilar retinal perspectives can be satisfactory unless the visual pictures represent with tolerable distinctness the features of the object that lie in different focal planes. This is provided for, in ordinary vision, by the power of accommodation possessed by the eye, which, while focussed exactly to any one plane, can also include in its visual picture (within certain limits) what is either nearer or more remote. Now it seems probable that, as Professor Abbe has urged, this power of accommodation comes into play in microscopic stereoscopy, but there can be no question that the visual distinctness of the parts of an object lying within and beyond the focal plane, and therefore the completeness of the stereoscopic image, mainly depends upon the "focal depth" of the objective employed,—which, as already explained, is a function of its angular aperture. When, however, objectives of long focus and small aperture are employed in binocular microscopy, although each of the two perspective projections may be fairly distinct throughout, the effect of solid relief will be very inconsiderable, because the pictures are not sufficiently dissimilar to one another,—the case being exactly analogous to that of the stereoscopic combination of two photographic portraits taken at an angle of no more than a few degrees from each other. Still, with an objective of 1½ inches focus and an angular aperture of from 15° to 20°, a very distinct separation is made of the focal planes of transparent sections of structures having no great minuteness of detail,—such, especially, as injected preparations,—the solid forms of their capillary networks being presented to the mind's eye with a vividness that no monocular representation of them can afford. When a 1 inch objective of 20° or 25° is used, the stereoscopic effect becomes much more satisfactory; so that objects of moderate projection (such as many of the siliceous *Polycystina*, *Diatomaceæ*, &c.) can be seen in nearly their natural projection, and, if the focal adjustment is made for a medium plane, with tolerable distinctness both of their nearer and remoter parts. With a ⅔ inch of 30° or 35°, the stereoscopic relief becomes more pronounced; but the diminution of the focal depth prevents the several planes of objects in strong relief from being as distinctly seen at the same time. A ½ inch objective of about 40° of aperture, however, affords the most satisfactory results with suitable objects,—full stereoscopic relief being gained without exaggeration, so as to present, *e.g.*, the discoidal diatoms and the smaller *Polycystina* in their true forms, whilst their nearer and more remote parts are seen with sufficient distinctness to require only a very slight adjustment of the focus for their perfect definition. Still more minute objects may be well shown by $\frac{4}{10}$ths and ¼th objectives whose angular aperture does not exceed 50°; but it can be shown both theoretically and practically[3] that the dissimilarity of the two perspective projections of objects in relief formed by objectives of any angle much exceeding 40° is such as to exaggerate the stereoscopic effect; besides which, every enlargement of angular aperture so greatly diminishes the focal depth of the objectives that only those parts of the objects which lie very near the focal plane can be seen with distinctness sufficient for the formation of a good stereoscopic image. Hence, for the purposes of minute histological research, the stereoscopic binocular is (in the present writer's opinion) almost valueless; since, if any distinct perspective differentiation can be gained with objectives of the short focus and enlarged angle that are most suitable to such investigations, that differentiation will be so great as to produce a highly exaggerated stereoscopic effect. If such objectives be used binocularly at all, they must be so mounted that their back lenses are in very close proximity to the prism; and the (transparent) object must be illuminated by an achromatic condenser of sufficient aperture to send through it pencils of sufficient divergence to produce the secondary image.

In regard to the advantage derived from the use of the stereoscopic binocular, with the powers, and upon the objects, suitable to produce the true effect of solid form, the writer can unhesitatingly assert, as the result of a long and varied experience, that in no other way could he as certainly or as vividly image those forms to himself, and that in prolonged work upon such subjects he is conscious of a great saving of fatigue, which seems attributable not merely (perhaps not so much) to the conjoint use of both eyes as to the absence of the mental effort required for the interpretation of the microscopic picture, when the solid form of the object has to be ideally constructed from it (chiefly by means of the information obtainable through the focal adjustment), instead of being directly presented to the mind's eye.[4]

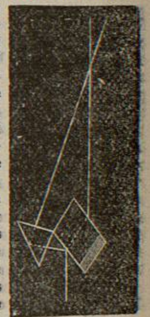


Fig. 26.

Non-Stereoscopic Binoculars.—The great comfort which is experienced by the microscopist in the conjoint use of both eyes has led to the invention of more than one arrangement by which this can be secured when those high powers are required which cannot be employed with the ordinary stereoscopic binocular. This is accomplished by Messrs Powell and Lealand by taking advantage of the fact that, when a pencil of rays falls obliquely upon the surface of a refracting medium, a part of it is reflected without entering that medium at all. In the place usually occupied by the Wenham prism they interpose an inclined plate of glass with parallel sides, through which one portion of the rays proceeding upwards from the whole aperture of the objective passes into the principal body with very little change in its course, whilst another portion is reflected from its surface into a rectangular prism so placed as to direct it obliquely upwards into the secondary body (fig. 26). Although there is a decided difference in brightness between the two images, that formed by the reflected rays being the fainter, yet there is marvellously little loss of definition in either, even when the $\frac{1}{25}$ inch objective is used. The disk and prism are fixed in a short tube, which can be readily substituted in any ordinary binocular microscope for the one containing the Wenham prism.

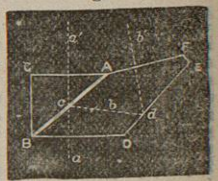


Fig. 27.

Other arrangements were devised long ago by Mr Wenham,[5] with a view to obtain a greater equality in the amount of light-rays forming the two pictures; and he has latterly carried one of these into practical effect, with the advantage that the compound prism of which it consists has so nearly the same shape and size as his ordinary stereoscopic prism as to be capable of being mounted in precisely the same manner, so that the one may be readily exchanged for the other. The axial ray *a*, proceeding upwards from the objective, enters the prism ABDEF (fig. 27) at right angles to its lower face, and passes on to *c*, where it meets the inclined face AB, at which this prism is nearly in contact with the oblique face of the right-angled prism ABC. By internal reflexion from the former and external reflexion from the latter about half the beam *b* is reflected within the first prism in the direction *cb*, while the other half proceeds straight onwards through the second prism, in the direction *ca′*, so as to pass into the principal body. The reflected half, meeting at *d* the oblique (silvered) surface DE of the first prism, is again reflected in the direction *db′*, and, passing out of that prism perpendicularly to its surface AF, proceeds towards the secondary body. The two prisms must not be in absolute contact along the plane AB, since, if they were, Newton's rings would be formed; and much nicety is required in their adjustment, so that the two reflexions may be combined without any blurring of the image in the secondary body.

---

[1] See *Trans. of Roy. Micros. Soc.*, N. S., vol. xv., 1867, p. 105; and *Monthly Micros. Jour.*, vol. i., 1869, p. 31.

[2] See *Jour. of Roy. Micros. Soc.*, 2d ser., vol. i., 1881, p. 298.

[3] See *The Microscope and its Revelations*, 6th ed., pp. 42–44.

[4] A very elaborate investigation, by Professor Abbe, "On the Conditions of Orthoscopic and Pseudoscopic Effects in the Binocular Microscope," will be found in the *Jour. of the Roy. Micros. Soc.*, 2d ser., vol. i., 1881, p. 203.

[5] *Transactions of the Micros. Soc.*, N. S., vol. xiv., 1866, p. 105.

For the prolonged observation, under high powers, of objects not requiring the extreme of perfection in definition,—such, for example, as the study of the cyclosis in plants,—great advantage is gained from the conjoint use of both eyes by one of the above arrangements.

MECHANICAL CONSTRUCTION OF THE MICROSCOPE.

The optical arrangements on which the working of the compound achromatic microscope depends having now been explained, we have next to consider the mechanical provisions whereby they are brought to bear upon the different purposes which the instrument is destined to serve. Every complete microscope must possess, in addition to the lens or combination of lenses which affords its magnifying power, a stage whereon the object may securely rest, a concave mirror for the illumination of transparent objects from beneath, and a condensing-lens for the illumination of opaque objects from above.

1. Now, in whatever mode these may be connected with each other, it is essential that the optical part and the stage should be so disposed as either to be altogether free from tendency to vibration or to vibrate together; since it is obvious that any movement of one, in which the other does not partake, will be augmented to the eye of the observer in proportion to the magnifying power employed. In a badly-constructed instrument, even though placed upon a steady table resting upon the firm floor of a well-built house, when high powers are used, the object is seen to oscillate so rapidly at the slightest tremor—such as that caused by a person walking across the room, or by a carriage rolling by in the street—as to be frequently almost indistinguishable; whereas in a well-constructed instrument scarcely any perceptible effect will be produced by even greater disturbances. Hence, in the choice of a microscope, it should always be subjected to this test, and should be unhesitatingly rejected if the result be unfavourable. If the instrument should be found free from fault when thus tested with high powers, its steadiness with low powers may be assumed; but, on the other hand, though a microscope may give an image free from perceptible tremor when the lower powers only are employed, it may be quite unfit for use with the higher. The method still adopted by some makers, of supporting the body by its base alone, is the worst possible, especially for the long body of the large English model, since any vibration of its lower part is exaggerated at its ocular end. The firmer the support of the body along its length the less tremor will be seen in the microscopic image.

2. The next requisite is a capability of accurate adjustment to every variety of focal distance, without movement of the object. It is a principle universally recognized in the construction of good microscopes that the stage whereon the object is placed should be a fixture, the movement by which the focus is to be adjusted being given to the optical portion. This movement should be such as to allow free range from a minute fraction of an inch to three or four inches, with equal power of obtaining a delicate adjustment at any part. It should also be so accurate that the optic axis of the instrument should not be in the least altered by any movement in a vertical direction, so that, if an object be brought into the centre of the field with a low power, and a higher power be then substituted, the object should be found in the centre of its field, notwithstanding the great alteration in the focus. In this way much time may often be saved by employing a low power as a "finder" for an object to be examined by a higher one; and when an object is being viewed by a succession of powers little or no readjustment of its place on the stage should be required. A rack-and-pinion adjustment, if it be made to work both tightly and smoothly, answers sufficiently well for the focal adjustment, when objectives of low power only are employed. But for any lenses whose focus is less than half an inch a "fine adjustment," or "slow motion," by means of a screw-movement operating either on the object-glass alone or on the entire body (preferably on the latter), is of great value; and for the highest powers it is quite indispensable. It is essential that in this motion there should be no "lost time," and that its working should not produce any "twist" or displacement of the image. In some microscopes which are provided with a fine adjustment the rack-and-pinion movement is dispensed with, the "coarse adjustment" being given by merely sliding the body up and down in the socket which grasps it; but this plan is only admissible where, for the sake of extreme cheapness or portability, the instrument has to be reduced to the form of utmost simplicity, as in figs. 28, 29.

3. Scarcely less important than the preceding requisite, in the case of the compound microscope, especially with the long body of the ordinary English model, is the capability of being placed in either a vertical or a horizontal position, or at any angle with the horizon, without deranging the adjustment of its parts to each other, and without placing the eye-piece in such a position as to be inconvenient to the observer. It is certainly a matter of surprise that some microscopists, especially on the Continent, should still forego the advantages of the inclined position, these being attainable by a very small addition to the cost of the instrument; but the inconvenience of the vertical arrangement is much less when the body of the microscope is short, as in the ordinary Continental model; and there are many cases in which it is absolutely necessary that the stage should be horizontal. This position, however, can at any time be given to the stage of the inclining microscope, by bringing the optic axis of the instrument into the vertical direction. In ordinary cases, an inclination of the body at an angle of about 55° to the horizon will usually be found most convenient for unconstrained observation; and the instrument should be so constructed as, when thus inclined, to give to the stage such an elevation above the table that, when the hands are employed at it, the arms may rest conveniently upon the table. In this manner a degree of support is attained which gives such free play to the muscles of the hands that movements of the greatest nicety may be executed by them, and the fatigue of long-continued observation is greatly diminished. When the ordinary camera lucida[1] is used for drawing or measuring, it is requisite that the microscope should be placed horizontally. It ought, therefore, to be made capable of every such variety of position; and the stage must of course be provided with some means of holding the object, whenever it is itself placed in such a position that the object would slip down unless sustained.

4. The last principle on which we shall here dwell, as essential to the value of a microscope designed for ordinary work, is simplicity in the construction and adjustment of every part. Many ingenious mechanical devices have been invented and executed for the purpose of overcoming difficulties which are in themselves really trivial. A moderate amount of dexterity in the use of the hands is sufficient to render most of these superfluous; and without such dexterity no one, even with the most complete mechanical facilities, will ever become a good microscopist. There is, of course, a limit to this simplification; and no arrangement can be objected to on this score which gives advantages in the examination of difficult objects, or in the determination of doubtful questions, such as no simpler means can afford. The meaning of this distinction will become apparent if it be applied to the cases of the mechanical stage and the achromatic condenser. For, although the mechanical stage may be considered a valuable aid in observation, as facilitating the finding of a minute object, or the examination of the entire surface of a large one, yet it adds nothing to the clearness of our view of either: and its place may in great degree be supplied by the fingers of a good manipulator. On the other hand, the use of the achromatic condenser not only contributes very materially, but is absolutely indispensable, to the formation of a perfect image, in the case of many objects of a difficult class; the want of it cannot be compensated by the most dexterous use of the ordinary appliances; and consequently, although it may fairly be considered superfluous as regards a large proportion of the purposes to which the microscope is directed, whether for investigation or for display, yet as regards the particular objects just alluded to it is a no less necessary part of the instrument than the achromatic objective itself.

As a typical example of the simplest form of compound microscope that is suitable for scientific research,—which, with various modifications of detail, is the one generally employed on the Continent,—the *Microscope de dissection et d'observation* (fig. 28) of M. Nachet, especially as constructed for portability (figs. 29–31), seems particularly worthy of description. In its vertical form (fig. 28) the solid foot to which the mirror is pivoted gives support to the pillar F, to the top of which the stage P, having a diaphragm-plate beneath it, is firmly attached. On the top of this pillar the tubular stem A is fitted in such a manner that it may be removed by unscrewing the large milled head L,—though, when this is well screwed down, the stem stands quite firmly. This stem bears at its summit a short horizontal arm, which carries a strong vertical tube that firmly grasps the "body" of the microscope, while permitting this to be easily slid upwards or downwards, so as to make a "coarse adjustment" of the focus. The "fine adjustment" is made by turning the milled head V, which either presses down the outer tube of the stem, or allows it to be raised by the upward pressure of a strong spiral spring in its interior. By unscrewing the milled head L, the stem A with its arm and compound body can be detached from the pillar; and, a small light arm H holding either single lenses or doublets being slid into this, a convenient dissecting microscope is thus provided. The only drawback in the construction of this simple model is its not being provided with a joint for

---

[1] A camera lucida adapted for use with the vertical microscope has been devised by M. Nachet.