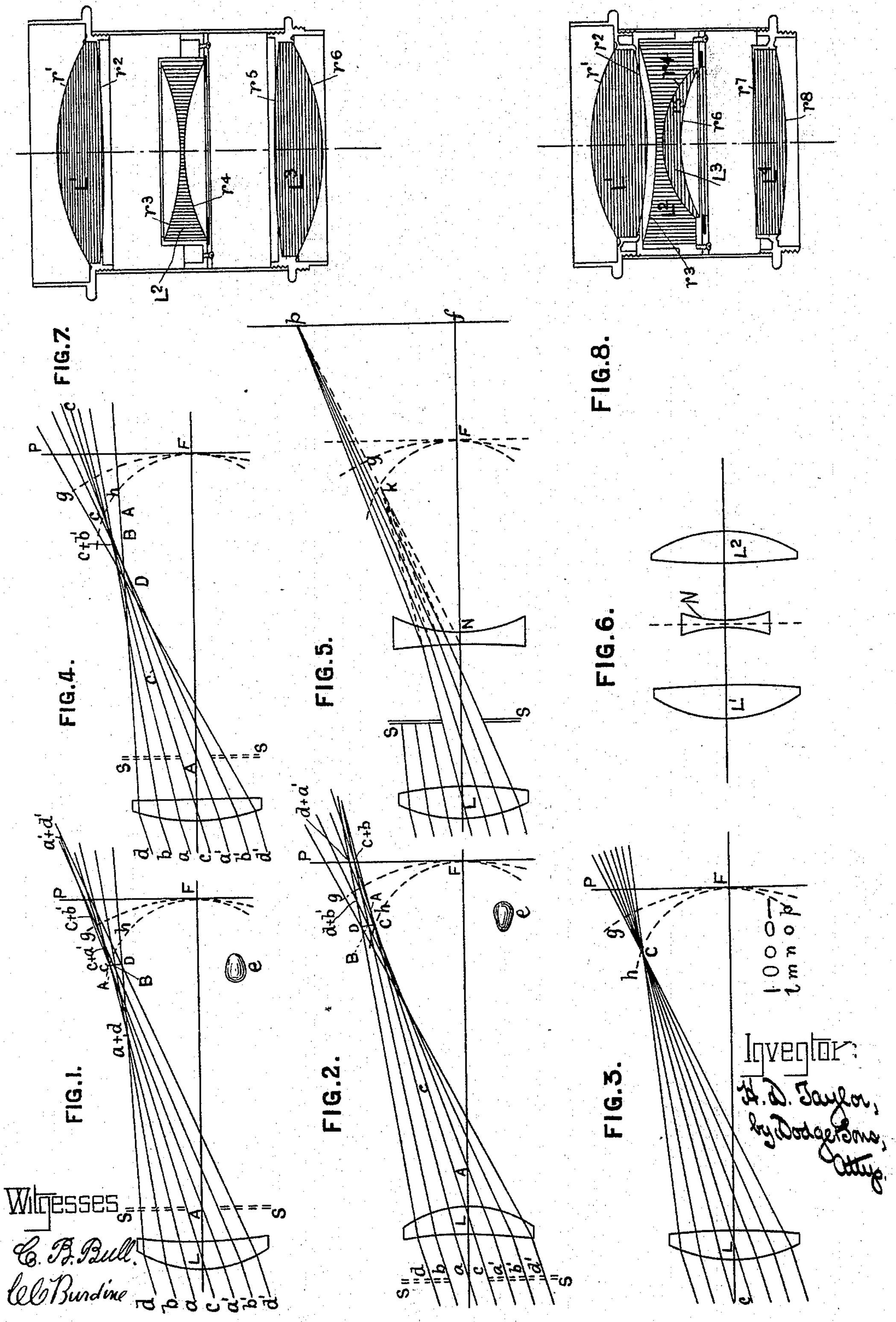
(No Model.) 2 Sheets—Sheet 1.

H. D. TAYLOR.

LENS.

No. 568,052. Patented Sept. 22, 1896.



Witnesses
C. B. Bull.
C. C. Burdine

Inventor:
H. D. Taylor,
by Dodge & Sons,
Attys.

(No Model.)

2 Sheets—Sheet 2.

H. D. TAYLOR.

LENS.

No. 568,052. Patented Sept. 22, 1896.

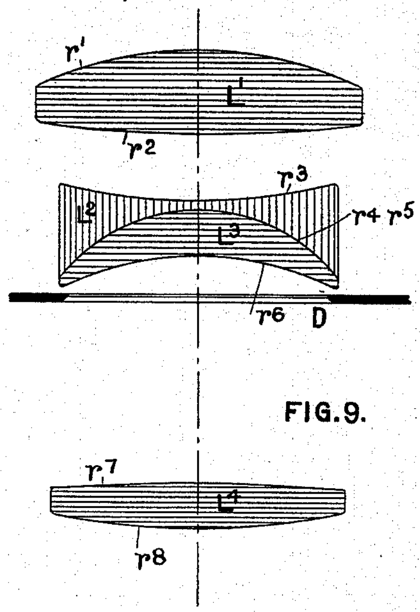


FIG. 9.

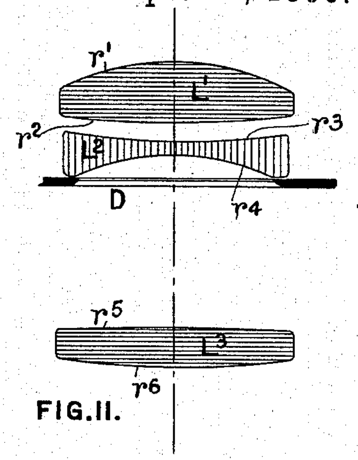


FIG. 11.

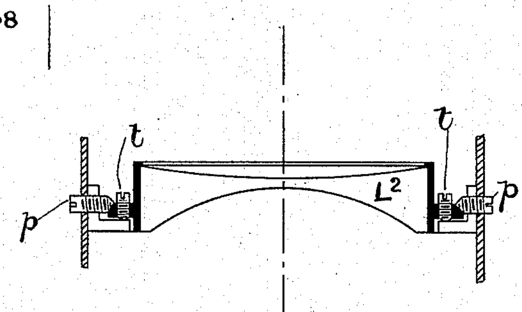


FIG. 13.

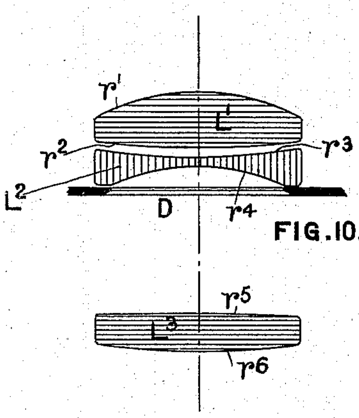


FIG. 10.

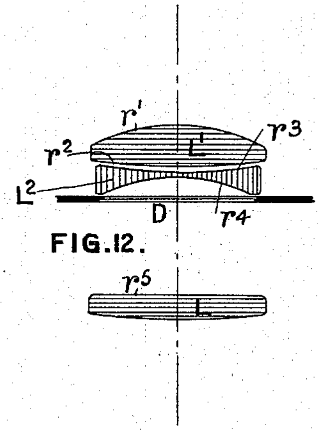
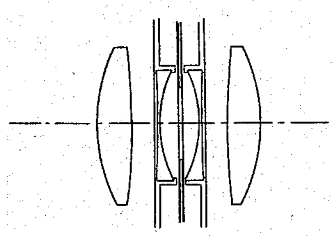


FIG. 12.

FIG. 14.



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

Inventor:
Harold D. Taylor,
by Dodger Sons,
Attys.

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. 568,052, dated September 22, 1896.

Application filed November 30, 1895. Serial No. 570,664. (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, in the Kingdom of England, have invented certain new and useful Improvements in Lenses, of which the following is a specification.

The invention is best described by aid of the accompanying drawings, of which—

Figure 1 represents the action of the front lens of any ordinary rectilinear doublet upon a beam or pencil of parallel rays passing obliquely through it. Fig. 2 similarly represents the action upon an oblique pencil of parallel rays of the back lens of any ordinary rectilinear doublet. Fig. 3 represents the action upon an oblique pencil of parallel rays of a lens having properties intermediate between those of Figs. 1 and 2. Diagram Fig. 4 represents the action of a simple lens having spherical aberration, but otherwise of the same type as Fig. 3. Fig. 5 represents the action of two lenses of equal focal powers, one positive and the other negative and both of the type of Figs. 3 or 4, upon oblique pencils of rays showing how a flat image is finally formed. Fig. 6 is a figure showing the case of two equal positive lenses of the type of Fig. 4, together with a negative lens placed between, having a focal power equal to the combined focal powers of the two positive lenses, and how the negative lens may be split into two plano concave lenses, each of which has a focal power equal to one of the positive lenses. Fig. 7 is an axial section of a rapid portrait-lens, Series I, composed of two simple positive lenses and one simple negative lens, all of the type illustrated in Fig. 4. Fig. 8 is an axial section of a rapid landscape or portrait lens, Series III^{a}, composed of two positive lenses of the type Fig. 4 and a compound negative lens of similar type. Fig. 9 represents a portrait-lens, Series II, composed of two simple positive lenses of unequal powers and a compound negative lens. Fig. 10 represents a rapid landscape-lens, Series III^{b}, composed of two simple positive lenses of unequal powers and a simple negative lens. Fig. 11 represents a rapid landscape or portrait lens composed of two simple positive lenses of unequal powers and a simple negative lens. Fig. 12 represents a rapid landscape-lens of wider angle than any of the preceding and composed of two simple positive lenses of unequal powers and a simple negative lens. Fig. 13 illustrates the form of adjustable cell for holding the negative lens in the case of any of the above combinations. Fig. 14 illustrates a combination of two positive lenses and a negative lens formed of two parts and inclosing the diaphragm between them.

In order to make clear the essential difference of principle between the photographic lenses made according to this specification and my older specification, No. 540,122, and the older forms of photographic lenses manufactured and used up to this date, it will be necessary to shortly explain, first, the older optical devices employed in such lenses for the purpose of correcting the oblique pencils of light against curvature of field and astigmatism, and, second, the new principle of correction employed by me and embodied in the herein-specified lenses for attaining the same ends in a much simpler manner and more radically perfect degree.

Fig. 1 represents the action of the front lens of an ordinary symmetrical doublet, which is nearly always a double achromatic combination of ordinary crown and flint glasses having the exterior form of a meniscus lens, placed with its convex surface outward to receive the parallel rays *c a b d a' b' d'* from any distant point. Supposing these rays to be oblique, then the corresponding focus at C, formed by the naked lens L, is of a peculiar form. (By the term "naked lens" I mean a lens whose effective aperture is bounded merely by its own periphery.) Let A—F be the optic axis and F the principal focus. It is well known to opticians that the image formed by a naked lens of a distant landscape is not a flat one, but is violently curved, and marred also by a greater and greater amount of astigmatism according to the angular distance of the image from the optic axis. Let it be supposed that the oblique rays *c a b d a' b' d'* are proceeding from a very distant point of light. All such rays contained in the plane of the paper, which is supposed to cut through the center of the lens, are said to be rays in the primary plane, or primary rays, to which the following remarks apply: Any two rays situated extremely closely to the central oblique ray $c - C$ intercross or come to a focus close to the point C and almost upon the line $c - C$; but the two rays a and a' falling on the lens at equal distances on either side of $c - C$ do not intercross or focus on the line $c - C$, but at the point A, situated slightly below $c - C$. The more widely-separated pair of rays b and b' focus at the point B, still farther below the point C, while the pair of widely-separated rays d and d intercross or focus at a point D at a considerable distance below the line $C - c$. This line $C - D$ may be considered to be, roughly speaking, perpendicular to the optic axis $A - F$. Its length is exaggerated in the figure for the sake of clearness. This successive lateral displacement of foci for symmetrical pairs of rays, such as a and a', b and b', d and d', increasing rapidly according to the distances of each pair of rays from the oblique axis $c - C$, brings about at the focus $C - D$ a sort of balloon-shaped image, Fig. 1 e, or "coma," as it is generally termed by opticians. In this case the effect may best be called "inward" coma, because the lateral displacement of foci for symmetrical pairs of rays is inward toward the optic axis $A - F$, and, moreover, the more diffused and larger end of the coma is also directed inward toward the optic axis. The effect of this lateral displacement of foci for symmetrical pairs of rays, such as a and a', b and b', d and d', is very important with regard to the consequent effects upon the foci or intercrossing points of any pairs of rays which are unsymmetrically situated with regard to $c - C$. Such pairs as a and d, c and a', c and b', a' and d', for instance, for their intercrossing points or foci are necessarily displaced either nearer to or farther from the lens L. Thus the two rays a and d focus at the point $a + d$ much nearer to the lens, c and a' focus at the point $c + a$, c and b' at $c + b'$, a' and d' at the point $a' + d'$, and these points are successively farther away from the lens. It follows, therefore, that if a stop or diaphragm $s - s$ is placed at any distance behind the lens L, so as to limit the pencil's effective for forming the image, only allowing rays to pass which are refracted eccentrically through the lens, such as the eccentric rays c and b' in Fig. 1 and those included between them, then a considerable flattening of the image must take place, owing to these particular oblique and eccentric rays having their focus at the point $c + b'$ much nearer the focal plane $F - P$, if not upon or beyond it. Thus it may be said of a lens like that shown in Fig. 1, when used for parallel or divergent rays, that it is capable of considerable "diaphragm corrections" or that its image is capable of being flattened by the presence of a smaller circular aperture or diaphragm $s - s$ placed axially behind it.

Fig. 2 fairly well represents the case of an ordinary achromatic meniscus single photographic lens or the back lens of a photographic doublet lens. In this case the meniscus lens, being inverted, has just the opposite effects on parallel rays to those shown in Fig. 1. The foci for symmetrical pairs of rays, such as a and a', b and b', d and d', are displaced to the points A, B, and D, successively, farther away from the optic axis than the point C on the central oblique ray. Instead of inward coma, the lens gives outward coma, the outlying and more diffused extremity of the coma, Fig. 2 e, being directed outward away from the axis $A - F$. It is obvious that if the curved image yielded by such a lens is to be flattened, then the stop or diaphragm must be placed in front of the lens, at $s - s$, for instance. This stop only allows to pass the eccentric rays c and b and those between, and c and b have their foci at the point $c + b$ much nearer to or upon the focal plane $F - P$.

Having now dealt with the rays in the primary plane, that is, those rays contained in the plane of the paper, it will be necessary to consider the case of those rays belonging to the same oblique incident pencil which are contained in the plane cutting the lens along a cord which is perpendicular to the plane of the paper or diagram and contains the oblique axis $c - C$. It would be extremely difficult to diagrammatically illustrate the course of such rays. I have pointed out that the image formed by a naked lens is always violently curved along a curve $F - h$ for rays in primary planes. The radius of this curvature is a fixed quantity for any given lens and is practically independent of the degree of convergence or divergence of the rays first incident on the lens, provided the original object is a flat surface normal to the axis of the lens. The radius of curvature of the image formed by primary rays is generally three-elevenths of the principal focal length and only varies within narrow limits, according to the refractive indices, &c., of the glass or glasses employed. On the other hand, the image formed by the naked lens by means of those rays contained in a secondary plane cutting through the center of the lens is formed along a much flatter curve $F - g$, and the radius of curvature of this curve, generally three-fifths of the principal focal length, is a fixed quantity for any given lens and is likewise practically independent of the degree of convergence or divergence of the rays first incident on the lens (if the original object is flat and normal to the axis) and varies only within small limits, according to the refractive indices, &c., of the glass or glasses employed. In the case of ordinary crown-glass lenses, whether simple or achromatized, the image formed by rays in secondary planes is curved to a radius just about 2.2 times the radius of curvature of the image formed by rays contained in primary sections of the same pencils, and it follows that for any given oblique pencil the focal point formed by rays in the primary plane is situated, approximately, 2.2 times as far short of a plane

F — P, passing through the focus and perpendicular to the optic axis, as the focal point at g, formed by rays in the secondary section. With a properly-fashioned lens and by means of diaphragm corrections it is quite possible to lengthen out the foci for rays in primary planes to such a degree as to form a flat image upon the plane F — P, but it can be shown that it is in nearly all cases impossible to simultaneously flatten the image formed by rays contained in secondary sections of the same pencils, for it can be mathematically demonstrated that any diaphragm correction which lengthens out the focus of rays contained in a primary section of an oblique pencil by a certain amount c is invariably accompanied by a lengthening out of the focus for rays contained in a secondary section of the same pencil whose amount is just one-third of the correction in primary section, or $\frac{c}{3}$ but it has been shown that, in the case of the naked lens, the deviation of focus for a primary section of an oblique pencil from the plane F — P is, in the case of ordinary glasses, about two and one-fifth times the deviation of focus from the plane F — P for a secondary section of the same pencil. Hence if the diaphragm corrections are just sufficient to form a flat image for primary sections of the oblique pencils, it is evident that the corresponding diaphragm corrections for secondary sections of the same pencils will not be sufficient to fully compensate their curvature of image, and therefore the image formed by rays in secondary sections will remain curved, and to a radius generally equal to somewhat more than double the focal length. This difference of foci for rays in primary and in secondary sections of the same oblique pencil constitutes what is known as the "marginal astigmatism" of photographic lenses. In the case of all lenses made of ordinary crown and flint glasses and compensated by the usual diaphragm corrections, it has been found impossible to obtain an image both flat and free from astigmatism at the same time. If a flat image is obtained, it is astigmatic. If an image free from astigmatism is obtained, then it is considerably curved (to a radius equal generally to one and one-half times the principal focal length.) There is, however, a new sort of glass now obtainable combining a very high refractive index with a very low dispersive power, and another sort combining a low refractive index with a relatively high dispersive power, which may be so combined together as to form an achromatic meniscus whose curvature of image for rays in primary planes is just three times the curvature for rays contained in the secondary section of the same oblique pencil, and these curvature aberrations are therefore in the right relation for being simultaneously corrected by means of diaphragm corrections, and so a flat image, also free from astigmatism, can be obtained; but the thorough carrying out of the above principle in combinations made of these exceptional glasses unfortunately precludes the use of a large relative aperture.

In order to obtain a lens of a large relative aperture which at the same time has a flat image or field of view in conjunction with a general freedom from astigmatism at the outskirts of its field, I have recourse to a principle of correction which, as far as I know, is entirely novel. This principle may be explained as follows: Fig. 1 shows a case of a lens giving inward coma and consequently capable of having its image flattened by placing a diaphragm behind it. Fig. 2, on the other hand, shows a lens having the opposite characteristic of outward coma and capable of having its image flattened by placing a diaphragm in front of it. It is obvious then that a form of lens should be possible intermediate in form between these two which should give neither outward nor inward coma. This is actually the fact, and Fig. 3 shows the action of such a lens. Here the foci of all symmetrical pairs of rays, such as a and a', b and b', d and d', fall practically at the same point C upon the oblique axis C — C if the lens is free from spherical aberration, as in Fig. 3, or if not free from spherical aberration, as in Fig. 4, which represents a simple lens, then the foci of all such symmetrical pairs of rays fall upon the oblique axis c — C, although not all at the same point. In either case the oblique focus is a symmetrical formation. In the case of Fig. 3, since all the rays pass through the same focal point C, it is plainly evident that diaphragms placed axially either in front or behind the lens can have no effect whatever in modifying the curvature of its image. Such an aplanatic lens, giving symmetrical oblique refraction, may therefore be said to have its diaphragm corrections eliminated. The appearances seen at the focus of a distant point of light, formed by such a lens, pass through the successive phases $l\,m\,n\,o\,p$ as the lens is receded from; first the luminous line l, which is formed at C vertically to the plane of the diagram, and, lastly, the luminous line p, which is formed at g and lies in the plane of the diagram. These and the intermediate appearances are quite symmetrical. In the case, however, of the uncorrected simple lens in Fig. 4, although the oblique focus is likewise symmetrical, yet it is evident that the placing of a diaphragm s — s either in front of or behind such a lens must necessarily, owing to the spherical aberration of the lens, have the tendency to curve its image more than before, since the diaphragm only admits eccentric sets of rays like a and d', which focus at the point $a'+d'$, short of the ultimate focus at C. But it is possible to eliminate diaphragm corrections from such a simple uncorrected lens having positive spherical aberration by the following device: Given the position of the diaphragm behind the simple lens in Fig. 4 and the distance of the object from the lens, it is easy to give the lens a form which is more bulged out toward the left hand, so as to approximate slightly to the case of Fig. 1 by an amount easily assignable by calculation, and which will bring about such an amount of inward coma as to give rise to diaphragm corrections which will just neutralize those diaphragm corrections dependent upon the spherical aberration. Thus the diaphragm corrections dependent upon inward coma can be made to flatten the image just as much as the diaphragm corrections dependent upon positive spherical aberration tend to further curve the image, and thus I obtain a simple lens which may as truly be said to have its diaphragm corrections eliminated as in the case of the aplanatic lens shown in Fig. 3. For while the lens shown in Fig. 4 differs from the lens Fig. 3, in having its spherical aberration uncorrected, yet it resembles it in regard to the essential qualities of having its curvature of image uninfluenced by diaphragm corrections. The algebraic sum of the diaphragm corrections tending to flatten its image on the one hand and to further curve its image on the other hand is zero, or approximately so; but this condition can only be attained provided the distance between lens and stop is not more than one-third (roughly speaking) of the focal length. All such simple lenses therefore have their images curved to the normal degree, uninterfered with by diaphragm corrections, for a given distance of the object. It is exclusively such simple lenses as these, with their diaphragm corrections substantially eliminated, that are employed by me for the two outer positive lenses of all my combinations. Thus in all lenses of this type as used by me the curvature error of the focus for rays in primary sections of a given oblique pencil is always about 2.2 times the curvature error of the focus for rays in the secondary section of the same oblique pencil. This ratio of 2.2 may be looked upon as practically constant in all lenses used by me.

It can be proved that exactly the same law of curvature of image and rules as to diaphragm corrections and the elimination of diaphragm corrections apply to negative lenses as well as to positive lenses, and I will now show how a flat image, almost perfectly free from astigmatism, may be obtained by judiciously combining together positive and negative lenses whose diaphragm corrections have been eliminated. Fig. 5 shows a simple positive lens L of this type, and N is a negative lens of the same type and made of glass of the same or nearly the same refractive index and of the same focal power as L, and $s-s$ a diaphragm or stop placed conveniently between them. The function of this diaphragm is that of regulating the aperture of the combination and the evenness of illumination of the image, and its presence has little practical effect upon the curvature of the final image. The diaphragm corrections of L are supposed to be eliminated on the condition that the rays first incident on it are parallel as if coming from distant points.

The lens N being placed in any desired position between L and its image must also have its diaphragm corrections eliminated so that the presence of the diaphragm $s-s$ between them shall have no effect upon the curvature errors of either lens. Under these conditions the positive lens L tends to produce an image $F-k$ for rays in primary planes of the normal curvature and an image $F-g$ for rays in secondary planes, also of the normal curvature; but the negative lens N considerably extends the focal length $N-F$ and tends to throw a larger image upon the plane $f-p$, and this image must be approximately flat and free from astigmatism, since the curvature errors of N, being normal and uninterfered with by diaphragm corrections, are equal and opposite to the curvature errors of the positive lens L, since the two lenses are of equal focal power, or the rays may be traced backward, as follows: Supposing $f-p$ to be the original flat object, then oblique rays in a primary plane originating from the point p, after refraction through the negative lens N, appear to come from the point k, while rays originating from f on the axis appear, after refraction through the negative lens, to diverge from the point F and the virtual image of the original $f-p$ which is formed at $F-k$ is curved to the normal radius equal to three-elevenths of the principal focal length of N; but the principal focal length of N is equal to the principal focal length of L, and therefore the virtual image $F-k$ is curved to the same radius as is the real image of distant objects on the left formed by the positive lens L. Therefore the rays apparently diverging from the point k will, after being refracted through the positive lens L, emerge on the left in a condition of parallelism. Conversely, rays in primary planes entering the lens L from an infinitely distant plane object or landscape on the left hand will, after refraction through both lenses, come to focus upon a flat surface $f-p$ perpendicular to the optic axis; and precisely the same reasoning applies to the rays contained in secondary sections of the same pencils. In this case also the curvature errors of the two lenses are equal but opposite, and therefore neutralize one another. In this way a flat image may be obtained which is also free from astigmatism through a considerable angle of view. This simple example of only two lenses serves to illustrate the principle, but in practice two lenses only cannot be employed owing to two defects necessarily inherent in such a combination, one being the presence of an unsightly amount of negative distortion of marginal straight lines and the other being the failure of such a lens to adapt itself to copying or enlarging, for it can only give a flat image for rays of a certain degree of divergence. For instance, if the lens shown in Fig. 5 were used on a near object on the left, then the rays entering L would become strongly divergent and diaphragm corrections tending to flatten the image formed by L would ensue. At the same time the rays entering N would grow less convergent and the effect would be to give rise to diaphragm corrections in N, whose tendency would be the same as the diaphragm corrections in L, and the final effect would be that an image would be formed actually curved backward. I get over these difficulties by the simple device of dividing my positive lens into two portions and placing my negative corrector lens between them, thus forming a triple combination. The above principle of corrections remains equally in force, as may be gathered from Fig. 6, which roughly represents such a triplet lens having its two positive lenses L_1 and L_2 alike in power and shape, but turned in opposite directions. The whole combination is shown in Fig. 6 as though being used for copying a diagram to equal size, the rays entering L_1 diverging to the same degree as the rays leaving L_2 are converging, and each lens is in itself supposed to be free from diaphragm corrections under these circumstances. In such a case the negative lens N would be equiconcave, and since its focal power has to be approximately equal to the sum of the focal powers of the two positive lenses it is obvious that if the negative lens is imagined to be split along the dotted line into two equal plano-concave lenses then we should have virtually two double combinations placed together in reverse order—first, the double combination, consisting of a positive lens L_1 and a negative concavo-plane lens, being the left-hand half of N, these two being equal in principal focal length or focal power, according to what has preceded, and, second, the double combination, consisting of a plano-concave lens, being the right-hand half of N, and a positive lens L_2, these two also being equal in principal focal length or focal power. Therefore the curvature errors of the positive lens L will be compensated by one half of the negative lens N and the curvature errors of the positive lens L_2 will be compensated by the other half of the negative lens N. Such a combination is free from distortion, and, moreover, compensates itself more or less perfectly when used on a distant subject, for if the rays first entering L_1 become parallel or nearly so, instead of divergent, then diaphragm corrections arise in the case of L_1 whose tendency is to make its image more curved than normal; but at the same time, owing to the much-lessened divergence of the rays entering L_2, diaphragm corrections arise in its case whose tendency is to flatten its image, and these corrections more or less perfectly neutralize those operating in the other lens L_1, while no very appreciable diaphragm corrections can arise in the case of the negative lens so long as the oblique pencils pass centrally or almost centrally through it, as they must do if N is thin and the diaphragm is placed very closely to it. If the two positive lenses are unequal in power, then the negative lens may be imagined split into two correspondingly unequal portions, each one being equal in focal power to the positive lens next to it, and the above explanations will again apply. In such manner most of the lenses made according to my principle may be designed to answer as well for copying or enlarging as for distant work. Given the fact that each lens used in my combinations is substantially free from diaphragm corrections when the rays first entering are parallel or have a certain assigned degree of divergence, then the triplet combination as a whole will remain sufficiently free from diaphragm corrections supposing the combination is used for rays having any other likely degree of divergence, and thus, diaphragm corrections being substantially eliminated from my combinations, then the whole or nearly the whole burden of flattening the final image and compensating its marginal astigmatism is thrown upon the negative lens, whose errors of curvature of image are, as I have shown, of substantially the same character and amount but opposite in sign to the curvature errors of the positive lenses, provided that the focal power of the negative lens is approximately equal to the sum of the focal powers of the two positive lenses. I thus discard almost altogether the old principle of diaphragm corrections hitherto relied upon for flattening the image of photographic lenses in favor of the above-explained principle, which renders possible a much more perfect correction for astigmatism in conjunction with a flat image of considerable angular extent. I do not claim priority for the mere expedient of mounting a negative lens behind a positive lens or between two positive lenses for the purpose of merely helping to flatten the final image, for these devices were long ago carried out in Professor Petzval's orthoscopic lens, also in Sutton's, Dallmeyer's, and Ross's triplet lenses; but it can be shown that in none of these lenses does the focal power of the negative lens amount to more than a fraction, four-tenths, or so, of the sum of the focal powers of the positive lenses, while a very large part of the flattening of the final image is due to the influence of the usual diaphragm corrections, the idea of substantially eliminating the diaphragm corrections and throwing the whole or nearly the whole burden of flattening the final image and correcting marginal astigmatism upon a negative lens apparently not having occurred to these inventors.

Having explained as best I can the main principle on which all the lenses described in this specification are based, I should point out that the substantial thicknesses of the lenses, and more especially of the front lenses employed in my combinations, render it necessary to accuracy in estimating their focal powers to make a small reduction for the thickness. A thick bi-convex lens having the same curves as a thin lens has a rather smaller focal power than the thin lens. Throughout this specification the term "focal power" as applied to simple lenses is intended to mean the reciprocal value of the equivalent focal length of a lens, such equivalent focal length being the distance between the posterior focal center or principal point of the lens and the point on the optic axis where an image of an infinitely distant object is formed, supposing the aperture of the lens is cut down small enough to prevent its spherical aberration interfering. I should also point out that a combination consisting of two positive lenses and a negative lens placed between them of a focal power equal to the combined focal powers of the two positive lenses must necessarily have a positive focus unless all three lenses are very thin and placed in contact. The greater is the separation between them the greater becomes the focal power of the whole combination or the shorter the focal length. Nevertheless for triplet combinations of relatively large aperture in proportion to focal length the curves of the lenses must be deep and the thicknesses of the lenses relatively great; but very deep curves and relatively large thicknesses are objectionable on the ground that they give rise, at the final focal points of oblique pencils, to certain aberrations of a secondary order in the shape of wings of light, &c. Therefore in practically applying the principle of correction above explained I have found that the finest results in shape of a well-defined flat image of considerable angular extent are not in all cases to be obtained by carrying out the above principle too rigorously, but by adopting a slight compromise I find that it generally suffices best not to make the power of the negative lens quite equal to the sum of the powers of the two positive lenses, but to fall short of the latter by a small amount, and the extent of the deficiency permissible depends very intimately upon the relation between the refractive indices of the positive and negative lenses, respectively. If the refractive index of the negative lens for the D ray is decidedly higher than the refractive index of the positive lenses for the same ray, as in the case of lens, Series I, Fig. 7, then the focal power of the negative lens must not be allowed to be less than about ninety-six per cent. of the combined focal powers of the two positive lenses, or a final flat image practically quite free from astigmatism cannot be obtained. If, on the other hand, the refractive index of the negative lens is substantially lower than that of the two positive lenses, as in the cases of Series II, Fig. 9, Series III^b, Fig. 10, Series IV, Fig. 11, and Series V, Fig. 12, then a further relaxation of the power of the negative lens becomes theoretically and practically permissible, consistently with the attainment of a flat image substantially free from astigmatism. The reason for this is that every increase in the refractive index of a simple lens over the quantity 1.50 leads to a slight deviation from the ratio 2.2 to one and a slight approach toward the ratio three to one for the curvature errors of an oblique pencil for primary and secondary sections, respectively. Thus the curvature errors of a highly-refractive lens are slightly more adapted for simultaneous correction by diaphragm corrections than the curvature errors of a lens of low refractive power. This fact alone renders it possible to relax the relative power of the negative lens by as much as four per cent. in the case of Series V, Fig. 12. If to this is added the further relaxation, above alluded to, in the way of compromise, then the focal power of the negative lens need not in the most favorable cases, like Series III^b, Fig. 10, Series IV, Fig. 11, and Series V, Fig. 12, amount to more than about ninety per cent. of the combined focal powers of the two positive lenses. Therefore, my principle of optical correction against curvature of image and astigmatism as applied in practice amounts to this: that I adopt two simple positive lenses of such a form that their several or collective diaphragm corrections are for much the greater part eliminated when the whole combination is in use, and I correct much the greater part of their errors of curvature of field and astigmatism by means of a simple or compound negative lens placed between the two positive lenses, the focal power of this negative lens amounting in the most favorable cases described herein to about ninety per cent. of the combined focal powers of the two positive lenses. Thus there is left a residuum of curvature and astigmatic errors of the two positive lenses which remains uncorrected by the negative lens. This residuum of curvature and astigmatic errors is more or less perfectly corrected by means of the residuary diaphragm corrections which are allowed to remain for that purpose in the two positive lenses and to a certain extent in the negative lens.

The greater the excess of refractive index of the positive lenses over that of the negative lens the less is the required relative focal power of the negative lens and the larger is the residuum of curvature and astigmatic errors which can be almost perfectly corrected by the residuary diaphragm corrections, and every relaxation of power of the negative lens leads to an increase in the power of the whole combination, or, in other words, highly-refractive positive lenses combined with a negative lens of the lowest possible refractive power permit of the flattest curves and the smallest thicknesses for a given aperture and focal length. This leads to the comparative absence of residual aberrations of a secondary order at the oblique foci, and therefore to greater perfection of image, in conjunction with greater ease and despatch in practical construction. Should glasses of still higher refractive power become available in the future for the positive lenses in conjunction with glasses of still lower refractive power for the negative lenses, then a further relaxation of the relative power of the negative lens may become possible, leading to still further improvement.

So far I have dealt with the principle adopted in my lenses for correcting the curvature and astigmatic errors of the oblique rays. I will now, before giving the curves and other particulars relating to my lenses, touch upon the other important corrections against spherical aberration and chromatic aberration which must be more or less perfectly carried out in any lens that is to be practically useful. It has almost always been the practice to make each lens of a doublet or triplet lens in itself compound and self-corrected against spherical and chromatic aberrations. However, Professor Abbe, of Jena, in a triplet lens patented a few years ago in England and Germany, practically demonstrated that it was possible to make a triplet lens in which the two outside positive lenses were perfectly simple, while the chromatic and spherical aberrations both of the central direct pencil and the oblique pencils were simultaneously corrected by means of a compound lens of scarcely any focal power or even positive placed half-way between the two positive lenses; but this central correcting-lens was not designed to contribute anything toward the flattening of the image and eliminating marginal astigmatism, whereas in my lenses I make my negative correcting-lens perform the triple function of, first, correcting the final image against curvature and astigmatism, thus permitting an unusually flat and perfect image of considerable angular extent to be attained; second, correcting both the direct and oblique pencils against chromatic aberration; third, correcting both the direct and oblique pencils sufficiently against spherical aberration.

Fig. 7 represents a rapid portrait-lens, Series I, with a full opening of $\frac{F}{3.7}$ made according to my principle. It consists of only three simple lenses and forms with an aperture of $\frac{F}{4}$ a flat and very good image over the whole of a plate whose greater side is equal to one-half of the equivalent focal length.

The glasses employed are as follows:

The positive lenses L_1 and L_3 are made of a hard and beautifully-colorless borosilicate crown-glass having the following optical properties: Index of refraction for the D ray equals 1.5108; difference between refractive indices for D and G rays or $\mu G - \mu D$ equals .01037; reciprocal value of the dispersive power for rays C to F equals 62.1.

The negative lens L_2 is made of a light silicate flint-glass having the following optical properties: refractive index for D ray equals 1.6042; difference between refractive indices for the D and G rays or $\mu G - \mu D$ equals .02086; reciprocal value of the dispersive power for rays C to F_1 equals 38.2.

I will now give the radii of curvatures of the surfaces, the central or axial thicknesses of the lenses and their finished diameters and the axial air-spaces between them, expressing them, as throughout this specification, in fractions of the equivalent focal length of the whole combination, so that if any lens of a certain focal length is required, all that is necessary is to multiply the figures or fractions corresponding to that combination by the focal length required and the proper radii, &c., will then be obtained. Convex surfaces have a + sign before their radii and concave surfaces a − sign before their radii. Moreover, in all cases excepting the first I shall enumerate the surfaces in the order in which the light passes through them, supposing the various combinations are used upon distant objects, in which case the first lens or L_1 is called the front lens.

First surface radius r_1, sixth surface radius r_6, equals +.2636; second surface radius r_2, fifth surface radius r_5, equals +1.507; third surface radius r_3 equals −.2977; fourth surface radius r_4 equals −.2415; finished diameter of L_1 equals .282; axial thickness of L_1 equals .059; finished diameter of L_2 equals .233; axial thickness of L_2 equals .002; finished diameter of L_3 equals .273; axial thickness of L_3 equals .059; axial air-space between L_1 and L_2 equals about .109; axial air-space between L_2 and L_3 equals about .125.

It should be pointed out that the correction for spherical aberration in this portrait-lens is not perfect, there being a zone of rays (focusing shorter than the rest) at about half-way between the edge and center of the aperture when $\frac{F}{4}$ is used; but this zonal aberration is not so great as to interfere with as much sharpness of definition as is most suitable for portrait work. The diaphragms for regulating the aperture are placed as closely as possible behind the negative lens L_2, and the aperture of such diaphragm necessary to give a working aperture of $\frac{F}{4}$ should be .177, expressed in the same manner as the previous figures. It should be understood that this lens should be tested upon distant or moderately distant objects.

I will now give the figures for a rapid lens, Series III[a] giving a wider angle of view than the preceding. This lens is shown in Fig. 8 in about correct proportion. Its full working aperture is $\frac{F}{6.5}$ and with that aperture it will give a well-defined flat image up to the corners of a plate whose longer side is equal to four-fifths of the equivalent focal length, while with $\frac{F}{8}$ stop it will about cover a plate whose greater side is equal to the equivalent focal length. The two positive lenses L_1 and L_4 are made of a borosilicate crown-glass having the following optical properties: Refractive index for the D ray equals 1.5101; difference between refractive indices for D and G rays equals .01010; reciprocal value of the dispersive power (C to F) equals 63.7.

The second lens L_2 is composed of a silicate glass having the following optical properties: refractive index for the D ray equals 1.5365; difference between refractive indices for D and G rays equals .01348; reciprocal value of its dispersive power (C to F) equals 51.2.

The third lens L_3 is composed of densest baryta crown-glass having the following optical properties: refractive index for the D ray equals 1.6110; difference between refractive indices for the D and G rays equals .01386; reciprocal value of its dispersive power (C to F) equals 56.3.

L_1—Radius of first surface r_1 equals +.2158; radius of second surface r_2 equals +.4655.

L_2—Radius of third surface r_3 equals −.3472; radius of fourth surface r_4 equals −.1150.

L_3—Radius of fifth surface r_5 equals +.1150; radius of sixth surface r_6 equals −.1910.

L_4—Radius of seventh surface r_7 equals +1.265; radius of eighth surface r_8 equals +.5843.

L_1—Finished diameter equals .158; axial thickness equals .0603.

L_2—Finished diameter equals .142; axial thickness equals .0044.

L_3—Finished diameter equals .142; axial thickness equals .0218.

L_4—Finished diameter equals .165; axial thickness equals .0393.

Axial air-space between L_1 and L_2 equals about .008; axial air-space between L_3 and L_4 equals about .090; aperture of diaphragm necessary for $\frac{F}{6.5}$ equals .134; aperture of diaphragm necessary for $\frac{F}{8}$ equals .1040. The fourth and fifth surfaces are cemented together.

I have not adopted a symmetrical construction for this lens, for there is the fact that the diaphragms regulating the aperture have to be placed to one side or other of the negative lens if the latter is a cemented combination, which renders it advantageous to make the front lens much more powerful than the back lens. Each of the three main lenses of this combination is calculated to be in itself substantially free from diaphragm corrections when the distance between the original object and the front lens L_1 is $\frac{1}{2.7}$th of the distance of the final image from the back lens L_4, the focal length of L_4 being 2.7 times the focal length of L_1. This lens is almost equally good for copying and enlarging.

Series II—Fig. 9.

A portrait-lens of full aperture $\frac{F}{4}$ which is rendered aplanatic or free from spherical aberration by the adoption of a double combination for the negative lens. The two positive lenses L and L_4 are made of a dense baryta crown-glass of the following optical properties: Refractive index for the D ray equals 1.5751; difference between refractive indices for D and G rays equals .01286. The reciprocal value of its dispersive power, as usually reckoned, or the refractive index for the D ray minus 1 divided by the difference between the refractive indices for the C and F rays equals 57.1.

The negative element L_2 is made of a light silicate flint-glass having refractive index for the D ray equal 1.5482; differences of indices for D and G rays equal .01560; reciprocal value of the dispersive power (C to F) equals 45.7.

The element L_3 is made of densest barium crown-glass having refractive index for the D ray equal 1.6114; difference of indices for D and G rays equals .01389; reciprocal value of the dispersive power (C to F) equals 56.3.

L_1—Radius of first surface r_1 equals +.294; radius of second surface r_2 equals +1.161.

L_2—Radius of third surface r_3 equals −.4637; radius of fourth surface r_4 equals −.1365.

L_3—Radius of fifth surface r_5 equals +.1365; radius of sixth surface r_6 equals −.2385.

L_4—Radius of seventh surface r_7 equals +1.427; radius of eighth surface r_8 equals +.557.

The fourth and fifth surfaces are cemented together.

L_1—Finished diameter equals .25; axial thickness equals .0635.

L_2—Finished diameter equals .213; axial thickness equals .0065.

L_3—Finished diameter equals .213; axial thickness equals .033.

L_4—Finished diameter equals .225; axial thickness equals .035.

Axial air-space between L_1 and L_2 equals .050; axial air-space between L_3 and L_4 equals .1706; aperture of diaphragm D for $\frac{F}{4}$ equals .197; aperture of diaphragm D for $\frac{F}{5.65}$ equals .135. Its angle of view is such that a lens of seven and one-half inches focal length will cover a plate measuring four and one-fourth inches by three and one-fourth at full aperture.

Series III^b*—Fig.* 10.

This is of the same rapidity $\frac{F}{6.5}$ and angle of view as Series III^a, but with a simple negative lens.

The two positive lenses L_1 and L_3 are made of densest baryta crown-glass, having refractive index for the D ray equals 1.6114; difference in refractive indices for D and G rays equals .01389; reciprocal value of the dispersive power (C to F) equals 56.3.

The negative lens L_2 is made of a light flint-glass, having refractive index for the D ray equals 1.5679; difference in indices for D and G rays equals .01707; reciprocal value of the dispersive power (C to F) equals 43.45.

L_1—Radius of first surface r_1 equals +.170; radius of second surface r_2 equals +.945.

L_2—Radius of third surface r_3 equals −.560; radius of fourth surface r_4 equals −.159.

L_3—Radius of fifth surface r_5 equals +3.623; radius of sixth surface r_6 equals +.770.

L_1—Finished diameter equals .157; axial thickness equals .040.

L_2—Finished diameter equals .157; axial thickness equals .007.

L_3—Finished diameter equals .157; axial thickness equals .0283.

Axial air-space between L_1 and L_2 equals .008; axial air-space between L_2 and L_3 equals .112; aperture of diaphragm D for $\frac{F}{6.5}$ equals .131; aperture of diaphragm D for $\frac{F}{8}$ equals .108.

Series IV—Fig. 11.

This is a more rapid lens than the last, having a full aperture of $\frac{F}{5.6}$ with which it will cover sharply a plate whose longer side is equal to about two-thirds of the focal length. It is specially designed for very rapid landscape work and also for projection with the optical lantern.

L_1 and L_3 are made of a densest baryta crown-glass having refractive index for the D ray equals 1.6110; difference between indices for D and G equals .01386; reciprocal value of the dispersive power (C to F) equals 56.3.

L_2 is made of ordinary light flint-glass having refractive index for the D ray equals 1.5754; difference between indices for the D and G rays equals .01810; reciprocal value of its dispersive power (C to F) equals 41.7.

L_1—Radius of first surface r_1 equals +.1944; radius of second surface r_2 equals +1.283.

L_2—Radius of third surface r_3 equals −.5785; radius of fourth surface r_4 equals −.1819.

L_3—Radius of fifth surface r_5 equals +3.113; radius of sixth surface r_6 equals +.664.

L_1—Finished diameter equals .180; axial thickness equals .0429.

L_2—Finished diameter equals .171; axial thickness equals .0093.

L_3—Finished diameter equals .180; axial thickness equals .0303.

Axial air-space between L_1 and L_2 equals .0163; axial air-space between L_2 and L_3 equals .129; aperture of diaphragm D for $\frac{F}{5.65}$ equals .149; aperture of diaphragm D for $\frac{F}{8}$ equals .105.

Series V—Fig. 12.

This is a wider angle-lens than any of the preceding and has a full aperture of $\frac{F.}{7.7}$ Its angle of view is such that a lens of eight inches focal length will cover with full aperture a plate measuring eight and one-half by six and one-half inches with sharp definition.

The two positive lenses L_1 and L_3 are made of densest baryta crown-glass having refractive index for the D ray equals 1.6114; difference between indices for D and G rays equals .01389; reciprocal value of its dispersive power (C to F) equals 56.3.

The negative lens L_2 is made of an extra light flint-glass, having refractive index for the D ray equals 1.5482; difference between indices for the D and G rays equals .01559; reciprocal value of its dispersive power (C to F) equals 45.7.

L_1—Radius of first surface r_1 equals +.1457; radius of second surface r_2 equals +1.013.

L_2—Radius of third surface r_3 equals −.5593; radius of fourth surface r_4 equals −.1327.

L_3—Radius of fifth surface r_5 equals +10.12; radius of sixth surface r_6 equals +.6975.

L_1—Finished diameter equals .135; axial thickness equals .0299.

L_2—Finished diameter equals .127; axial thickness equals .0046.

L_3—Finished diameter equals .135; axial thickness equals .0183.

Axial air-space between L_1 and L_2 equals .0038; axial air-space between L_2 and L_3 equals .0895. Aperture of diaphragm D for $\frac{F}{7.7}$ equals .1145; aperture of diaphragm D for $\frac{F}{8}$ equals .110; aperture of diaphragm D for $\frac{F}{11.3}$ equals .080.

In the case of all these simple triplets the specified thicknesses of the lenses, especially of the front and negative lenses, must be followed with great exactness if uniform results are expected. If either the negative or front lenses are made too thick, a more or less over-corrected field (convex toward the lens) will result, and vice versa. Also the exact edging or centering of the lenses is of the utmost importance if the best results are to be obtained. Not only must the optical centers of the lenses lie exactly upon a common axis, but the lenses themselves must be accurately perpendicular or square with respect to that axis;

and since errors so commonly arise in the turning of a series of metal cells held in alinement by a tube with screwed surfaces I have therefore found it in the highest degree conducive to expeditious and certain adjustment of my combinations to mount the negative lens in a separate cell, which can be moved laterally across the optic axis and also tilted with respect to that axis by means of small screws. It is also advisable to fix the negative lens, if compound, in its cell by a black cement instead of bezeling it in. This cement may be made of hard balsam and lampblack or balsam and black sealing-wax. Fig. 13 gives a section of a simple form of this arrangement. Here *p p* and *p* are three or four conical-pointed screws, which are threaded through the tube and bear upon the chamfered edge of the negative-lens cell. These three screws have the effect of pushing the cell in any direction laterally when the opposing ones are relaxed, and also have the effect of clamping the cell down in its place when all these are tightened. The other three or four screws *t t t* are for tilting the negative lens: They are threaded through the flange of the negative-lens cell and push against the fixed ring or flange *f* and raise the cell if the corresponding pushing-screw *p* is first relaxed.

The procedure in adjusting all of the above-described lenses is generally as follows:

First. Shorten up air-space between L_1 and L_2 until the combination shows just a little positive spherical aberration when tried telescopically along the optic axis with an eyepiece, the test-object being an artificial star placed at some distance away in a darkened room.

Second. If, when examined along the axis, the disk of light seen when inside of focus is unsymmetrical and shows a stronger and brighter edge inclined to redness upon one side, say the right hand, then this points to the negative lens being laterally out of center and in this case toward the right hand. By means of the three screws *p*, *p*, and *p* the negative lens in its cell must be moved a trifle toward the left hand. This operation must be repeated until the disk of light is perfectly symmetrical both inside and outside of focus; yet it may appear oval, owing to the negative lens being out of square.

Third. The combination should next be examined for symmetry of field. Dividing the field or ground glass, as viewed from behind the camera, as usual, into left-hand, right-hand, top, and bottom parts for reference, if the oblique rays are found to focus longer on the right hand than on the left and show an overcorrected astigmatism on the right hand relatively to the left it shows that the negative lens is out of square, and in this case the fault will be cured by tilting the negative-lens cell farther away from the screen on the right-hand side by means of the screws *t*, *t*, and *t*, and so on. If this adjustment is carried out approximately until the next test has been applied, it will in most cases be sufficient.

Fourth. The field should next be examined for curvature. A distant weathercock is a very good test object, especially if it presents both upright and horizontal straight lines. Such an object is first carefully focused upon the center of the screen and the position of the camera-slide marked. Then the camera is rotated so as to permit the weathercock to be focused at the two right and left edges of the plate which the lens is intended to cover, and the mean position of these lateral foci is compared with the position of the central focus. There should be no difference between the central and oblique foci if the lens is correctly adjusted. If the oblique focus is shorter than the central focus by a very small amount, the error may often be corrected by shortening the distance between L_1 and L_2 if there be sufficient excess of positive spherical aberration to permit of this. If this cannot be done, then the fifth surface L_5 must be slightly flattened, or the seventh surface, in the cases of Series II and III^a. If, on the other hand, the oblique foci are longer than the central focus and the field is thus overcorrected, then, if the distance between L_1 and L_2 cannot be increased because of the consequent spherical aberration, recourse must be had to deepening the fifth surface r_5 a trifle. Such alterations, however, should not be required if the glasses are true to this specification and if the curves and thicknesses are carefully followed out.

Fifth. After the image has thus been adjusted for flatness and any residual errors in squaring on or laterally adjusting the negative lens eliminated, the combinations should then be examined for distortion. If the air-spaces and thicknesses prescribed herein are exactly followed out, there should be no distortion in the image, but if slight deviations of the glasses from the normal optical characteristics render necessary slight alterations in the curves, as above indicated, then it is advisable to reëxamine the combination for distortion. A vertically-stretched wire is the best test object. The lateral image of this wire should be rigidly straight and of course accurately coincide with straight lines ruled on the screen parallel and close to the edges of the plate the lens is intended to cover. If the lens shows any trace of barrel-shaped distortion, then the back air-space A_2 must be decreased by shortening the tube, and if any trace of pincushion distortion is shown then the back air-space A_2 must be increased.

Sixth. After all the optical adjustments have been completed the three screws *p p p* should be filed down flush with the tube or else be concealed, according to the fashion of the mounting.

It is not at all necessary to the embodiment of my principle that the negative lens should be a cemented combination if made of two lenses. For instance, Fig. 14 sketches out a perfectly symmetrical combination in which the negative lens consists of two equal lenses turned opposite ways with the diaphragm placed half-way between them. Such an arrangement has certain features much in its favor.

A large number of various combinations of three lenses and of three or four elements are possible besides the few actually specified herein, all involving the same principle of correction. I have not given a drawing of a metal lens-mount in this specification, because a great variety in mounts is possible and each manufacturer prefers a mount to suit his own requirements.

I would point out that it is not absolutely necessary that the more powerful of the two positive lenses should be placed at the front of the combination. Triplets can be made with the weaker lens to the front, but all my experiments have shown that the results are not so good. Nor is it necessary that both positive lenses should be made of the same sort of glass. If made of different glasses, then the refractive index of the most powerful of the two positive lenses should be held as substantially characteristic of both positive lenses.

I claim as my invention—

1. A lens for photography or lantern projection composed of two simple positive lenses and a compound negative lens placed between and separate from the two positive lenses; all three lenses being severally so designed as to be collectively free from all but a residuum of diaphragm corrections, when the whole combination is used in the normal manner with its front lens presented to the subject or its image, whichever is largest; while the focal power of the compound negative lens is nearly equal to, generally about ninety per cent. of, the sum of the powers of the two positive lenses; the main burden of correcting the oblique pencils of light against curvature of image and astigmatism thus falling upon the negative lens, while a residuum of ten per cent. or thereabout of the curvature and astigmatic errors of the several lenses is more or less perfectly corrected by the residuary diaphragm corrections which are allowed to remain for that purpose; by which device a flat image, characterized by a substantial freedom from marginal astigmatism, is secured.

2. A lens for photography or lantern projection composed of two simple positive lenses and a simple negative lens placed between and separate from the two positive lenses; all three lenses being severally so designed as to be collectively free from all but a residuum of diaphragm corrections when the whole combination is used in the normal manner with its front lens presented to the subject or its image whichever is largest; while the focal power of the negative lens is nearly equal to, generally about ninety per cent. of, the sum of the powers of the two positive lenses; the main burden of correcting the oblique pencils of light against curvature of image and astigmatism thus falling upon the negative lens while a residuum of ten per cent. or thereabout of the curvature and astigmatic errors of the several lenses is more or less perfectly corrected by the residuary diaphragm corrections which are allowed to remain for that purpose; by which device a flat field characterized by a substantial 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.