The Development of the Photographic Objective[1]

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INTRODUCTION

IN this paper, an attempt will be made to follow the development of photographic lenses from 1812 to the present day, chiefly stressing the reasons which led designers to adopt the types they did, and trying to follow their strivings after something better. The period to be discussed divides itself naturally into two parts, the "old" period from 1812 to 1886, and then the "anastigmat" period from 1886 to the present day. The separation of these periods was brought about by the introduction of the barium glasses by Abbe and Schott at that time. The discussion will be confined to the most prominent lens types, rather than attempting to list every lens made.

THE LANDSCAPE LENS

The first camera was merely a camera obscura with a photographic plate substituted for the ground glass screen of the earlier instrument. The lens in the camera obscura was originally a simple biconvex crown-glass lens, which would give fair definition in the center of the picture, but the image rapidly deteriorated at points more than a few degrees out. The first real attempt to improve this lens was made in 1812 by W. H. Wollaston, who suggested the use of a simple meniscus lens having a stop or diaphragm in front, with the concave side of the lens facing the diaphragm. In this way he produced his "Periscopic" lens giving quite good pictures at an aperture of $f/8$, and excellent ones at $f/16$, the definition being quite sharp out to as much as 25° from the axis. This lens has remained the most used type of photographic lens up to the present day, being fitted to millions of the world's cheapest cameras.

The first attempt to improve the simple Wollaston meniscus lens was made by C. Chevalier in 1821. He retained the meniscus outward form, but managed to achromatize the lens by the use of a negative flint and positive crown lens cemented together. In this way he removed the axial and transverse chromatic aberrations, making a lens in which the visual and actinic light came to the same focus and in which the images in different colors were of the same size. To appreciate the value of this improvement, we should realize that with a simple lens the difference between the visual and actinic focus varies with the distance of the object, so that no universally satisfactory means of allowing for it is available except in "fixed focus" cameras such as are used today. Further developments were made by T. Grubb in 1857 who varied the construction by placing the crown lens in front, thus having all three faces concave towards the stop; and by J. H. Dallmeyer who in 1865 suggested splitting the crown component into two, placing one on each side of the flint lens. In this way he was able to cover a field of 37° from the axis. This represented the limit to which these simple types of landscape lens could be carried, before the introduction of the "new" glasses.

THE PORTRAIT LENS

In the early days of the Daguerrotype, a simple landscape lens working at $f/11$ or $f/16$ could be made to give useful photographs of extended objects outdoors, by allowing a sufficiently long exposure, but it was of far too small an aperture for easy portraiture indoors. The story goes that a Professor Ettingshausen saw the Daguerrotype process in operation in Paris in 1840, and realized what an advantage it would be to have a lens of much larger relative aperture. He therefore approached Professor J. Petzval of Vienna, a mathematician only 33 years old, suggesting that he should try to design such a lens. Within about a year, Petzval had

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[1] The substance of an Invited Paper given at the Annual Meeting of the Optical Society of America, October, 1933.

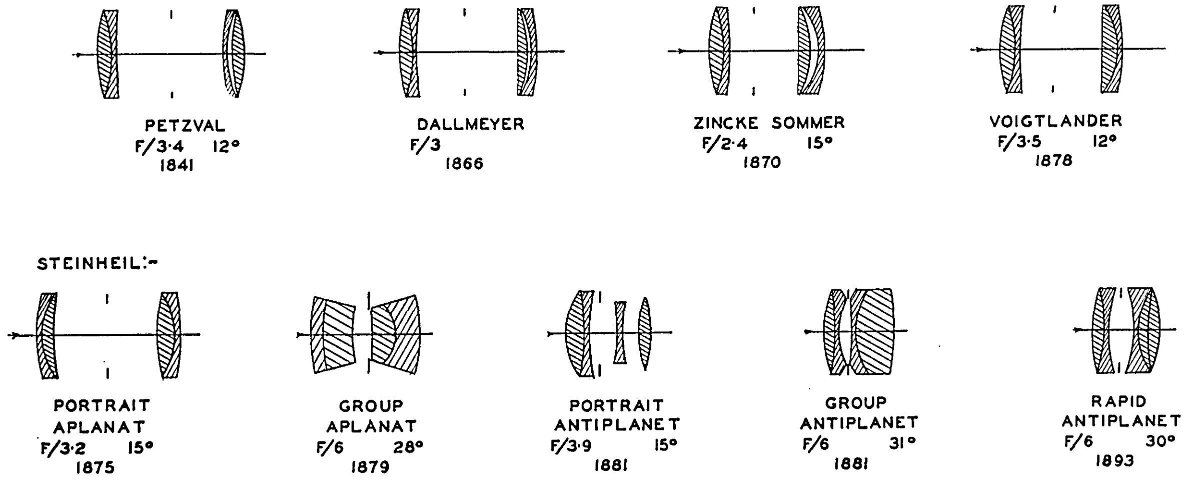

FIG. 1. Some portrait lens types.

produced the required design for a lens of aperture $f/3.4$, giving good definition over a field of 10° or 12° from the axis. This was amply large enough for ordinary portraiture, as it is in fact a real advantage if the surrounding objects are not quite so sharply focussed as the subject himself. The lens was made by the firm of Voigtländer of Brunswick.

This portrait lens of Petzval (Fig. 1) was an amazing accomplishment. Unfortunately we do not know by what methods he worked, but whatever they were, he had to invent and develop his procedure as he went along. He had no hint whatever from other lenses, and the only glasses available were ordinary crown and flint. It is not too much to say that his lens made portrait photography possible, and its popularity has been such that it is still manufactured and used in considerable numbers; it was the fastest lens made until about 1910 when anastigmats of greater aperture became available.

The original lens of Petzval was improved in subsequent years by other designers, notably by J. H. Dallmeyer in 1866 (Fig. 1), who inverted the order of the separated components of the rear element, thus increasing the aperture somewhat; by H. Zincke Sommer in 1870 who raised the aperture to $f/2.4$ and the semi-field to 15°; and lastly by Voigtländer in 1878 who contrived to cement the back element as well as the front, thus removing two glass-air surfaces. R. Steinheil in 1875–1893 designed and made a number of interesting lenses under the names of "aplanats" and "antiplanets," for portrait and group photography, in which he tried to flatten the field by a partial fulfillment of the Petzval theorem (see below). These lenses were introduced too late, and were superseded by the anastigmats before their merits were recognized.

EFFECTS OF GLASS-AIR SURFACES

Each glass-air surface in a lens reflects back some 5 percent of all the light that falls upon it. This makes some diminution of the brightness of the picture, but its most serious effect occurs when this once-reflected light is again reflected, this time back into the camera. Consequently a lens having many glass-air surfaces sends much stray light into the camera, tending to illuminate the shadows and give a flat-looking, non-contrasty picture. Sometimes, too, these repeated internal reflections give rise to real images of distant objects, or of the iris diaphragm, which may happen to come sufficiently near the photographic plate to form a "flare spot" or ghost image. This scattering of light by glass-air surfaces accounts for the high degree of brightness and contrast noticeable in photographs taken with a camera equipped with a simple landscape lens, as compared with the same photograph taken with a complex anastigmat.

THEORETICAL ADVANCES

Although Gauss in 1841 had developed the paraxial theory of lenses very completely by his discussion of principal planes, no systematic

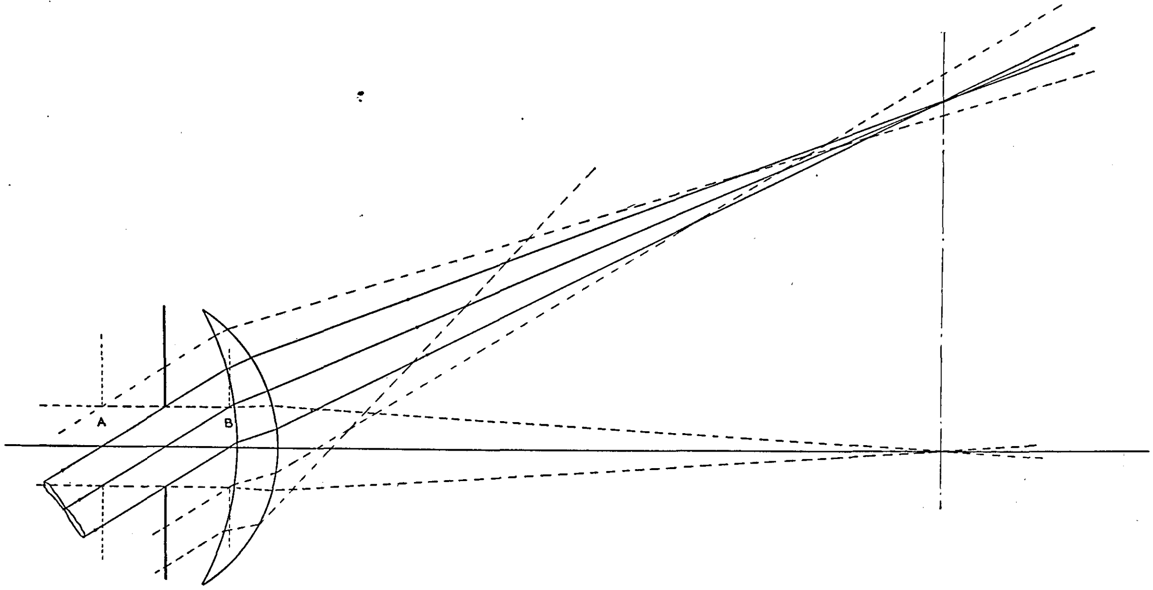

FIG. 2. Path of rays through a landscape lens.

study of the aberrations had been made until 1855 when Seidel published a number of epoch-making papers on the theory of lenses. He recognized five separate "aberrations," now well known as spherical aberration, coma, astigmatism, curvature of field, and distortion. Seidel's formulae[2] for the magnitude of these aberrations in a given case are still used, although sometimes in a somewhat modified form, by designers today.

One of the most fundamental and useful laws arising from the general theory of lenses is that giving the effects of shifting the stop along the axis, on the magnitude of the aberrations. It is clear from the diagram (Fig. 2) that the presence of the stop serves to isolate a narrow bundle of rays out of the entire incident beam, and that a stop at a different distance from the lens would isolate a quite different bundle, coming to a focus of a different sort and at a different position. For example, a stop at the position marked *A* in Fig. 2 would isolate a bundle of which the upper and lower rays cross at a point decidedly below the central ray, whereas if the stop were at *B*, the upper and lower rays would cross above the central ray. Hence if the stop is close to the lens, the image has large negative coma, and if it is too far from the lens, the coma is positive. It is to be expected that at one particular position, the coma will be entirely corrected, which is indeed the case. It should be noticed too that this stop position for zero coma also isolates those rays which will give a field turned as far away from the lens as possible.

The algebraic statement[3] of the effect of stop-shifts on the various aberrations is given by these equations:

$$Sph^* = Sph,$$

$$Coma^* = Coma + K \cdot Sph,$$

$$Ast^* = Ast + 2K \cdot Coma + K^2 \cdot Sph,$$

$$Ptz^* = Ptz,$$

$$Dist^* = Dist + \tfrac{1}{2}K \cdot Ptz + 3K \cdot Ast + 3K^2 \cdot Coma + K^3 \cdot Sph.$$

Here the asterisk indicates the changed value of an aberration due to a stop shift defined by the quantity *K*. Thus we notice that if a lens has some spherical aberration as well as some coma, the coma may be removed by a suitable value of *K*, i.e., by a suitable choice of stop position. We can now appreciate the process of designing a

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[2] M. Born, *Optik.* (Springer), page 101.

[3] A. E. Conrady, *Applied Optics and Optical Design,* (Oxford), page 343.

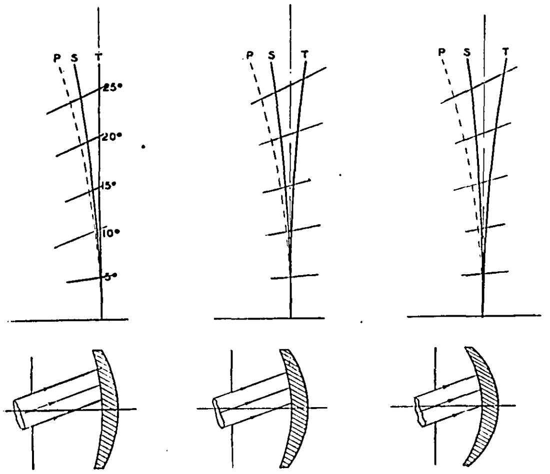

FIG. 3. Effect of bending a simple landscape lens.

landscape lens. Such a lens must have some spherical aberration in it, in order that its coma (a far more serious defect in a photographic lens) may be removed by a suitable choice of stop position. Having removed the coma, rays are traced through this stop to determine the curvature of field. Then the shape, or "bending," of the lens is changed and the process repeated until the curvature of field is what is required. In Fig. 3 three shapes of a simple Wollaston meniscus lens are shown in each of which the stop has been placed at the correct position for the elimination of coma, and the shapes of the sagittal and tangential fields are shown. (The "sagittal field" is the surface containing the foci of radial lines in the image; the "tangential field" contains the foci of lines lying tangential to the field.) It should be noticed that in Fig. 3 there is a fixed dotted curve shown in each diagram, and that the tangential image at any given obliquity is always about three times as far from this dotted curve as the sagittal image. This dotted curve is the "Petzval surface" and represents the curvature of the field as computed by paraxial formulae, in the absence of any astigmatism. It has a very constant curvature, depending only on the structure of the lens, and not at all on the distance of the object or on the stop position. It is represented by the symbol *Ptz* in the list of stop-shift effects on page 75. The possible modes of distribution of the astigmatic focal lines relative to this Petzval surface are shown in Fig. 4, corresponding to various values of the astigmatism, negative, zero, and positive, respectively. Hence if the Petzval field is curved, there must be either curvature of field or astigmatism or both present; but if the Petzval field is flat, then zero astigmatism is automatically accompanied by a flat field.

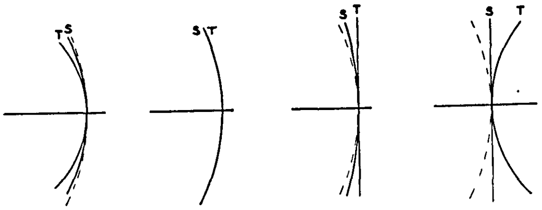

FIG. 4. Astigmatism. Relation between Petzval surface and image curves.

Since with simple thin lenses this Petzval surface is inevitable, the designer has to decide how he will compromise between curvature of field and astigmatism in designing his lens. A favorite choice is to have as flat a tangential field as possible; but many lenses are made in which other compromises have been adopted.

DISTORTIONLESS LENSES

About the year 1858, the wet collodion process of photography had become definitely established, thus making indoor architectural photography possible with landscape lenses; then for the first time the inevitable distortion of those lenses became sufficiently marked to be objectionable. J. T. Goddard, in 1859, therefore attempted to design some lenses in which distortion was considerably reduced. The first, his "Double Periscopic" consisted of the simple meniscus lens of Wollaston's "Periscopic" type together with a zero-power meniscus-shaped doublet placed between the stop and the lens. This design was subsequently improved by T. Dallmeyer in 1888 in his "Rectilinear Landscape" lens. Other workers suggested various distortionless lenses (Fig. 5), which soon tended to become symmetrical about a central stop. There are so many advantages in the use of a symmetrical construction as to deserve a special study.

SYMMETRICAL LENSES

About 1860 it gradually began to be realized that a lens symmetrical about a central stop is

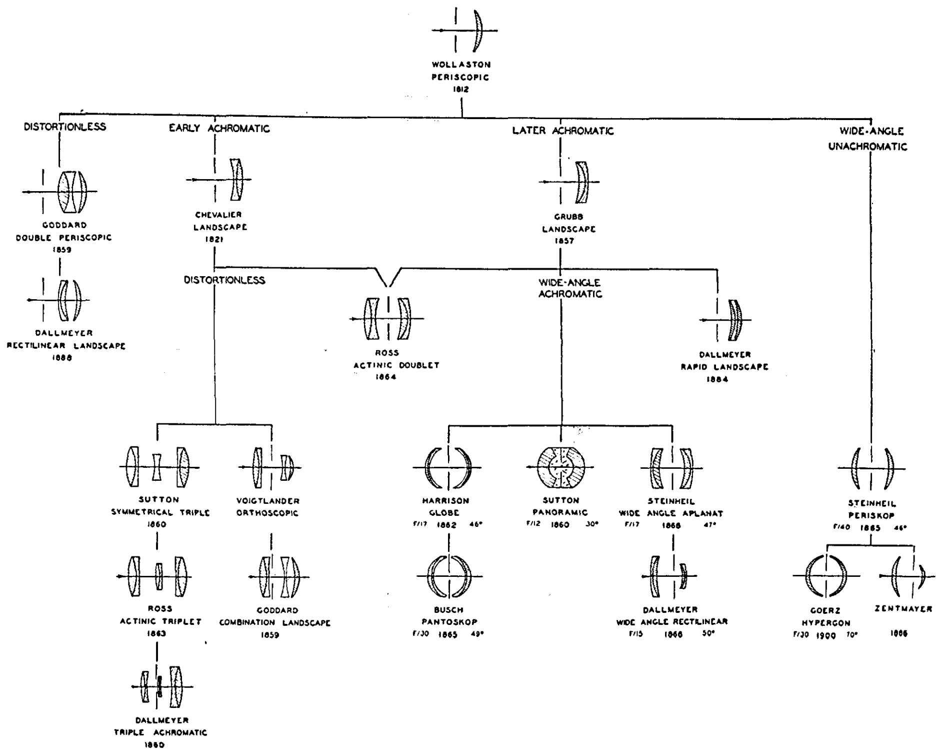

FIG. 5. Early landscape and wide-angle types. (Not corrected for spherical aberration.)

automatically corrected for distortion, merely by virtue of its symmetrical construction. Moreover, such a lens is automatically freed also from the other transverse aberrations, coma and transverse chromatic aberration. A deeper analysis by R. H. Bow and T. Sutton showed that these corrections are not complete except for unit magnification, but that distortion and transverse chromatic aberration are corrected if the system is spherically and chromatically corrected relative to the entrance and exit pupils. But even if this condition is not perfectly satisfied, these three transverse aberrations are still greatly reduced in magnitude.

Symmetrical lenses had been made by T. Davidson in 1841, who placed two Chevalier landscape lenses face to face about a central stop, and by G. Cundell in 1844 who did the same thing with two Wollaston periscopic lenses. Neither of these men, however, appears to have realized the advantages of the symmetrical construction and the double lenses never became popular.

From 1860 to 1866, a craze came in for making lenses to cover a field of an extremely wide angle. Sutton in 1860 invented his "Panoramic" lens, containing water, with a butterfly diaphragm to equalize the illumination over the field. This lens covered a field of 30° from the axis, at an aperture of $f/12$. In 1862, Harrison and Schnitzer of New York produced the "Globe" lens, so called because its outer surfaces formed part of a single sphere. This was very popular for a considerable time, and covered a field of 46° from the axis at $F/17$. This lens was later modified by Busch in 1865 as the "Pantoskop," covering 49° at $F/30$. In 1865, A. Steinheil produced the "Periskop," consisting, like Cundell's lens, of two identical simple Wollaston menisci face to face. This covered a 46° field at $f/40$, but suffered from a difference between actinic and visual foci, since it was unachromatized. Zentmayer, in Philadelphia, suggested making a hemisymmetrical doublet like the Periskop, in which the rear element was a small-scale model of the front element. A real advance was made by T. Ross in

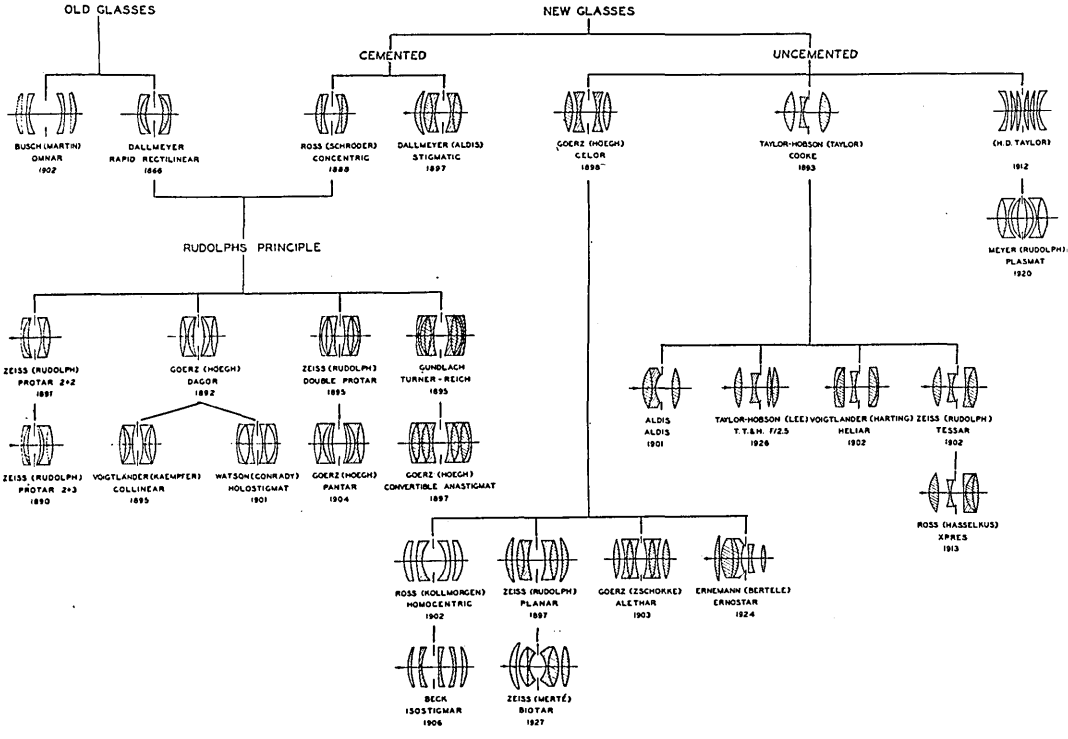

FIG. 6. The chief anastigmat types.

1864, who combined together two achromats, one of the Chevalier type and the other of the Grubb type, to make the "Actinic Doublet." A diagram of this lens suggests the later "Protar" of Zeiss, but it was of quite dissimilar construction. The climax of the wide-angle craze was reached by Goerz in 1900 with the unachromatized "Hypergon," which covers a field of no less than 70° from the axis at an aperture of $f/30$.

By far the most successful symmetrical lens was the "Rapid Rectilinear" which was introduced simultaneously and independently by Dallmeyer and Steinheil in 1866. In appearance, this resembled two identical Grubb achromatic landscape lenses facing a central stop (Fig. 6), but the construction was in reality quite different. If we refer again to the formulae giving the effects of a shift in the stop position on the aberrations, we see that a suitable choice of stop position may be used to remove astigmatism if the lens has some coma, even if it is spherically corrected. By then arranging two such lenses symmetrically about a central stop, coma is automatically removed, no matter how much coma is present in the separate components. The components of a Rapid Rectilinear lens, therefore, are spherically corrected, and have large coma which is made use of to remove astigmatism by a suitable choice of stop position. Hence, by putting two such lenses together, we get a symmetrical system, which is corrected for spherical and chromatic aberration in each element; for coma, transverse chromatic aberration, and distortion by virtue of the symmetry; and for astigmatism or any desired compromise between astigmatism and Petzval curvature by a suitable separation between lens and stop. This lens, commonly called an R.R., worked at $f/8$ or $f/7$ and covered a field of some 25° from the axis very well. The only difference between Dallmeyer's R.R. and Steinheil's Aplanat was the choice of glass, as Dallmeyer used ordinary crown and flint, whereas Steinheil used light and dense flint glass. It was made by almost every manufacturer and has been an immensely popular lens for 40 years; its manufacture was only reluctantly given up about the time of the great war. The separate elements of an R.R.

cannot be used alone because of the bad coma, but the whole system was a huge improvement over all previous lenses, except portrait lenses, in that it was spherically corrected and consequently could be made to work up to $f/8$. It had only four glass-air surfaces, and the whole system was sufficiently compact to reduce the vignetting effect of the barrel to a reasonable minimum. The R.R. lens completely superseded all the existing types with the exception of the Portrait Lens and the simple and achromatic landscape lenses.

THE PETZVAL THEOREM

In order to understand the nature of the complete revolution in lens designing which occurred when Abbe and Schott introduced the new barium glasses in 1886, we must consider in some detail the Petzval surface which has already been mentioned several times.

If a lens is used to form an image of an extended plane object perpendicular to the lens axis, it is evident that the middle of the object will be closer to the lens than the outer parts of the object. Hence we should expect the outer parts of the image to be decidedly closer to the lens than the middle of the image. This is the cause of the curvature of field produced by a lens. The radius of this curvature,[4] in the *central* part of the field, assuming a lens of *small* aperture, is given by R where $(1/R)=\sum[(N'-N)/rNN']$. In this paraxial formula, r represents the radius of curvature of a refracting surface, in the lens, separating media of index N and N', respectively, the summation being made for all the surfaces of the complete lens system. Thus the radius of curvature of the field is independent of the separations of the surfaces, the object distance, and the stop position. This theorem is commonly ascribed to Petzval, but it was known much before his time being stated and proved in Coddington's *Optics* which was published in 1829.

Previous to 1886, the only glass types available were those obtained by adding successively increasing amounts of lead to ordinary crown glass. Table I shows some typical "old" glasses.

TABLE I.

Type	Index N	Abbe number V
Hard crown	1.5175	60.5
Extra light flint	1.5290	51.6
Light flint	1.5427	47.5
Light flint	1.5746	41.4
Dense flint	1.6041	37.8
Very dense flint	1.6501	33.6
Very dense flint	1.7402	28.4

If we attempt to find practical methods of satisfying the Petzval condition, three interesting cases arise:

(a) *A single lens.* In this case, the Petzval condition becomes $r_1=r_2$. Thus the lens will only have any positive power if it is made thick and of a meniscus form. This explains the predominance of thick meniscus lenses in photographic objectives, notably in Steinheil's "Group Aplanat."

(b) *A separated achromat.* If it is required to fulfil the conditions both for achromatism and for the Petzval sum, it is necessary to have a separated combination of a convex crown and a concave flint lens, the separation between them being chosen so as to satisfy this condition.

$$(V/N)_a(1-m)^2=(V/N)_b.$$

Here suffixes a and b refer to the crown and flint lenses, respectively, and m is the ratio of the separation to the focal length of the crown lens (a). For example, by using ordinary hard crown and dense flint glasses, $(V/N)_a=39.5$, and $(V/N)_b=22.2$; thus a value of $m=0.27$ will serve to satisfy both the required conditions. This method of making an achromatic lens which also fulfils the Petzval condition seems to have been overlooked until K. Martin, of the Busch Company, designed his "Omnar" lens in 1902 based on this principle.

(c) *A cemented achromat.* Here the condition is that $(V/N)_a=(V/N)_b$, since m in the last paragraph is zero. This condition requires that the V's and N's of the two glasses should rise and fall together. A glance at the list of old glasses given above shows that the use of lead in the glass makes the N rise and the V fall, which is opposite to the requirements of the Petzval theorem. Consequently Abbe and Schott in 1880 tried to produce glasses of high index and high V, which could be used with a light flint of low index and

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L. C. Martin, *Applied Optics*, Vol. I, page 139.

relatively low V, to produce a thin achromat having a flat field. Their efforts were successful in 1886 when they discovered the barium crown glasses, which have just the desired property.

To show the extent of their success, it is of interest to compare the two pairs of glasses given in Table II. It is clear how much more nearly alike are the values of V/N for the new glass pair as compared with old. It should be noted also how the V and N rise and fall together in the new achromat combination.

TABLE II.

Old achromat				New achromat			
	N	V	V/N		N	V	V/N
ELF	1.5290	51.6	33.8	DBC	1.6234	56.3	34.7
LF	1.5632	42.9	27.4	LF	1.5427	47.5	30.8
	(diff.)	8.7	6.4		(diff.)	8.8	3.9

RUDOLPH'S PRINCIPLE

As soon as the new glasses were available, four or five designers at once attempted to use them in lenses. H. S. Schröder at the firm of Ross, in 1888, made a kind of Rapid Rectilinear lens with the new glasses, which was issued under the name of "Concentric," but it was not remarkably successful and was later replaced by the "Homocentric." Miethe, in the same year, designed a lens using the phosphate and borate glasses which Schott introduced at the same time as the barium glasses, but they were unstable and were later withdrawn. Mittenzwei also designed a cemented triple lens with an aperture of $f/3.4$ for portraiture; but none of these early attempts was particularly successful.

The first really successful design using the new glasses as a means of flattening the field was made by Dr. P. Rudolph, of the Zeiss Company, in 1890. He found that by making a kind of unsymmetrical Rapid Rectilinear lens, using old glasses for the front element and new glasses for the rear element, and by making the front element of zero focal power, he could make the astigmatism and Petzval curvature of the front element equal and opposite to those arising at the rear element, at the same time correcting the various other important aberrations. In the front element the contact face was dispersive, and in the rear element, owing to the abnormal order of the refractive index, it was collective; he therefore called this the "Principle of the Opposed Gradation of Refractive Indices."

A number of series of these lenses were made, of aperture from $f/4.5$ to $f/18$, covering fields of from 20° to 45° from the axis. The rear element was either a doublet for low apertures or a triplet for the larger apertures. The definition was excellent over the entire picture, and the field extremely flat. This lens was originally called the "Anastigmat," but the name was later changed to "Protar" when the word anastigmat became adopted as the generic term for all lenses having a reduced value of the Petzval sum. It is still made, especially as a wide-angle lens of about $f/12$ aperture.

In 1891, Dr. Rudolph tried to combine the normal and anomalous pairs of glasses into a single unit, by using three lenses cemented together, the central one being concave and the others convex, such that the index steadily advanced from lens to lens, and the V-value was least for the central lens. An imaginary line through the middle lens would divide the system into two parts, the front part being an old achromat and the rear part a new achromat. In this way he produced the "Triple Protar," which was however improved in 1902 as the "Ortho Protar" by using a strong biconvex central lens with a weak negative lens cemented on each side of it, making a meniscus outer form. Here again the index steadily increased from one end of the system to the other. In 1894, Rudolph produced the "Quadruple Protar" in which an old and a new achromat were cemented directly together, with their inner glasses being now quite dissimilar thus making a wider field possible with better corrections. This lens was convertible, meaning that each half could be used alone, or combined with another lens of the same type but built to a larger or smaller scale. In order that the separate units of a symmetrical lens may be used alone, each element must be independently corrected for coma and transverse chromatic aberration and distortion, since the symmetrical principle cannot now be invoked to correct those transverse aberrations. Thus the problem of designing a convertible lens is much harder than that of designing a symmetrical nonconvertible lens such as the Rapid Rectilinear, the Celor, or the Planar.

Von Höegh of the firm of Goerz followed closely on Rudolph's footsteps in designing lenses of these types, producing in 1892 the "Dagor" which is extremely similar to the "Triple Protar" of Rudolph. He also designed in 1897 a quintuple cemented convertible combination which was soon abandoned on account of the expense of its construction. He also developed a quadruple cemented system in 1904 under the name of "Pantar," in which Rudolph's principle was used to give the required corrections.

The convertible lens reached its peak of popularity between about 1890 and 1905. The success of this type was really due to the invention of the dry plate in 1878. The photographer using the old "wet" plates had to carry such a huge amount of equipment when out on a photographic expedition, that a few extra lenses made no appreciable addition to his load, but when the much simpler field cameras with long bellows, and dry plates, became popular, the convertible "set" of lenses with a maximum aperture of *f*/6 (and later *f*/4.5) was ideal for such a camera. However, by about 1900, the hand camera, and especially the roll-film camera, had become so popular as to be almost universally used, and the covertible lens could then no longer be employed, as there was not sufficient bellows extension available and frequently no ground glass screen for focusing. It has therefore almost disappeared from the market.

THE CELOR TYPE AND ITS MODIFICATIONS

Turning back once again to the discussion of the Petzval theorem given above, it was there shown that this awkward condition can be satisfied by suitably separating the components of an achromatic lens. Such a separated achromat suffers from bad transverse chromatic aberration, but by arranging two similar lenses about a central stop, this is automatically eliminated by the symmetrical principle and a good anastigmat can be produced. Von Höegh's "Celor" of 1898 was of this type, a barium crown being used with a light flint, in order to reduce the separation as much as possible. The process of the design is similar to that of the Rapid Rectilinear lens, but a new degree of freedom is available as we now have two separate lenses each of which may be "bent" independently of the other. By departing from strict symmetry, improvements can be made, and von Höegh in 1907 managed to raise the aperture of the Celor successfully to *f*/3.5. Several other designs of this type were made by Zschokke and Urban, of the Goerz Company; and the same general type was adopted by Steinheil in his "Unofocal" (1901) which was a symmetrical lens with a rather wide airspace between the lenses in each element. It is so called because all four component lenses have equal focal length and the same refractive index but different dispersions. The "Homocentric" of Ross, designed by Kollmorgen, was issued in 1902, which had the same general form as the Celor but all the lenses were menisci; and the Beck "Isostigmar" of 1906 had no less than five separate single lenses, the fifth being an additional negative lens placed between the other two. The presence of ten glass-air reflecting surfaces is a very real disadvantage in this type of design. K. Martin, of the Busch company, produced the Omnar in 1902, using only old glasses.

Other important modifications of the simple Celor type have been made. The chief of these is Rudolph's Planar of 1897, which was a symmetrical lens like the Celor but in which each negative lens was made into a hyperchromatic cemented negative doublet. This increased the negative chromatic aberration of the negative lenses, and was equivalent to making them of a much more dispersing glass. This lens covered a semifield of 25° at an aperture of *f*/3.3, and has been made by many other firms since. By making the Planar decidedly unsymmetrical, the Zeiss "Biotar" with an aperture of *f*/1.4 for 16 mm motion pictures, was produced in 1927.

Another remarkable modification of the Celor was the "Ernostar," made by the Ernemann Company in 1924. This lens successfully covered a picture $2\frac{1}{4} \times 3\frac{1}{4}$ inches in size at an aperture of *f*/1.8, a performance surpassing anything up to that time. The first negative lens was made into a thick cemented triplet, and the lens was entirely unsymmetrical (Fig. 6).

One of the most outstanding types of anastigmats ever produced was the "Cooke" lens designed by H. Dennis Taylor in 1893. This looks like a Celor in which the two negative lenses have been combined into a single lens, but actually a Cooke lens is designed directly from first principles and is not a modified symmetrical lens. The three lenses in it have very little power if placed into close contact, fulfilment of the Petzval condition being thus secured, the focal power being obtained by separating the elements suitably. The simplicity and cheapness of the Cooke lens has attracted many manufacturers, but the chief maker is still the original one, namely Taylor, Taylor and Hobson of Leicester, England. In 1926 Lee attained an aperture of $f/2.5$ by splitting the rear convex lens into two closely placed thin convex lenses.

Other modifications of the Cooke type are shown on the right-hand side of Fig. 6, of which the most famous lens is the Zeiss "Tessar," designed by Rudolph in 1902 and improved by Wandersleb in 1907, which is like a Cooke lens with the rear element made into a cemented doublet. This has been made by many firms in many sizes and variations, the maximum aperture being about $f/3.5$. The Ross "Xpres," designed in 1913 by Stuart and Hasselkus may be regarded as a Tessar in which the rear element is a cemented triplet instead of a doublet. Another popular type is the "Aldis" lens, which resembles a Cooke in which the first airspace has been removed by cementing lenses I and II together. The front doublet has no focal power, but is used merely to remove the aberrations of the rear biconvex simple lens.

Attempts have been made to design a lens of the Celor type in which the convex elements are inside, adjacent to the stop, and the concave elements are outside. H. D. Taylor patented such a design in 1912, in which he found it necessary to split each convex lens into two, thus giving twelve glass-air surfaces! A more successful design was the "Plasmat" designed by Rudolph in 1920 and manufactured by the firm of Meyer in Goerlitz. Each element of this lens is like the opposite element of the Planar. This lens has been constructed in apertures up to $f/1.5$ for motion picture purposes.

TELEPHOTO LENSES

A Telephoto lens is simply one consisting of a convex front element and a concave rear element, separated by a considerable distance, so that the second principal point of the whole system is out in front of the convex element. Under these circumstances, the true focal length, which determines the size of the picture, is much greater than the back focus, which determines the "bellows-extension" of the camera. "Telephoto Magnification" is taken as being the ratio of the true focal length to the back focus.

The earliest recorded application[5] of such a lens to photography is the use of a Galilean telescope thrown out of focus, by I. Porro in 1851. This was followed in 1891 by specially designed achromatic negative lenses which were to be used behind an ordinary photographic lens as a "telenegative" lens. Unfortunately, there is a theorem that it is impossible to get a flat tangential field by combining two aplanatic lenses either of which has a curved field. Hence a thin telenegative lens used with a fully corrected positive lens must give a curved field if the final image is to be free from spherical aberration and coma. However, at $f/11$ or less, the telenegative lens was fairly useful, especially as the magnification could be varied by altering the separation of the two systems, but even this led to trouble because the spherical aberration of the negative lens could only be corrected for one separation.

The user of telephoto lenses at first thought he wanted a magnification of at least 8 times, but he gradually realized that 2 or 3 times is all he really needed. Consequently, and with great improvement in the image, Zeiss in 1898 produced a complete telephoto lens, in which the power was 2× to 3× and the aperture $f/6$ to $f/10$. This lens was followed by many others of a similar type, notably the fixed-focus Busch "Bis-Telar" telephoto lens designed by Martin in 1906, which had a magnification of 2 and an aperture of $f/7$; and the Zeiss "Magnar" of Rudolph and Wanderslab, which magnified 3 times at $f/10$.

In 1902, Dallmeyer produced the "Adon," which was a small 2× or 3× afocal Galilean

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[5] Waterhouse, Proc. Opt. Convention 1905, p. 115.

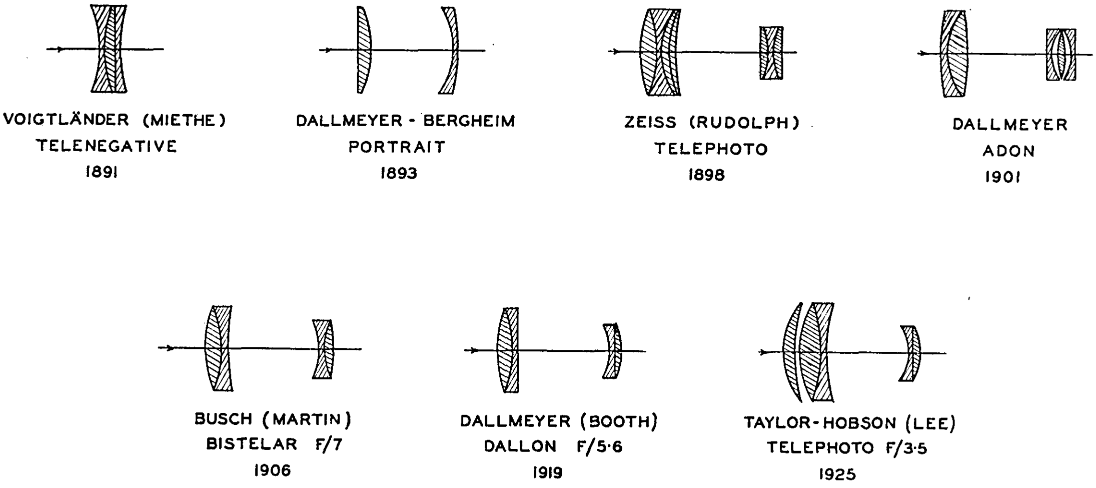

FIG. 7. Some telephoto lenses.

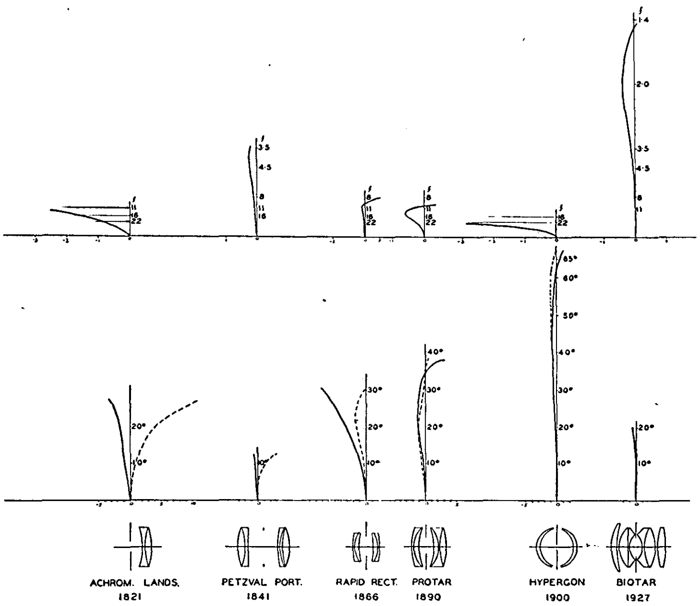

FIG. 8. Aberration and field curves.

telescope made to slip on in front of the ordinary camera lens. Soon it was found that the Adon could with slight alteration be used separately as a telephoto lens, and it was subsequently (1912) enlarged to an aperture of $f/4.5$ or $f/6$ as a separate telephoto system. In 1914, Booth[6] designed the Cooke telephoto lens of aperture $f/5.6$, and 2× magnification, which started the move towards large apertures, and he followed this by the Dallmeyer "Dallon," $f/5.6$, in 1918. Other firms followed this plan, which reached a climax in the Cooke 2× telephoto $f/3.5$ designed by Lee in 1925; and the Cooke Distortionless telephoto $f/5.0$, magnification 2.3, also designed by Lee (Fig. 7).

An interesting use of a reversed telephoto lens placed with the concave element facing the distant object and the convex element towards

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[6] Booth, Proc. Opt. Convention 1926, 861–877.

the plate, is seen in Hill's lens for whole-sky photography.[7]

THE FUTURE

The possibilities open to a designer in developing new lens types are almost unlimited, except that he must use only the available varieties of glass. Most new types have been introduced in an effort to achieve a greater aperture or a greater angular field or both, to improve the distribution of inevitable aberration residuals, to reduce the number of glass-air surfaces, or to cheapen existing designs. Another potent factor is the avoidance of patents held by other manufacturers. Attempts have been made, also, to improve the uniformity of illumination over the field by shortening the overall length of the lens barrel, or by making the lenses larger in diameter than the greatest stop with which they are used.

An indication of the progress that has been made is seen in Fig. 8. In the upper diagrams, spherical aberration is shown plotted against aperture, and in the lower diagrams are shown the sagittal (dotted) and tangential (full) field curves.

The tendency today is towards greater and greater relative apertures, mainly for use in motion picture work where fields of frequently only 8° to 10° from the axis are used. The climax is at present the Zeiss "R-Biotar" with an aperture of $f/0.75$, which covers a 16-mm picture with a focal length of 50-mm, representing an angular field of only 9° from the axis. More rapid photographic materials lead to a demand for faster lenses, because new possibilities in indoor photography under low illumination, etc., become available, which were not contemplated 10 years ago. Moreover, it happens very fortunately that this demand for faster lenses is largely in the motion-picture field, where only very short focal lengths are needed. Now, as the focal length of a lens of given construction is reduced, the aberrations are reduced in proportion, while the permissible *tolerances* remain unchanged. Thus much greater relative apertures become possible in lenses of small size than in similar lenses of larger size.

The zonal residual spherical aberration of these large-aperture lenses often becomes so large that attempts have been made to produce aspheric surfaces to reduce it. A simple and accurate means of generating nonspherical surfaces of any desired form would revolutionize the whole science of lens design, and would make possible simple types of lenses having apertures and fields at present quite unattainable. This would be further helped very greatly by a wider range of available glass types, especially glasses with a high index and also a high V-value, beyond anything at present available in dense barium crown glass. As far as theory is concerned a new calculus is really required, that will enable us easily to take a light-wave of a given form, follow it along to the image, and determine the light distribution in that image in a few minutes! Such a determination, if available, would make interferometer methods of lens testing of much greater value to lens designers than they are at present.

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[7] Proc. Opt. Convention 1926, 878.