Photographic Lenses

and how they are made

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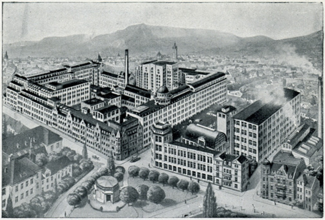

The Carl Zeiss Works

at Jena

MANY interesting and instructive volumes have been written on the subject of photographic lenses, but in the main these have treated of the construction of the finished product rather than the methods used to achieve such results.

The constant growth of the use of anastigmat lenses has led us to believe that a treatise on the production of a modern photographic lens from its very beginning would at least prove to be of interest to both the owner and prospective owner of such lenses.

For obvious reasons we have used the famous Carl Zeiss works at Jena as an example, but the methods described may be that of any manufacturer of high grade objectives.

If, therefore, our story will enable the reader to gain a clearer insight into the whys and wherefores of anastigmat lenses, it will not have been written in vain.

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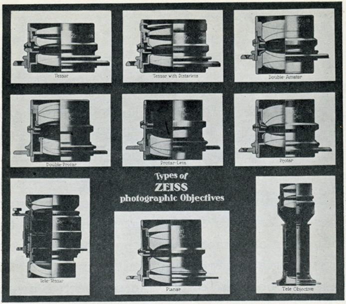
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Photographic Lenses
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THE history of the development of the photographic lens furnishes the key to all other progress in photography, for every advance in the chemistry and practice of photography has had its pace set by the optical capacity of the photographic lens, and so it has come about that a height of development has been attained which far transcends the wildest imagination of the past. Yet how many people are there who have an adequate conception of the infinite amount of genius and toil which lies recorded in the life history of a modern photographic lens? Such a lens is indeed so wonderful an epitome of mental effort and mechanical skill that it may be worth our while to retrace its path from the computer's mind to the photographic camera.

The photographic objectives, as now used for practical purposes, consist of a more or less extensive number of component lenses. It may be asked why this should be so, since it is well known that an ordinary reading glass is capable of producing upon the ground glass screen of the camera an image of external objects. This is true enough, but so soon as we proceed to examine such an image more closely, we shall see that it is hopelessly defective. Its general sharpness leaves much to be desired, and such as it is, it rapidly declines from the middle to the edge of the image. These defects may not be so very striking when the image is viewed as a camera obscura picture, but they stand out in all their glaring intensity when recorded upon the photographic plate. Photography here introduces requirements which at once places the photographic lens in the category of difficult problems, and indeed it has taken generations to solve them step by step. A single lens cannot fulfill these requirements to any degree, and it needs therefore a combination of several lenses to overcome the many defects which arise. Modern photographic lenses are accordingly composed of a considerable number of lenses. In most cases they comprise 4, 6, indeed 8, and even 10 lenses associated to form an objective. From this it must not be thought that the mere number of component lenses of which an objective is made up is a criterion of its quality.

Note the construction of the *Zeiss Double Amatar.* The combination consists of six lenses arranged in sets of three cemented together with Canada balsam. Each of the three front lenses, or of the three back lenses, is made of a distinct kind of glass. Why this is so you will see later. *The Zeiss Tessar* construction is comparatively simple, for it consists only of four thin lenses, two of which are cemented together, while the other pair is separated by a stratum of air, forming the so-called air-space lens. While the objective is simple enough as far as the mere number of lenses is concerned, its actual manufacture demands an extreme degree of precision: the distance between the lenses, for example, requires to be exact within 1-100 millimetre or 1-2500th part of an inch.

Let us now see what are the essential defects of a simple lens which stand in the way of the formation of sharply defined images and which force the optician to employ such complicated means.

We cannot possibly attempt to enter into the theory of the photographic lens, but we shall do well to briefly consider the general aspect of lens defects.

The rays which fall upon a converging lens, such as an ordinary reading glass, near the rim of the lens are refracted towards the axis in a more pronounced degree than those which are incident at the middle. In consequence rays which proceed from a point are not made to meet exactly at another point, and hence the resulting image of the point is far from sharp. The defect which arises from this source is called *spherical aberration*.

White daylight, as well as the light from artificial sources, consists of rays of different colors and qualities, which in the aggregate constitute what we know as white light. These rays of different qualities are refracted by a lens in different degrees, which occasions a further species of image defects. These defects are comprised under the term "*chromatic aberration*." They are far more pronounced in the case of oblique and skew rays than in that of rays that are parallel to the axis, so that the sharpness of the image deteriorates very rapidly from the centre to the edge. Since both these defects are turned to advantage in the making of soft focus lenses, they will be more fully explained under that heading.

A simple lens, moreover, fails to reproduce straight lines near the edge of the image as *straight lines*. On the contrary it gives rise to distortions which very frequently entirely vitiate the picture. The nature and intensity of these distortions depend upon the form of the lens and the position of the stop.

Again, the image formed by a simple lens does not lie in one plane, but on a spherical surface, and hence it is impossible to obtain an image which is sharp at the centre, and, *without re-focusing*, also at the edges. Another exceedingly disturbing defect arises from *astigmatism*, which likewise occasions a rapid deterioration of the sharpness of the image towards the edges.

All these defects, with the exception of distortion, can be lessened or removed by the use of small stops, —that is true enough. But this greatly diminishes the light-transmitting power of the lens so that it becomes much too slow for taking instantaneous photographs. Modern photography demands, therefore, objectives in which all these defects are corrected from the outset, so that they will give sharp and undistorted pictures over the entire plate when working at full aperture. The spherical and chromatic aberrations can be removed by cementing together two lenses of appropriate curvatures and made from glasses with different optical properties, so that their defects may be similar but opposite in kind, and so neutralizing the errors. By this means we obtain a landscape lens. Two landscape lenses of this kind facing each other and having a stop in the middle between them form an *aplanatic or Rapid Rectilinear* lens, in which the correction of spherical and chromatic defects goes hand in hand with the elimination of the coma, a form of spherical aberration and distortion. In order that the very objectionable defects, due to astigmatism, may be removed, it is necessary to add further lenses or to construct the objective on a different plan altogether.

For a long time it was thought to be impossible to remove the two last named defects, or at least to remove them both at the same time, since no glasses were then in existence by which theoretical achievements could be translated into fact. When new glasses were discovered it became possible to make great advances in the improvement of photographic lenses, and so lenses came into being in which these two last named defects were entirely absent, or at least reduced to a practically inappreciable amount.

We have observed that the various lens systems are made up of four to eight components which are partly detached and partly cemented lenses. Each of the two or three front or back lenses of a combination consists of distinct kinds of glass which are the outcome of very exact trials. The cementing medium is Canada balsam.

As we have already seen, the glass of which the lenses are made is not an arbitrary matter. On the contrary, this glass must have very definite qualities. Foremost among these qualities are the *refractive index and the color dispersion.* A pencil of light passing through a prism is deflected from its original course. The degree of the deflection depends upon the refractive power of the glass of which the prism is made. The refracted pencil spreads out as it passes through the prism, so that when it reaches a white screen it does not form an exact image of the narrow slit from which it proceeded, but will be seen to have been drawn out into a colored band. The prism does not refract *uniformly* all the colored rays of which the white light is made up. It deflects the violet and blue rays to a greater extent than the green rays and these again to a greater extent than the yellow and red rays. In conesquence, the colored rays of the illuminated slit do not meet in one place, where their mixture would have furnished white light, but are ranged side by side, thereby forming the *spectrum*, of which we have a familiar example in the rainbow. The color dispersion varies widely for different kinds of glass. Many glasses produce long bands, others yield much shorter bands; in some the blue end is more distended, in others this happens at the red end. We thus see why simple lenses, which are simply curved prisms, are bound to have the defect of chromatic aberration.

Formerly it was believed the color dispersion and refractive power were mutually dependent. They are so, as a matter of fact, more or less, but not to anything like the extent as was supposed, at a time when crown and flint glasses only were known. The crown glasses have a comparatively low refractive power and at the same time are only able to form a short spectrum band, whereas in the case of the flint glasses a high refractive power is associated with a considerable amount of dispersion. The manufacture of modern optical glasses, however, has rendered largely fictitious the old distinction between crown and flint glasses, in that now there are glasses which have a comparatively low refractive power and nevertheless furnish spectrum bands of great length and conversely. With two kinds of glass, that is to say, an old crown glass and flint glass, it is not possible to unite more than two colors, say *yellow* and *blue*, at a single point. The remaining rays continue to give rise to a more or less noticeable blurred fringe, which is known as the "secondary spectrum." Photographic lenses with a secondary spectrum are nevertheless well adapted for the ordinary purposes of photography, and it is not till we come to face the problems of three-color photography that it becomes necessary to bring to a common focus other colors of the spectrum, i. e., red. Objectives of this order of correction are called "*apochromatic* lenses." They are now used almost exclusively in photographic process work.

The two classes of the old *crown* and *flint* glasses were for a long time the only means which were available for the construction of lenses. Fraunhofer, at the beginning of the last century, realized that these two kinds did not suffice for the realization of his newly computed telescope objectives. It is not saying too much that Fraunhofer inaugurated by his achievements the era of modern applied optics. It was he who first associated systematic knowledge and a scientific system with the art of lens making, which until then had been a mere matter of handicraft. He was also first to describe exact methods for making strictly spherical surfaces.

Wonderful as were the achievements of Fraunhofer, there still remained a tremendous stride to be taken before the technical methods now in use could be developed. The uncertain element of personal skill has now been superseded in a large degree by a highly organized system of mass production with the assistance of every available developed and minutely elaborated scientific and mechanical refinement. This is apparent in the construction of a combination of lenses. In the old days the optician guided by experience and a more or less trustworthy intuition, would grind lenses by way of a trial, combine them, and then proceed to vary the curvatures of the lenses and their combinations until the desired result was attained in a more or less complete manner.

This procedure by trial and error was a tedious and uncertain business. Fraunhofer was the first to replace it, at least to a considerable extent, by a system of *predetermination*. This method was further developed by Steinheil. It was, however, left to *Prof. Abbe*, the then Director of the University Observatory at Jena and subsequently head of the Carl Zeiss Works, to evolve a complete system of predetermination of *all the data* for the construction of microscopic objectives made by Carl Zeiss. Despite all these achievements there would have been little tangible advance in applied scientific optics, if a want of suitable glasses had been allowed to persistently stand in the way of the improvement of optical instruments. It was Abbe who time and again brought into view the enormous improvements which might be effected if only the requisite glass were at the disposal of the producers of lenses. Inspired by his reiterated utterances, Dr. Otto Schott, who had graduated in the school of the Westphalian glass industry, conceived the idea of varying the optical properties of glass by introducing new materials into their formulas. He became associated with Prof. Abbe, who had at once realized the full significance of these experiments. It is to their systematic combined working that we owe the unexampled development of modern practical optics. As Abbe had done in the making of lenses, so Schott proceeded along strictly scientific lines in his experimental glass smelting operations, in that he systematically investigated the correlations between the optical constants of the glasses and their composition and the effect of the introduction of new constituents. He succeeded in the course of his experiments in producing glasses the properties of which had formerly been a pious dream-wish of investigators, but the fulfillment of which had never been looked for as a realizable thing.

Before we proceed to consider the making of lenses we shall do well to review the process by which the optical lenses are made, and we shall do so in the form of an imaginary tour of inspection through a modern optical glass works, such as the Jena glass works.

While passing the enormous stores of raw materials which the establishment works upon, the uninitiated may find it difficult to realize how the opaque substances which he there sees heaped up, come to furnish the beautifully clear and transparent material which he afterwards sees as glass. Chemically considered, glass is a solid solution of silica and silicates, which are obtained by fusing together quartz sand, soda and lime.

These substances were in the main the raw materials from which the old glasses were made. The materials from which the *new* optical glasses are made include in addition borates, phosphates, barium compounds, lead compounds, and fluorites, hence metals, such as sodium, barium, and lead, are likewise among the constituents of these water-clear glasses. Some kinds of flint glass contain even as much as seventy per cent of their weight of lead and are nevertheless perfectly transparent.

Every kind of glass is obtained by melting a mixture of these compounds, and naturally every glass has its own particular formula.

The technical effect of the fusion of the optical glass is as interesting as its production is difficult. The trouble begins with the preparation of the melting pots, which are made of alumina. The material of which they are made should part with little or nothing to the mass of the melting glass. On the other hand, they must be able to resist the enormous heat of the boiling mass. The pots are accordingly made on the spot. The pots, some five feet in diameter, are stored in a gigantic shed accommodating on the aggregate one thousand pots. Storage of such large numbers is necessary as the pots require to stand for many months, to dry out quite slowly before they may be fired. Before use they are warmed up in special ovens, after which they are charged with the mixture. Every pot holds about two tons of glass material. In the event of the pots having a flaw, such as an externally invisible crack which has formed during the process of drying, it may happen that they burst during the process of melting, with the result that their valuable contents are lost.

The component materials for the various meltings are stored in large siloes. They are mixed mechanically. The mixture is heaped up in the pot and melted down by gaseous fuel at a temperature of about 1500° C. (2750° Fahrenheit.) During the process of melting the raw materials act upon one another and gases form which rise in bubbles within the more or less viscous mass. This is also the reason why it is not possible to obtain optical glass which is entirely free from bubbles. For a long time the success attending these melting operations was very incomplete, and only a small portion of the ingot had the desired properties owing to imperfect mixing. This evil can be overcome to a certain extent by stirring. The idea of stirring the incandescent liquid mass was simple enough, but it is nevertheless an ingenious and most important artifice, which was originated by a Swiss joiner named Guinand, who was the first to melt glass for optical purposes. The stirring is done with the aid of a bar of alumina, which is suspended from a gear within the melting furnace so as to dip vertically into the molten mass, and is moved therein in a circle, until all differences in the constitution of the various parts disappear by mixing. The melting process requires about 18 hours before it is complete. From time to time an experienced operator withdraws a sample from the ingot by means of an iron rod. This test sample supplies a criterion as to whether the homogeneous fusion of the ingot is complete. As soon as this is found to be satisfactory the melting pot with its contents of about two tons of incandescent liquid mass is drawn from the fire by means of large tongs moving on trolleys. The pot, which is white-hot, is transferred to another furnace, where it is allowed to cool down slowly within a week. During this period of cooling the glass contracts and in so doing breaks up into irregular pieces resembling ice blocks. In many cases the pot breaks up as well in consequence of the strains set up by this contraction.

The resulting pieces of glass are then sorted, and cracked pieces are completely severed with a hand hammer, so that any cracks which may already be present may not continue and result in defects when the material comes to be worked up later on. From the resulting broken up pieces the good ones only are selected for the purpose of reducing them to the regular form of plates which the optician receives for making his lenses and prisms.

The rough pieces picked out in this way are then remoulded in a separate re-heating furnace in rectangular moulds of fireclay until the glass becomes viscous, so as to fill the mould. When in this way the glass has assumed the shape of the mould it is subjected to the *fine annealing process*, a very slow cooling which usually requires one month, but in the cases of large pieces may be extended over a period of 2 to 3 months. This slow cooling is necessary to free the glass from *internal strains:* for, though the stirring has the effect of producing a chemically homogeneous glass, stresses are likely to be set up during the process of cooling, which renders it quite useless for optical purposes. Now, any piece of glass in a state of intense compression acquires the properties of crystalline bodies and is double refracting, that is to say, it splits up a single incident ray into two rays. It goes without saying that this is a property which cannot for a moment be tolerated in a photographic lens. Before the glass is passed on to the optician it is therefore carefully tested with respect to internal strains as well as the presence of striae, or veins. This, however, cannot be done without further preparation, for the glass plates as furnished by the re-moulding process are not transparent but have a rough and uneven surface. The plate is therefore roughly ground and polished on two opposite sides, so that the glass may be tested by transmitted light with respect to the presence of bubbles and striae.

Experienced workmen, looking through the polished edges of the plate towards a suitable source of light, such as a mercury vapor lamp, at once recognize those portions of the glass which differ from the adjoining portions by a difference in the light-refracting properties. If we let a drop of sugar solution fall into a tumblerful of water, the sugar solution, being heavier than water, will sink to the bottom, and in doing so it will leave a visible trail which is due to the dilute sugar solution having a refractive index differing from that of pure water. The striae in glass present a very similar appearance. Closely packed fine striae are dangerous enemies, and and any piece of glass containing these is at once rejected. Frequently flaws arise which in their appearance resemble a fine lace texture stretched across the mass of glass. These *cloudy layers* arise from the re-fusion during the remoulding process of a crack in the glass which has escaped observation in the previous tests. The examination for internal strains, which as we have seen, occasions *double refraction* within the glass, is made by polarised light.

Slabs obtained from the ingot are placed side by side over a large black glass mirror set at an appropriate angle and examined through a Nicol prism which travels along a rail. There is a source of light in front of which is placed a Nicol prism, the so-called *polariser*, from which polarised light proceeds to the right towards the observer. This polarised light passes through the glass block in the middle and the latter is carefully examined from place to place by means of a telescope focused upon it. This telescope has mounted in front of it another Nicol prism, the so-called *analyser*. When the polariser and analyser are in such a position relative to each other that the planes of polarization are at right angles to each other, no light will reach the eye of the observer unless refracted out of direct line by the glass being tested. If the glass is normal, no refraction will take place, but if there are any strains in the glass they will give rise to a rotation of the planes of polarization, and show as beautifully colored irregular patches.

In the end it is found after the application of these preliminary tests that about 85 per cent of the whole mass of glass is to be rejected as useless, also that a hundred-weight of glass produced often furnishes only 15 pounds of glass which is adapted for optical purposes. The rejected glass cannot be redeemed by re-melting but has to be sold as waste product to other glass-houses where glass is used for the manufacture of ordinary glassware. For any attempt at re-melting would only have the effect of producing glass in which the flaws to be avoided would be present in a highly accentuated degree.

When glass is required for making lenses over 12 inches in diameter it follows from all this that the pieces obtained from a broken-up pot of glass cannot be used, and it becomes necessary in this case to pour the liquid mass into a large iron mould and allow it to cool therein quite slowly. As before, the surface of this moulded piece is polished at two places on both sides. The usable portions are picked out and trimmed and then re-moulded in the usual way. The glass is now ready for disposal to the manufacturing optician.

By the latter it still requires to be tested with respect to its optical constants, for different batches are not identical in their optical properties. Despite the exercise of the utmost care in weighing off the constituents there are always small variations. The manufacturing optician therefore cuts from the plates supplied to him small pieces, which he proceeds to grind and polish in the form of prisms to enable him to ascertain the optical constants. The deviations from the standard values are in the majority of cases very slight, yet too great to be ignored. The calculated data of the optical instrument for which the glass is required need therefore some slight rectification by small alterations in the radii, the thicknesses of the lenses, their distances apart, etc., so as to bring them into line with the slight variations in the constants, assuming, of course, that the calculator has completed the fundamentally important work of the computation of the entire system of lenses.

The mathematical methods of optical computation cannot be gone into here. It must suffice to say that all the requisite data has to be laboriously calculated in succession with the aid of trigonometrical formulae. When a successful combination has been arrived at which satisfies all given requirements an exact drawing with a description of the radii, thicknesses, diameters of lenses and the kinds of glass to be used is handed into the workshops.

The first step there is to make the grinding tools which are required to shape the lenses. These are in the form of flat cups of cast iron or brass having the reverse curvature to that which the finished lens is required to have. To make a converging lens with a convex surface a concave tool is accordingly required, whereas a mushroom-headed tool will be needed for making a concave lens. The surfaces of these tools are turned on the lathe with the utmost precision with the assistance of fine measuring instruments. Before proceeding to grind the lenses the unworked glass plates require to be reduced to a form which will save a maximum of material and labor. The plates are accordingly cut into pieces which are but little thicker than the thickest portion of the required lens. This sawing operation was formerly performed with a kind of fiddle-bow saw, the blade of which was replaced by a steel wire. By means of this, together with emery and water, the glass was sawed into pieces. Today this is done invariably with the aid of a rotating iron disc, the rim of which is charged with fine diamond splinters. The wheel is set in very rapid rotation by a motor and cuts up the glass in a very short time. The approximate contour of the required lens is now drawn with a pencil upon the slab of glass, and all superfluous material nibbled off by means of pliers with soft iron jaws. The piece is then given an approximately circular form on a grinding stone with the assistance of sand and water. When the piece has been prepared in this way in the rough the operation of lens grinding proper begins.

The grinding tools which have already been described are moved to and fro, while the piece of glass which is to be ground is cemented to a rapidly rotating spindle, whereby it is pressed against the tool. It is usual to grind several lenses together by cementing a considerable number of them to a large tool of the reverse curvature and working them jointly.

The abrading material used is emery together with water. Coarse emery is employed first for obtaining the required form. By the gradual introduction of finer grades of emery the rough portions of the surface are smoothed down, until finally it presents a finely-greyed appearance. The workmen control the grinding process and see to it that there is always sufficient abrading material and water between the work piece and tool. During the process of grinding, the surfaces are constantly tested by delicate measuring instruments. *Every* surface of *each* single lens is examined repeatedly in this way. Since the tools themselves are subject to abrasion during the process they themselves require to be continuously tested as well.

Apart from the prescribed curvatures of the surfaces of the lenses, their thickness requires to conform rigorously to the calculated amount, as this constitutes an important element in the required optical scheme. In fact the thicknesses of the lenses must be realized within the 1/2500th part of an inch. A special instrument is used for measuring the thicknesses of lenses. The lens which is to be tested is placed upon a plate and the freely movable contact pin made to rest upon it. By means of a reading telescope the thicknesses may be read off with the utmost precision upon a fine scale.

When the lenses have acquired the desired form on two sides, the next step is to polish them. This is done in a similar manner as the grinding, the grinding tool being replaced by the polishing tool and the emery by jeweller's rouge. The polishing tool is simply an impression of the so-called *standard-proof lens* in pitch and is obtained after the manner of a sealing wax impression by lining the grinding tool with pitch and pressing into this, while still soft, the counter-mould. The lens is then operated upon with rouge and water until it has taken on a firm polish.

Polishing in the pitch tool with rouge gives the best possible results, since in this way the spherical form comes out best. A dry method is preferred in those cases only where the polished surfaces serve as an intermediate stage in manufacture. To apply this method cloth or paper is fixed by an adhesive to the tool and rouge rubbed into the latter.

The lens is now subjected to a final and exceedingly severe test. For this purpose it is not sufficient to apply mechanical means, and hence it becomes necessary to adopt an optical method. The test is made with the aid of the standard proof lens. Everyone is familiar with the colors of soap bubbles, and many will have noticed the rainbow colors which a thin film of oil produces when floating on water, and some may have observed that when a spectacle glass as worn by a long-sighted person is placed upon a glass plate a series of narrow rings in close succession is visible at the point of contact. A similar appearance occurs when two glass plates are pressed together. Here, too, colored rings are formed. The phenomenon is due to the formation, by reflection of light at the free surfaces of thin films, of *interference colors*, which are governed by the thickness of the film. The walls of the soap bubble, the thin layer of oil and the thin stratum of air between two glass plates pressed together constitute thin films of this kind. When they are of uniform thickness at all points they exhibit *one* color only which depends upon the thickness of the film.

Taking advantage of this principle, optical workshops provide themselves with extremely accurately made standard proof glasses for all curvatures with which they are concerned in their lens making operations. A standard proof glass of this kind has the reverse curvature to that of the lens which is to be tested, and to test the latter it is pressed upon the proof lens. Any faulty part will at once be made manifest by the appearance of colored rings, since at such a point there will be air strata or different thicknesses. If the lens which is to be tested has an exact curvature without a fault the entire surface of the proof lens will appear colorless, or if the deviations of the surfaces amount only to fractions of *one* wave-length they will exhibit a single color. The method is so exceedingly sensitive that slight warming of a portion of the lens by the warmth of the hand suffices to give rise to irregular colors. It goes without saying that the radii of curvature of the proof glass must be measured in millimetres in the most exact manner, if they are to serve as the basis of lens surfaces to be tested with their aid.

The apparatus designed for measuring these radii of curvature is of extreme delicacy. The proof glass lies with the surface which is to be measured facing downwards on a tapering metal ring of an exactly measured diameter, and a freely movable pin is pressed from below against the surface of the proof lens. The amount of the so-called versed sine of the proof glass surface can be read on a scale and the appropriate radius of curvature calculated therefrom. Since the radii require to be measured accurately to 1/2500th of an inch, it goes without saying that these measuring instruments must be made with extreme precision.

When the lenses have acquired perfectly polished surfaces and when by the tests applied to them they have proved to strictly conform to calculation the next task is to "centre" them. This means to so grind the periphery of the lens that the optical axis is at the centre of the cylindrical boundary of the lens. The optical "axis," it should be noted, is the line joining the centres of the spheres which form the free lens surfaces.

For testing this adjustment there are two methods, an *optical* and a *mechanical* one, and, as before, the optical method is the more accurate of the two. It is based in principle upon the reflecting properties of polished lens surfaces. The lens which is to be centred is cemented by one of its surfaces to the chuck of a lathe and a flame, or point of light set up at some little distance from it. When the lens is made to rotate the two images of the flame formed by reflection at the two spherical surfaces will be seen to rotate about one another if the optical axis does not coincide with the axis of rotation of the lens. If both are coincident the reflected image appears to stand still. The lens is trued on the chuck, that is to say, it is brought into such a position that the reflected image appears to stand still, by displacing and tilting the lens over the cementing medium. When this has been accomplished the outer boundary of the lens is ground down to a cylinder on the lathe.

Where centred lenses require to be cemented together so as to form a single compound lens, this is done by means of Canada balsam.

Cementing is done by applying a drop of Canada balsam to the carefully cleaned and warmed lenses. They are then placed upon one another, and by gentle pressure air and excess of balsam expelled. When the balsam has cooled the lenses will be firmly united, but they require once more to be trued up on the lathe, in order that the optical axis of the two lenses may accurately coincide. The finished combination is then lacquered black at the cylindrical boundary, to obviate reflection of light at the translucent rim. It is now ready to be set in the lens mount.

The mounting is mostly done on lathes with treadle motion. The degree of precision with which this operation is performed is the same as that applied in the processes of grinding and polishing, for it will be remembered that the distances between the component lenses of the objective enter into the calculation and must therefore be adhered to within the smallest fraction. Extreme care must also be exercised to avoid any excessive pressure and still more so any one-sided pressure being exerted by the mount upon the lens, as this would give rise to internal strains in the glass, or it might even cause otherwise perfect lens surfaces to be distorted in a more or less pronounced degree. When all the various stages in the making of a lens, as here described, have been carried out with rigorous precision, even then a conscientious optician does not feel entitled to place the resulting product on the market. Each finished objective is tested individually by specially appointed lens testers, before it is allowed to enter the worlds' markets. Once again it is tested for striae, strains and other possible flaws in the glass, and finally it is subjected to a practical photographic trial on the test chart. Also, the focal length, accurately within fractions of a millimetre, is determined for each objective. Its agreement with the value prescribed by the calculation furnishes a criterion as to what extent the practical achievement conforms with the calculation. Process lenses, as well as mirrors and prisms used in conjunction with these are examined separately in the photo-mechanical laboratory so as to ensure that exceptional degree of optical correction which is needed for this purpose. It will be readily appreciated that such a degree of precision in the system of manufacture with its incidental phases of weeding out is quite incompatible with mass production as ordinarily understood, and that this necessarily influences the cost of such products. Instruments produced in this way *cannot possibly* be "cheap." On the other hand, the ultimate possessor of such an instrument has the satisfaction to know that his objective is equal to its producer's promise.

And it will also be realized that such an instrument should not be expected to answer requirements which are in conflict with the natural laws of optics. Many sins are committed in this respect. When the optician's work does not come up to such visions of the impossible, certain enthusiasts are too prone to blame the instrument. Thus, it happens very often that an intending purchaser of a lens attaches an exaggerated value to the absence of bubbles, and, indeed, insists that the lenses should be entirely free from these. The wish to possess such a lens without a trace of bubbles is intelligible enough, but unfortunately, it is utterly impossible to accede to it for reasons which we have already explained above. The optician will certainly take great pains to eliminate any material which might in the slightest degree detract from the practical value of an objective. But a few bubbles are not to be reckoned in this category. When it is considered that the smallest stop with which a photographic objective is used has an area of about 4 square millimetres, while the aggregate area of the bubbles, contained in an objective, amounts to about 1/2 square millimetre, it follows that the loss of light which may be occasioned by the presence of these isolated bubbles amounts to a negligibly small percentage, no more than about ten per cent of the light-transmitting capacity which the objective has when operating with its smallest stop. When, however, we consider that in the majority of cases the objective operates with far larger stops, the loss of light occasioned by the presence of these bubbles becomes utterly insignificant. Indeed, in the case of an objective 1.18 inches in diameter its rapidity is only reduced by the 1/9000th part of its rapidity at full aperture. We have already pointed out that the presence of small gas bubbles cannot be avoided in optical glass making. To the uninitiated these bubbles are particularly conspicuous, and he is inclined to endow them with exaggerated significance. While they are entirely unavoidable in the production of the new glasses, they are nothing more than *blemishes which can offend the eye only*, since the loss of light which they occasion is too slight to be appreciated. The true amount of this loss may be realized by a small calculation. Let us suppose a certain lens 3 cm. in diameter to contain 10 bubbles 0.1 mm. in diameter. This would mean that within a surface of 706 square millimetres a portion of 0.0785 square millimetres large would be ineffective, so that the total loss of light occasioned by the bubbles would be only 1/9000th of the incident or transmissible light. When the lens is stopped down to 1 cm. this opening will contain two bubbles. In this somewhat *unfavorable* case the loss of light would therefore be 1/5000th of the total transmissible light. These are amounts which have no practical significance whatever, and the most punctilious photographer would certainly not trouble to take any account of them when estimating the required time of exposure in any given case.

You will thus see that manufacturing opticians are well within their logical rights when refusing to admit the presence of bubbles as reasonable grounds for complaint.

It will have occurred to you that the production of photographic lenses involves a vast expenditure of time and that in a much higher degree it makes very great demands upon manual skill. True, in large establishments, as you have seen, the operations are considerably simplified and abridged by the introduction of special machines. Nevertheless, in optical manufacture far more is left to the personal skill of the workmen than in any other branch, and this is not likely to be superseded for some time to come by mechanical devices.