(No Model.)

4 Sheets—Sheet 1.

H. D. TAYLOR.

LENS.

No. 540,122.

Patented May 28, 1895.

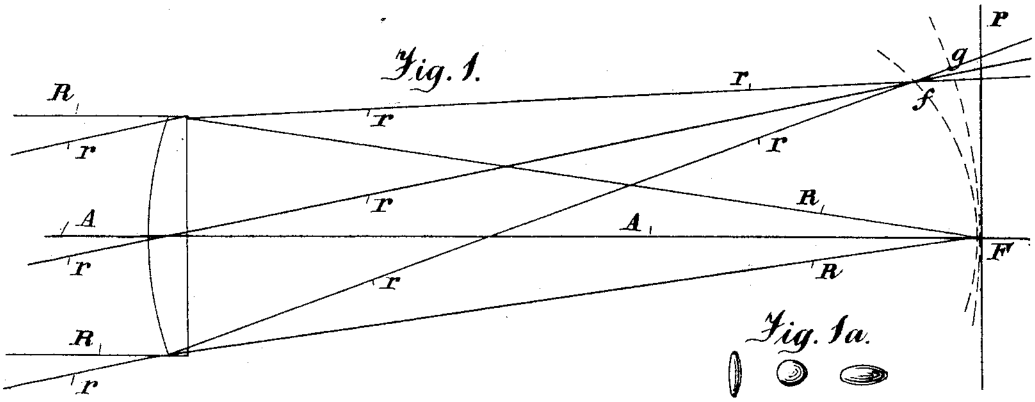


Fig. 1.

Fig. 1a.

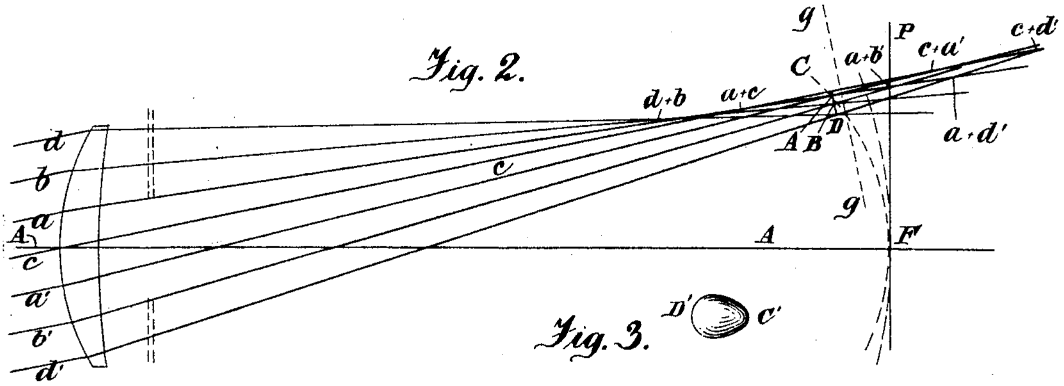


Fig. 2.

Fig. 3.

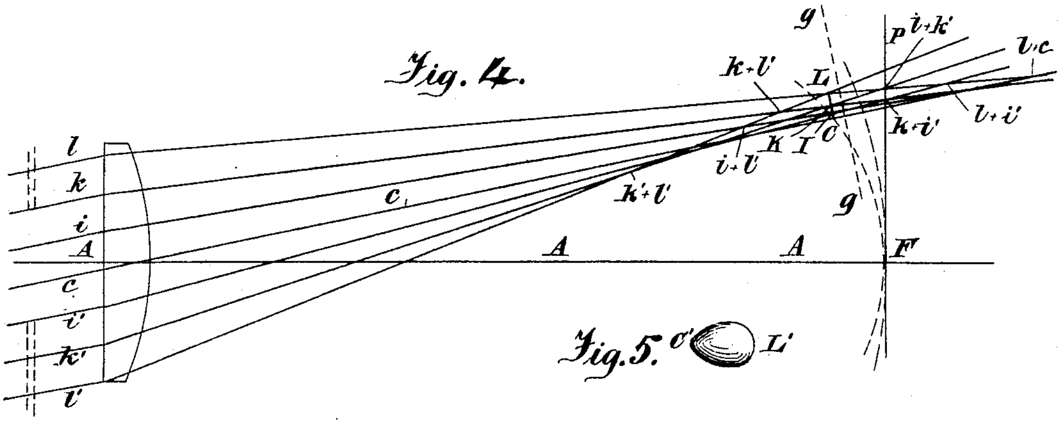


Fig. 4.

Fig. 5.

Witnesses:

C. B. Bull

Harold Dennis Taylor
Inventor,

By Dodge & Sons
Attys

THE NORRIS PETERS CO. PHOTO-LITHO., WASHINGTON, D. C.

(No Model.) 4 Sheets—Sheet 2.

H. D. TAYLOR.

LENS.

No. 540,122. Patented May 28, 1895.

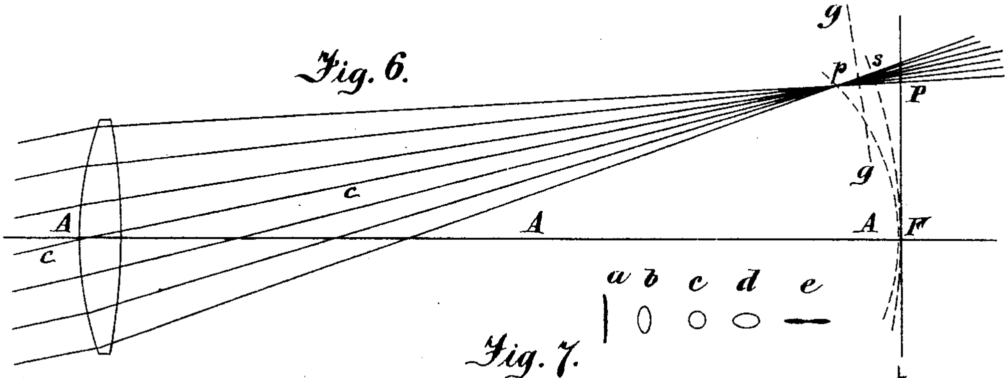


Fig. 6.

Fig. 7.

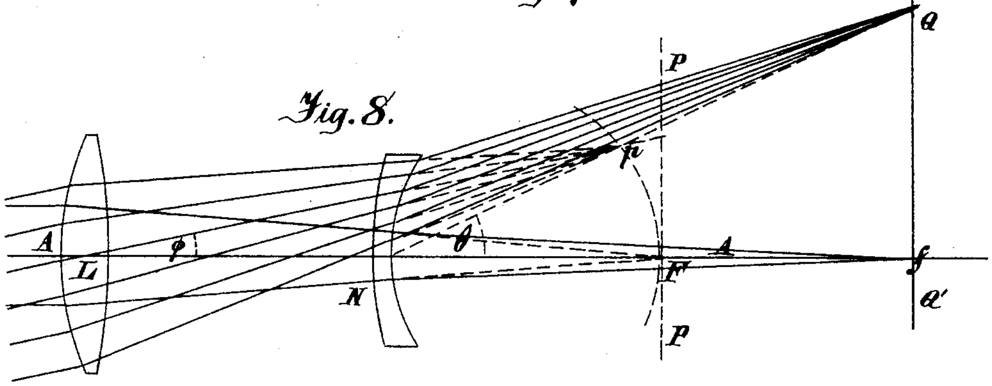


Fig. 8.

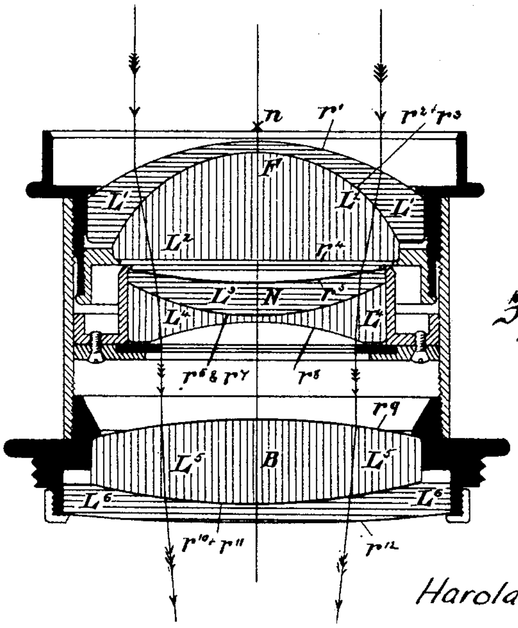


Fig. 9.

Witnesses:
W. C. Burdine
C. B. Bull.

Harold Dennis Taylor
Inventor
By Dodge & Sons
Attys.

THE NORRIS PETERS CO., PHOTO-LITHO., WASHINGTON, D. C.

(No Model.) 4 Sheets—Sheet 3.

H. D. TAYLOR.

LENS.

No. 540,122. Patented May 28, 1895.

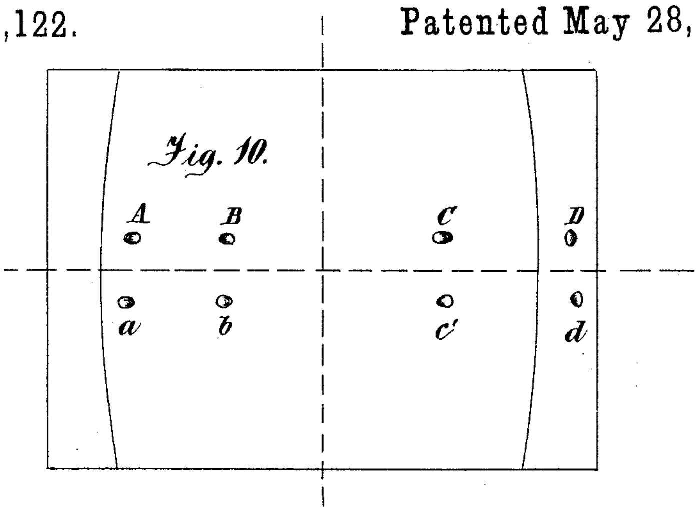


Fig. 10.

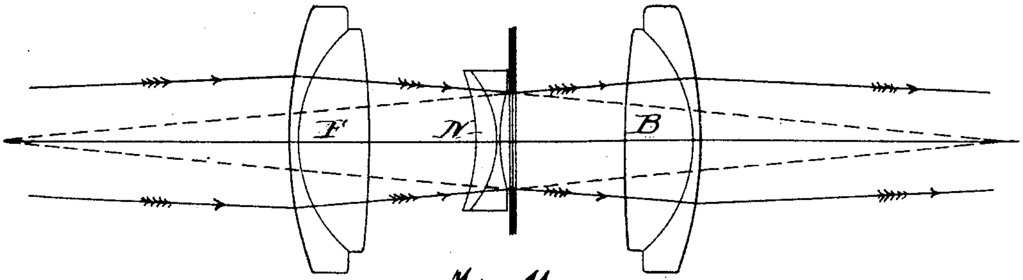


Fig. 11.

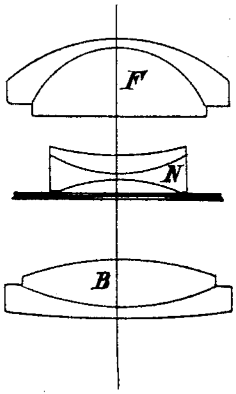


Fig. 12.

Harold Dennis Taylor
Inventor

By Dodge & Sons
Attys.

Witnesses:
C. W. Burdine
C. B. Bull.

THE NORRIS PETERS CO., PHOTO-LITHO., WASHINGTON, D. C.

(No Model.) 4 Sheets—Sheet 4.

H. D. TAYLOR.

LENS.

No. 540,122. Patented May 28, 1895.

Fig. 14.

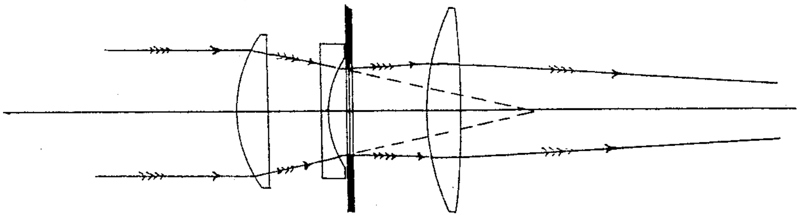


Fig. 13.

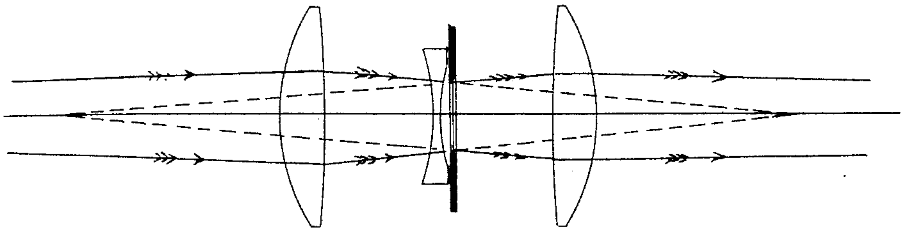


Fig. 15.

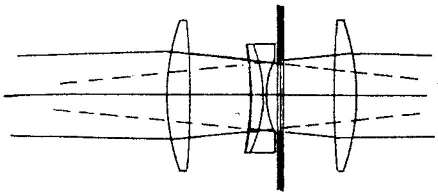
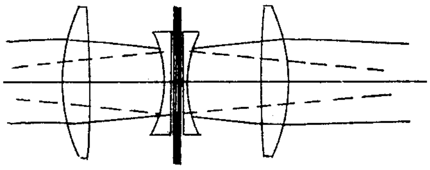


Fig. 16.



Harold D. Taylor

Inventor.

by Dodge & Sons

Attys.

Witnesses

W. Burdine

C. B. Bull.

THE NORRIS PETERS CO., PHOTO-LITHO., WASHINGTON, D. C.

UNITED STATES PATENT OFFICE.

HAROLD DENNIS TAYLOR, OF YORK, ENGLAND.

LENS.

SPECIFICATION forming part of Letters Patent No. 540,122, dated May 28, 1895.

Application filed February 5, 1894. Serial No. 499,140. (No model.)

To all whom it may concern:

Be it known that I, HAROLD DENNIS TAYLOR, a subject of the Queen of Great Britain, residing at York, in the county of York, England, have invented certain new and useful Improvements in Lenses, of which the following is a specification.

In order to make clear the essential novelty of the methods of correction employed in my invention for correcting the pencils of light passing obliquely through my lenses against curvature of image and astigmatism, it will be necessary for me to briefly review the methods of correction hitherto relied upon by the designers and makers of almost all photographic lenses hitherto made.

In Figure 1 of the accompanying diagrams is illustrated the curvature of image incidental to all positive lenses, whether simple or compound. A pencil of parallel rays R, R and R from a distant point on the optic axis comes to a focus at the principal focus F, upon the principal focal plane P—P; but an oblique pencil of rays such as r, r, r—does not come to a focus upon the plane P—P but much short of it. It can be shown that rays in a primary or meridional section of the oblique pencil, such as r, r, r come to a focus at the point f, while rays in a secondary or sagittal section of the oblique pencil come to a focus at the point g, considerably nearer to the plane P—P. Thus the image is curved very considerably. If we consider only rays in the primary of meridional sections of oblique pencils, then the image is curved to a spherical surface f—f of a radius generally equal to three-elevenths of the principal focal length, and this curvature is quite independent of the distance of the original object from the lens so long as it is in the form of a plane (a flat diagram, for instance) at right angles to the optic axis. Again, if we consider only rays in the secondary or sagittal sections of the same pencils, the image formed by such rays is also curved to a spherical surface g—g approximately to a radius generally equal to three-fifths of the principal focal length, and this curvature is again independent of the distance of the original from the lens. These radii of curvatures may be made to vary only between narrow limits, by variations in the materials of the lenses.

Now the want of concordance between the foci of the same pencil of rays considered in primary and in secondary planes constitutes, as is well known, the marginal astigmatism of a lens, and it can be proved that the amount of this astigmatism, when expressed as a correction to the focal power of a lens or the reciprocal of its principal focal length, is totally independent either of the form or materials of the lens or the distance of the original object from the lens, but depends simply upon the principal focal length of the lens and the degree of obliquity of the pencil of rays entering it. This is the same law which holds good in the case of oblique reflection from a spherical or parabolic mirror.

In Fig. 2 is shown the case of a miniscus like lens, supposed to be aplanatic or free from spherical aberration, in which the nature of the focus is shown more in detail but on an exaggerated scale. Here any symmetrically situated pairs of rays, such as a and a', b and b', d and d', in primary or meridional sections, all come to focus approximately upon the spherical surface C—F, but while the pair a and a' focus at the point A, b and b' focus at the point B, and d and d' focus at the point D, then focal points being successively displaced from the central ray c—c by greater and greater distances and in a direction toward the optic axis A—A. It will be observed that the above pairs of rays are spoken of as symmetrical because they strike the lens at about equal distances from but on opposite sides of the optic axis A—A. The consequence of the gradually increasing lateral displacement of the foci for these symmetrical pairs of rays is very peculiar.

It is evident, from Fig. 2, that the foci for any eccentric pairs of rays, such as a and b or a and d, are thrown much nearer to the lens as at the points $a+b$ and $a+d$, while the foci for eccentric pairs of rays on the other side of the optic axis such as c and a', a' and b', a' and d', &c., occur at points $c+a'$, $a'+b'$, $a'+d'$, &c., situated much farther from the lens, and even possibly beyond the principal focal plane P—P; and therefore, if a stop is placed on the axis, as shown in Fig. 4, behind the lens, which will only allow to pass those eccentric sets of rays whose foci are very much lengthened in the above manner, it is evident that the final image may be very much flattened; indeed, if the primary or meridional sections of the pencils are alone considered, the image formed by such rays may be completely flattened. As regards primary sections of the pencils, this explains the nature of diaphragm corrections; but it would be extremely difficult to explain the simultaneous effect of the same stop upon the same pencils considered in secondary sagittal sections; but it can be proved mathematically, as it has been demonstrated in practice, that it is absolutely impossible by means of diaphragm corrections to flatten the image for the same pencils considered in primary and in secondary planes simultaneously. If the image is completely flattened for pencils in primary sections, then the same pencils in secondary sections will still form an image very considerably curved in the usual direction and therefore the image is marred by marginal astigmatism. Whereas, if the diaphragm corrections are just sufficient to eliminate the marginal astigmatism, then the resulting image, although a distinct one, will be curved to a radius generally equal to one and one-half times the principal focal length. However, under the very exceptional conditions attained in a certain photographic lens recently introduced, in which the refractive index of the negative lens bears the same ratio to the refractive index of the positive lens cemented thereto as the focal length of the positive lens bears to the focal length of the negative lens, it is possible, by means of diaphragm corrections, to obtain a perfectly flat field for pencils of rays considered in primary and in secondary sections simultaneously, and the resulting image is thus free from marginal astigmatism as well as flat; but these very exceptional conditions render a large aperture out of the question.

Fig. 4 shows the action of diaphragm corrections in the case of a lens of the reversed meniscus form, whose characteristics are opposite to those of the lens shown in Fig. 2. Here flattening the image is obviously to be attained by placing the stop in front of the lens, as shown. If these lenses are examined when focused upon some distant artificial star, it will be found, in the case of Fig. 2, that the oblique image consists of a balloon-shaped coma (Fig. 3) the brighter end (*c*,) of which points away from the optic axis. In the case of Fig. 4, however, it will be found that the brighter end (*c′* Fig. 5) of the coma points toward the optic axis. All aplanatic lenses, when tried singly, show either one or the other form of coma so long as they have diaphragm corrections, that is, so long as their form is such that their images may be more or less flattened by placing a stop either behind or in front of them; and now in Fig. 6 is shown the action of a lens which is free from coma. In this case, all the rays in primary sections pass through one and the same focal point *p*, and it is evident at a glance that diaphragms placed either in front of or behind the lens can have no effect whatever upon the curvature of the image. Hence an aplanatic lens which is free from coma and gives a symmetrical oblique focus may be said to have its diaphragm corrections eliminated. If the oblique focus of such a lens is examined as in the previous cases, it will be found that the several symmetrical phases *a*, *b*, *c*, *d* and *e*, Fig. 7, will be passed through on receding from the lens. These are the effects of the inevitable astigmatism, but without the additional effects of coma superimposed; as in the case of Fig. 1^a.

Now my new method of correction consists in this: that I discard altogether the diaphragm corrections hitherto relied on for flattening the final image, and therefore I use only lenses of the type shown in Fig. 6, in which the diaphragm corrections are eliminated, and I flatten the final image and also correct its marginal astigmatism by introducing a negative lens of this type between two positive lenses of the same type, the focal power of the negative lens being approximately equal to the combined focal powers of the two positive lenses. Fig. 8 will help to illustrate this method of correction. L and N are respectively a positive and negative lens of equal focal powers and supposed to be made of much the same materials. Confining the attention to primary sections of the oblique pencils, the image formed by L is curved to the spherical surface *p*—P, to a radius equal to three-elevenths of the focal length; but the interposition of the negative lens N throws the final image on to the plane Q—Q; and this image is quite flat since the curvature corrections of N are equal to and opposite in character to the curvature corrections of L; or, tracing the rays backward, supposing a flat diagram to be placed at Q—Q, then the negative lens will form a visual image of it at P—*p* which is curved to a radius equal to three-elevenths of the focal length of N; but this image is precisely as much curved and in the same direction as the image thrown in the first place by the positive lens L. Wherever N may be placed behind the lens L, its curvature of image will neutralize the curvature of image of the positive lens L, and therefore the final image will be flat; and, since the relation between the curvature errors in primary and in secondary sections of the same pencils of rays can be shown to be the same in both lenses, if they are made of much the same materials, it is evident that the errors of curvature for secondary sections of the pencils will be equal and opposite in the two lenses and so will neutralize one another, and therefore the final image formed by rays in secondary sections will also be flat. Therefore the final image is flat and also free from marginal astigmatism; but this result can only be obtained when all the lenses concerned (two, in this case) are so formed as to be free from diaphragm corrections; but the objection to the use of such a double combination as Fig. 8 is two-fold: First, it necessarily gives a very objectionable amount of pincushion distortion, and, second, if designed for distant subjects it will be almost useless for copying or enlarging, and, if designed for copying, it is almost useless for distant subjects. I overcome these defects by dividing the positive element into two portions and placing the negative lens between, its focal power being approximately equal to the sum of the focal powers of the two positive lenses. Figs. 9, 11, and 12 are examples of this.

It can be proved that the principle of correction holds good in just the same sense as before when the positive element is thus divided.

Before proceeding to give the actual curves and practical directions for carrying out the lens shown in Fig. 9, which is, as yet, the only combination which I have had time or opportunity for perfecting, I will first point out that I do not claim as new the bare idea of placing a negative lens between two positive lenses for the purpose of making the image flatter; for, so long ago as 1858, a certain Mr. Sutton called attention in an imperfect way to the advantage of such a combination, and the idea was also practically carried out in Dallmeyer's triplet lens, Ross' triplet, Petzval's orthoscopic, and possibly other lenses, but neither Mr. Sutton nor anybody else seems to have grasped the idea that the diaphragm corrections should first be eliminated, or that they even could be eliminated, and the principle that the focal power of the negative lens should be approximately equal to the combined focal powers of the positive lenses seems to have escaped them, for, as a matter of fact, the degree of flatness of image actually attained in all the above mentioned lenses was, as I could prove, due principally to diaphragm corrections and only in a secondary degree to the action of the negative lens, whose focal power in all these cases was made only a fraction of the combined focal powers of the positive lenses combined. Thus the negative lens was not made anything like powerful enough, nor were the diaphragm corrections of the lenses eliminated.

It should here be pointed out that my reason for eliminating the diaphragm corrections of the negative lens of my combinations is not so much for the purpose of preventing it exerting effect by its diaphragm corrections upon the curvature of the final image, for such effect would be in any case small, since the stops for regulating the aperture are placed as closely as possible to the negative lens, as shown in Fig. 9, &c., but it is also for the very important purpose of preventing the formation of a "coma" or side flare at the final foci for oblique pencils. The two positive lenses, having their diaphragm corrections eliminated, do not produce any coma, and, therefore, if the final oblique foci are to be free from coma, a condition which is well known to be essential to good definition, then the negative lens also must be free from coma, which implies that its diaphragm corrections must be eliminated.

In the accompanying drawings, Fig. 9, is shown a longitudinal section through the one form of my lens which I have been able to work out completely. F is the front combination, which is exposed to the subject to be photographed. N is the negative combination, and B is the back combination.

The glasses of which the lenses are composed have the following optical properties and designations:

First lens L' and last lens L^6 are made of a rather light silicate flint glass with the following optical properties:

Refractive index for the D ray=1.603.	Difference between the indices of refraction for D and G rays=.02076.	Reciprocal of dispersive power= $\frac{.603}{.02076}=29.1$.

Second lens L^2, fourth lens L^4, and fifth lens L^5 are made of light phosphate crown having the following optical properties:

Refractive index for the D ray=1.5224.	Difference between the indices of refraction for D and G′ rays=.00939.	Reciprocal of dispersive power= $\frac{.5224}{.00939}=55.63$.

The third lens L^3 is made of ordinary extra dense flint glass, having the following optical properties:

Refractive index for the D ray=1.650.	Difference between the indices of refraction for D and G′ rays=.02577.	Reciprocal of dispersive power= $\frac{.650}{.02577}=25.2$.

I will now give the radii of the curvatures, expressing them decimally in fractional parts of the equivalent focal length of the whole lens, which is taken as unity. Thus, to obtain the curves or radii of curvatures for any particular focal length of lens, all that is necessary is to multiply the figures or fractional numbers given below by the equivalent focal length required, and thus obtain the necessary radii, expressed in the same units of measurement as the focal length—(in other words, the figures given in the schedule of curves below are the radii of curvatures expressed in inches, for producing a lens having an equivalent focal length of one inch). The diameters and central thicknesses of each lens are also expressed in fractional parts of the focal length. A plus (+) sign before each radius implies a convex surface and a minus (−) sign implies a concave surface.

Front Lens F.

L′.		L².	
r'.	r^2.	r^3.	r^4.
+.144	−.0816	+.0816	+4.5

Negative Lens N.

L³.		L⁴.	
r^5.	r^6.	r^7.	r^8.
−.421	+.140	−.140	−.156

Back Lens B.

L⁵.		L⁶.	
r^9.	r^{10}.	r^{11}.	r^{12}.
+.447	+.345	−.345	+1.730

L′	Clear front aperture=	.167
	Diameter somewhat larger.	
	Central thickness=	.006
L²	Clear aperture of front surface r^3 or diameter=	.146
	Central thickness=	.054
L³	Clear aperture=	.130
	Central thickness=	.0175
	Diameter somewhat larger than aperture.	
L⁴	Clear aperture of back surface r^8 =about	.110
	Central thickness=	.003
	Diameter somewhat larger than aperture.	
L⁵	Clear diameter of lens or aperture of r^{10}=	.170
	Central thickness=	.042
L⁶	Clear aperture of last surface r^{12}=	.195
	Central thickness=	.006
	Diameter somewhat larger than aperture.	

The central thicknesses, as given above, should be as closely followed out as possible. For instance, the rather large central thicknesses of L² and L⁵ are necessary in order to insure that the field of view shall be flat for actinic and visual rays simultaneously, and also secure a larger field of good definition than could otherwise be obtained. Of course, the diameters of the necessary wheels and gages will be obtained by doubling the above figures. This combination is a moderately wide angle lens. Its nodal point or the point from which its equivalent focal length is to be measured is at the point marked n just in front of the apex of front lens. It is intended to fully cover a plate whose length is equal to the equivalent focal length, with the hitherto thought impossible aperture of $\frac{F}{8}$. This it does, and with even illumination up to the sides of the field of view. For instance, a lens of seven and one-half inches equivalent focal length should cover a seven and one-half by five plate with reasonable sharpness up to the corners with $\frac{F}{8}$, and almost the full aperture of the lens should be visible when the eye is placed near one end of the opening in the frame carrying the ground glass screen. The diaphragms or stops regulating the aperture are placed as closely as possible behind the lens N, as shown in Fig. 12. The clear aperture of the stop necessary for the aperture $\frac{F}{8}$ is equal to the equivalent focal length X .098 or almost one-tenth of the focal length.

It should be borne in mind that the parallel beam of light which strikes the first lens with a breadth equal to $\frac{F}{8}$, is condensed to the breadth about $\frac{F}{10}$ when it enters the stop. The other stops for $\frac{F}{11.3}$, $\frac{F}{16}$, $\frac{F}{32}$, &c., of course, have their diameters settled by reference to the standard aperture for $\frac{F}{8}$. If desired, an iris diaphragm may be fixed behind the lens N, and the size of the tube made to accommodate it.

Working instructions.—The quickest way of roughing out the front lens L′ is to chuck the glass block in a lathe and turn out the hollow surface with a hardened steel tool or still better a diamond, keeping the glass all the time moistened with turpentine. Of course, the same method may be applied to all the deeper curved surfaces, if found more expeditious than the ordinary methods of grinding in tools with coarse emery. The light phosphate crown glass will be found softer in grinding than ordinary crown, more brittle and more apt to fly if incautiously heated. The polishing methods in which the optician is most skilled and finds most successful for deep curves may be used. So far, I have found wax polishers the best for the deeper curves. The lenses with the shallower curves may be worked up in blocks of three or upward, and polished either by a dry (for shallow curves) or a wet process (for deep curves). The phosphate crown polishes rapidly, but the worker, if using a wet polishing process for this glass, should be carefully cautioned against letting any of the wet rouge or putty powder dry upon its surface when finishing, or it cannot be got off again; and all trace of wet polishing material should be wiped off while kept moist by breathing or dipping into water. The polish of the light phosphate crown glass is, however, quite permanent. After being polished, each lens should be most carefully and exactly centered down and fitted into its cell or counter-cell, as the case may be. This operation should be done in a dioptric centering lathe, that is, a lathe in which the lens is made to run perfectly true by observation of the transmitted image as well as by the reflected image, for the latter test is not sufficiently reliable in its nature, especially as the reflections from both surfaces are not always clearly observable.

The fit of the lenses in their cells should admit of no perceptible shake, but they should be just able to rotate. The form of brass mounting which I have drawn to scale in Fig. 9 should be carried out with great truth. The threads should, for ordinary sizes, be about fifty to the inch and should not be chased up by hand, but by means of a screw-cutting lathe or a lathe with a traversing mandrel.

It is a most excellent precaution to reserve the final cut to be taken off the interiors of all the flanges or rings, which confine the lenses, to the very last. Thus, if the whole mounting is truly chucked by the cap flange C, then all the interior flanges which confine the lenses may be trued up together, first, by turning up the interiors of the back cell of lens B, which may then, if necessary, be unscrewed without disturbing the chucking; then the inside of the interior cell which is to carry lens N may be trued up, after which the body tube carrying this may be unscrewed and a final cut taken off the interiors of the front cell, which remains in the chuck. This, if carefully done, insures great truth in the alignment of the three lens combinations, on which alignment the success of the whole lens very seriously depends. After being properly centered and fitted into their respective cells, the back and front combinations may be finally cemented together with balsam. After baking and cooling, they should be carefully cleaned, then warmed again and placed in their proper cells, which also should be warmed. While all warm together, the counter rings of the cells should be screwed down sufficiently to just confine the lenses so that they may be just rotated in their cell between the fingers but without shake. This operation secures the correct centering of one lens over its fellow. When cold again, the counter rings should be adjusted, that is, the edge of the main cell should be rubbed down until the counter ring can be screwed home tight up to its shoulder without causing the lens to be at all nipped. The lens should then be capable of a slight amount of rotation, but without shake.

The negative lens L should be temporarily put together with some thin new balsam and then be pushed home in its cell. Its sticky edges should be sufficient to hold it there while the whole combination is being tested, for the purpose of seeing whether the negative lens N requires a slight alteration or not. For, owing to inevitable variations in the optical properties of the several glasses or in the curvatures, slight alterations of the negative lens will as often as not be necessary, if the lens is to be made as perfect as it is possible to make it.

The lens should be mounted temporarily in a trial camera carrying a ground glass screen rather larger than the plate which the lens is intended to cover, for instance, a lens of seven and one-half inches equivalent focal length is best tried with a whole plate screen measuring eight and one-half by six and one-half inches. This camera should have facilities for easy focusing, and its screen should be most accurately square to the optic axis of the lens. The first thing necessary is to properly adjust the distance between the front lens F and the negative lens N. The back lens B being taken out, the other two should be aimed axially at a very distant object, such as a weathercock. Then a small telescope, of a foot focal length or so, should first be focused upon the distant weathercock, and then it should be placed behind the lens N so as to view the distant weathercock through both lenses F and N. If now the distance between F and N is about right, then no very material alteration in the length of the telescope should be necessary in order to see the weathercock distinctly. In other words, the light should emerge in a parallel beam after traversing both lenses F and N, or, if not quite parallel, then preferably slightly divergent. Of course, shortening the main tube of the mount allows the cell carrying the lens F to be screwed nearer to N. The lens should now be tried with its back lens B in position. It should first be roughly examined for distortion. A vertically stretched thick wire is the best object to focus upon. Some accurately straight lines should be always ruled upon the focusing screen more or less near its magins, for comparison with the image of the wire. If any material amount of distortion of the type shown in Fig. 10 is visible, then the main tube of the lens must be shortened so as to allow the lens B to approach nearer to lens N until the distortion is quite removed. That being done, the lens should next be tested for correct centering, &c. An artificial point of light at the end of a long darkened room is the best for this purpose. Back somewhat within focus, so as to cause the image to show a disk of light about one-thirtieth of an inch, or one millimeter, in diameter on the center of the screen, the corrections for spherical aberrations may now be advantageously examined, or any zones of bad figuring detected if there are such. If the centering of the lenses and mount is all right, then, on rotating the camera from side to side and up and down, &c., the disk or oval of light projected on the screen should look precisely the same in size and shape and show precisely the same changes, if any, along whichever radius, drawn from the center of the screen, it may be caused to travel. If, along any meridian, the image at (say) three inches from the center differs materially from what it is at three inches from the center in the opposite direction, then there is something at fault. It may as easily as not be caused by the negative lens not being pushed perfectly home in its cell or up against its fellow, or there being a little looseness of fit in it.

After correct centering has been assured, the lens should be tested for flatness of field, by carefully focusing the distant weathercock on the center of the screen, and then rotating the camera so as to bring the image first near one margin of the screen and then near the other; when, if the field is perfectly flat, the image should remain very well defined up to the margins of the screen without any alteration of focusing being required. If, however, the best possible lateral image of the weathercock is obtained only by causing the lens to approach nearer to the screen, then the field of view is proved to be round or concave toward the lens. If the best marginal image is obtained by causing the lens to recede more from the screen, then the field of view is proved to be hollow or convex toward the lens.

Obviously, to correct a round field, the negative lens must be deepened or made stronger either on one side or the other; while, to correct a hollow field, the negative lens must be weakened by flattening either one side or the other. For instance, in the case of a seven and one-half inch lens, where, in order to accurately focus the weathercock at a point about three inches from the center of the screen, the distance between the lens and screen has to be lessened by one-sixteenth of an inch. The first surface r^5 of the negative lens will be about 3.20 inches radius, and to correct the above amount of roundness of field, this radius of 3.20. should be altered to about 3.15. A few extra tools, differing slightly in curve, for altering the outside surfaces of the negative lens, should generally be available. Very small alterations in these curves can be performed by manipulating with a polisher in the lathe or polishing machine. Supposing an alteration in the negative lens to be required, the next thing is to find which side of the negative lens it is requisite to alter. This is determined by the presence of "coma" if there is any. The lens must be again tried on the distant artificial star and the character of the "coma" observed, should there be any.

Fig. 10 represents the focusing screen. The slightly out of focus images shown at A, B, C and D represent a case of inward "coma" or coma in which the side flare or wing of light is directed toward the center of the screen, while *a*, *b*, *c* and *d* represent a case of outward "coma" or coma in which the side flare or wing of light is directed away from the center of the screen. Now the lens will never perform at its best, even if the field is flat, so long as any serious amount of "coma" exists, and it must always be eliminated consistently with the other corrections being attained.

Now the rules to be observed are as follows: Deepening the back curve r^8 of the negative lens produces outward "coma." Deepening the front curve r^5 of the negative lens produces inward "coma." Flattening the back curve r^8 produces inward "coma." Flattening the front curve r^5 produces outward "coma." Therefore, to cure a round field when the lens also shows outward "coma," deepen r^5. To cure a round field when the lens also shows inward "coma," deepen r^8. To cure a hollow field when the lens also shows outward "coma," flatten r^8 and to cure a hollow field when the lens also shows inward "coma" flatten r^5; but, if the field is about perfectly flat while the lens shows outward coma, then deepen r^5 and flatten r^8, the two alterations being such as to neutralize one another as regards effect upon the focal power of N. If the field is about perfectly flat, while the lens shows inward coma, then flatten r^5 and deepen r^8, keeping the focal power of N the same. Finally, should the field not be flat while the lens shows no "coma," then both sides of the negative lens should be either deepened or flattened simultaneously, as the case may be.

The lens will be found to perform the best, all things considered, when the image is perfectly free from coma at a distance from the center of the screen equal to half the equivalent focal length. It will then be found to give a slight amount of inward coma when the image falls half way between the aforesaid position and the center.

It should be remarked that, owing to the small dispersive power of the phosphate crown glasses and the presence of the positive lens L^3 of highly dispersive extra dense flint glass, the amount of secondary spectrum present at the focus of this lens is very considerably less than that present at the focus of any photographic lens made of ordinary glasses, and therefore, when the optician is testing this lens for color correction, he must expect, when the lens is properly corrected so as to refract the D and G′ rays to the same focus, to see considerably less red fringe inside focus and less green fringe outside focus than he has been accustomed to. It should also be remarked that the front combination F cannot be made truly aplanatic, for even when the curves are exactly spherical, a well pronounced zonal aberration will be noticeable. The zone of rays which are refracted through at about three-fourths of the semi-aperture from the center pass to the shortest focus; but when the whole triplet lens is tried with $\frac{F}{8}$ stop, no serious zonal aberration should be noticeable at the final focus if all the figuring is properly carried out.

After the negative lens has been properly corrected, it should then be finally cemented together and then fixed in its cell. It is decidedly preferable not to burnish it in, but to cement it in its cell by a mixture of rather stiff Canada balsam made black by admixture with lampblack. The whole triplet should then be tried again for symmetry of centering, for it may be found necessary to warm the mount again for the purpose of settling the negative lenses more home into its cell by judicious pressure. Often a one-sided pressure will cure a slight fault of this sort, which may easily arise if the layer of balsam between the two lenses is thicker on one side than the other. When cold, the triplet may be tried again until finally approved. This objective will answer perfectly well for lantern projection if the highest illuminating power is not exacted, and especially if the space is confined, while, if made on a very small scale, it will answer tolerably well for a microscope projecting lens; but I have not yet been able to work out the forms which will give as great an illuminating or light-grasping power as is often required for both the above purposes as well as for camera work. I can only sketch out one or two more useful forms of my invention which I shall doubtless perfect before long. For instance, Fig. 12 shows a more rapid form of my lens on the same lines exactly as the one which I have particularly described, only the back lens B is here more powerful relatively to the front lens F and the whole lens is meant to cover a plate, whose length is about two-thirds of the equivalent focal length, with an aperture of $\frac{F}{5.65}$ and very nearly even illumination.

Fig. 11 is a sketch of a symmetrical form of lens which embodies the principle of my invention.

In the cases of the lenses represented in Figs. 9 and 12, I have supposed the rays first incident upon the lens to be parallel as when coming from a distant subject, and the curves of all three combinations are so arranged that each combination F, N and B has its diaphragm corrections eliminated as nearly as practicable for the rays passing through it, on the condition that the rays, when first incident, are parallel; but I must point out what happens when the rays first incident become divergent as when coming from a very near subject. Diaphragm corrections now arise in the front lens F, whose tendency is to make the field of view hollow (in the sense defined above). Moreover, in the case of the back lens B, which is now also receiving divergent rays, it can be shown that the tendency of the consequent diaphragm corrections of lens B is to make the field of view round, and this tendency is of the opposite character to that exerted by lens F, and it can be shown that, not only are these two tendencies opposite in character, but that they are approximately equal in amount, so that the field of view still remains flat (if the original object is flat). This is tantamount to the following very important general proposition relating to this triplet, namely, that, if the two positive lenses F and B are simultaneously and individually free from diaphragm corrections, when the first incident rays have a certain degree of divergence or are parallel, then the triplet as a whole will remain free from diaphragm corrections for any other likely degree of divergence of the first incident rays. Therefore, the triplets shown in Figs. 9 and 12, although initially designed for yielding a perfect image of a distant subject, with the form of each lens calculated accordingly, are, as a matter of fact, about equally good in their performance when used for copying equal size; when of course the incident rays are very divergent. Thus the principle of my invention, that the whole burden of rendering the field of view flat shall devolve upon the negative lens, and that diaphragm corrections, being eliminated, shall contribute practically nothing to that end, still holds good. Therefore, the form of lens sketched in Fig. 11 naturally suggests itself. Here the whole lens is initially calculated with a view to copying a flat object to equal size. Therefore, the two positive lenses should be exactly alike in form and power but turned opposite ways and with the negative lens placed half way between them, and both individually designed to be free from diaphragm corrections when the incident rays are diverging as much as the emerging rays are converging, as shown in Fig. 11. Should such a combination as this be used on distant subjects, then the consequent diaphragm corrections of lens F, tending to round the field of view, will be almost perfectly neutralized by the consequent simultaneous diaphragm corrections in lens B, tending to hollow the field of view. Thus, under all circumstances likely to happen in practice, the flat image yielded by my lenses is brought about by the power of a negative lens only, and is in no appreciable degree due to those diaphragm corrections which are more or less relied upon for flattening the field of view in all photographic lenses hitherto made; the employment of which diaphragm corrections, as I have before pointed out, renders it impossible to obtain a flat field of view, which shall, at the same time, be free from astigmatism; excepting under those exceptional conditions before alluded to and carried out in Dr. Schroeder's and Stuart's concentric lens, which conditions, however, preclude any large aperture being attainable.

The rapidity of the symmetrical triplet shown in Fig. 11 depends upon the relative separation between the two positive lenses. Calling the focal length of the negative lens N, 1 or unity and the focal length of each positive lens 2 or thereabout, then the maximum rapidity or shortest equivalent focal length is obtained when the separation between F and N and between N and B is equal to 1. As this distance is reduced while keeping the focal lengths of all three lenses about the same, so will the equivalent focal length increase and the rapidity decrease; but each distance, found requisite for certain convenient degrees of rapidity, requires a different form to be given to the two positive lenses in order to insure the elimination of diaphragm corrections in each lens when the whole triplet is being used for copying equal size, which condition implies the elimination of the diaphragm corrections of the whole triplet under any other conditions under which it is likely to be used; but throughout these modifications, the form of the negative lens obviously need not be altered, since, when the triplet is being used for copying equal size, the rays traversing lens N are invariably converging to and diverging from two points situated at equal distances from the negative lens but on opposite sides of it, as shown in Fig. 11. This symmetrical form of my triplet certainly promises many practical advantages in manufacture when the curves are once determined, but it presents more theoretical and practical difficulties in working out than the forms which I have shown in Figs. 9 and 12 and particularly described before in the case of Fig. 9.

Having now dealt with the application of my method of correction to the case of compound lenses, supposed to be more or less aplanatic or free from spherical aberration, I will now show roughly how the same methods may be applied when the two positive lenses are simple and not compound.

Fig. 13 shows a simple symmetrical triplet in which the two positive lenses are exactly alike but turned opposite ways while the negative lens is equi concavi. In this case, the lenses are initially designed to be free from diaphragm corrections when the entering rays are diverging as much as the emergent rays are converging, that is, when the triplet is being used for copying equal size. In all these simple triplets, such as Figs. 13, 14, 15 and 16, the presence of spherical aberration in the uncorrected lenses makes it necessary that the two positive lenses should yield a certain amount of coma, in order to neutralize those diaphragm corrections which inevitably result from the presence of spherical aberration, for the presence of a stop or diaphragm behind the front lens and in front of the back lens in conjunction with the spherical aberration of the two positive lenses inevitably brings about diaphragm corrections which tend to make the final image still more curved, but by bulging the curves of the two positive lenses more outward by an amount ascertainable by calculation, I can introduce such an amount of coma as will give rise to diaphragm corrections tending to flatten the field just as much as the diaphragm corrections due to spherical aberration tend to round the field. Thus, by balancing these opposing tendencies, I obtain two simple positive lenses whose diaphragm corrections may strictly be said to be eliminated, as regards ultimate effect upon the curvature of the final image; and just as in the previous cases I can then throw the whole burden of flattening the field and correcting the marginal astigmatism upon the negative lens alone, whose focal power is made as approximately equal to the combined focal powers of the two positive lenses as is found necessary to that end.

In all the varieties of simple triplets such as I have sketched, the negative lens has to perform a three-fold office, first, to flatten the final image and correct the marginal astigmatism, as above explained; second, to correct the color aberrations of the two positive lenses and render the final image achromatic; third, to correct the spherical aberrations of the two positive lenses and thus render the final image aplanatic.

All the above corrections are so interlocked together and interdependent that the theoretical and practical difficulties which have to be overcome in perfecting such a lens are far greater than in the case of the compound combinations, although, when once the proper curves, &c., have been arrived at, for securing a first rate result, then there need be no difficulty in manufacturing any number of them.

The symmetrical form shown in Fig. 13 offers the greatest practical advantages and will doubtless be the form which I shall first bring to perfection. When this symmetrical form is being used for copying equal size, then the negative lens must be placed exactly in the middle between the two positive lenses, in order that the marginal image may be achromatic; but, when the same lens is used for distant subjects, as in ordinary camera work, then the image, and especially the marginal image, will no longer be achromatic, for the image painted by the blue rays will now be very slightly larger than the image painted by the yellow rays. Moreover, a little pincushion or negative distortion may be expected. In order to correct these defects, either the negative lens must be screwed slightly nearer to the front lens (the lens exposed to the distant subject) or else the front lens must be screwed slightly nearer to the negative lens, and means of quickly making this slight adjustment for more or less distant subjects should be provided.

Fig. 14 shows roughly a simple unsymmetrical triplet, which is initially designed for distant subjects and the lenses are severally free from diaphragm corrections when the rays first incident are parallel.

Fig. 15 shows a symmetrical form in which the negative lens is made compound in order to reduce its spherical aberration, by which device the two positive lenses can be placed much nearer to the negative lens, and a short simple triplet perhaps more adapted for wide angles of view is rendered possible.

Fig. 16 shows a simple triplet with the negative lens split so that the diaphragms or stops for regulating the aperture may be placed exactly in the center of the whole combination, instead of to one side of the negative lens, as in all the other cases.

I may point out that Prof. Abbe, of Jena, recently patented a triplet lens in which the two outside lenses are simple, but the flattening of the field of view is due almost entirely to diaphragm corrections, for the two positive lenses are made of a very pronounced meniscus form to attain that end, whereas all he claims for his central compound correcting lens is that it corrects the color aberrations and the spherical aberrations of the two outside positive lenses, while its focal power is either positive or zero or only slightly negative. Thus he in no way claims, for his central compound correcting lens, the function of flattening the final image and correcting the marginal astigmatism.

I claim as my invention—

A lens, composed of two substantially aplanatic and achromatic positive lenses, and a substantially aplanatic and achromatic negative lens placed between the two positive lenses; all three lenses being severally so designed as to be simultaneously free from diaphragm corrections or have their diaphragm corrections eliminated when the rays first incident on the front lens are either parallel or have a certain assigned degree of divergence; while the focal power of the negative lens is made as closely equal to the combined focal power of the positive lenses as is found necessary to the complete flattening of the final image or field of view; the whole burden of correcting the oblique pencil against curvature of image and astigmatism thus falling entirely upon the negative lens; by which device a flat field combined with general freedom from marginal astigmatism is secured.

In testimony whereof I have signed my name to this specification in the presence of two subscribing witnesses.

HAROLD DENNIS TAYLOR.

Witnesses:
CHARLES DOWNEY,
GEORGE WILLIAM CURRY.