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How I found the mechanism of intracapsular accommodation

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With the normal eye, except in old age, one can see clearly at different distances. To permit this, the lens alters its shape, so that the refractive power of the whole of the eye's optical system changes, in a way which resembles most closely that which takes place in a camera when one objective lens is exchanged for another without altering the extension of the bellows. This alteration of the eye's optical system is known as accommodation, and its mechanism has for long been an object of interest for research. In this connection, however, research has exclusively dealt with the way in which the alteration in the shape of the lens is brought about, and what alteration takes place in the eye apart from the lens. Now since the lens is enclosed in a capsule, one can say, in brief, that it is the extracapsular accommodation-mechanism which has so far been investigated and discovered. But if we ask what takes place within the lens-capsule during accommodation, we then pose the problem of the intracapsular accommodation-mechanism.

Without any knowledge of the structure of the lens, one might perhaps be inclined to think that this is a very simple problem. If one alters the shape of a water-filled bladder, some of the water particles will be displaced in relation to the others, and the streaming motion will not be of any particular significance. And the behaviour would be identical, if the bladder were filled, not with water, but with a substance of the consistency of the lens, in which the particles were freely movable in relation to one another. But it is just this respect in which the lens differs. It consists throughout of an infinite number of skilfully arranged, microscopically fine fibres, which terminate at various depths below both surfaces of the lens, and which run from one end to the other in coils lying in the direction of its edges. Since, on account of the speed with which accommodation takes place, we can exclude the possibility of fluid flowing through the fibre walls, and since the lens substance, as one can easily convince oneself, is clearly lacking in elasticity, it is obvious that on change in the shape of the lens during accommodation the various lens-fibres must remain of constant volume, and that a change of shape can only come

about through the displacement of the lens fibres relative to one another. But the fibres are fastened at both ends to the immediate surroundings, and it is therefore only in their central part that displacement of the individual lens fibres in relation to one another can take place, as a result of changes in the shape of the coils. It should now be obvious that to a given change in the shape of the lens there must correspond a definite displacement of the fibres within the lens-substance depending on their arrangement. Thus, there must exist a definite mechanism for accommodation within the lens capsule.

I shall deal later with the question of how the most essential feature of this mechanism could have been predicted on the basis of the anatomical structure of the lens. That the most important aspects could have been predicted occurred to me first, when I found the mechanism during the research I undertook to gain accurate knowledge concerning image-formation in the eye. These researches proved difficult, because the refractive power of the lens is by no means that of an ordinary homogeneous medium, the same throughout, with no change from point to point, since the lens substance consists of a heterogeneous medium with, at least in the young, a continually varying refractive index. The laws governing optical image-formation in such media were completely unknown, and much of what was thought to be known, proved to be wrong.

Even if it had been simply my intention to find these laws, I was nevertheless obliged in order to do this to realize the reformation of the theory of optical image-formation in general, which I had started and also have carried through, before daring to apply myself to the study of the problem in heterogeneous media. Essentially, therefore, the way in which I came to an understanding of the mechanism of intracapsular accommodation can best be described by giving a survey of my more important work on optical image-formation in general, and that in the eye in particular.

Most people even now think of optical image-formation as being a focusing of light rays issuing from one point on the object, to produce a corresponding point in the image. Most people would also agree that the impression one has from the picture which a good photographic objective projects on a screen, strengthens this idea. But it is obvious here that if the laws of optical image-formation were generally valid one should obtain an equally good image with other optical systems. However, since this is by no means the case, it follows that this theory of optical image-formation is not applicable here; thus a general law has to be found that does not simply relate to individual cases where the idea of a point is not to be taken in too rigid a sense.

A special case is found in the immediate neighbourhood of the axis of a centrally-aligned optical system consisting of rotation-areas. If one cuts off such an optical system with a small cylinder whose axis coincides with that of the optical system, one can say, with enough accuracy for practical purposes, that an object enclosed within this cylinder is reproduced through the system, point for point, and the accuracy of this statement increases in proportion as the diameter of the cylinder is reduced. But this is not strictly accurate, until the cylinder becomes so narrow that it coincides with the axis. One can express this in another way, by saying that point-by-point image-formation, with complete focusing, takes place in the paraxial region, but it should be noted that this region, if taken as being finite, is to be considered as a thread-like, enclosed axis, and that only the parts of the refracting surfaces of the optical systems that are cut off by this axis, come into consideration.

In order to represent this case approximately by physical means we must narrow the optical system as much as possible, without producing disturbing diffraction phenomena. If we do this with an ordinary biconvex lens, which we then place in the objective of a photographic camera, we find that a tolerable image can be produced in the neighbourhood of the point at which the optical axis of the lens intersects the plate; but if, without using the focusing-screen, we examine under high magnification the image now floating in the air, we also find, even with monochromatic light, that the mechanism of image-formation here differs from that in which every light ray arising from a point on the object strikes the same point in the image.

With a small aperture, and therefore, a small central field, one can say that the present theory of image-formation corresponds to reality with sufficient accuracy for practical purposes, so far as axially-symmetrical systems are concerned. In this way, a straight line in the object is always reproduced by a straight line in the image. This image-formation is therefore termed collinear. An additional feature of the collinear image-formation of an object-area at right angles to the axis, is conformity of the image with the object.

It follows clearly from what I have said, that when we consider the actual circumstances of optical image-formation within a system with a large aperture and a large image-field, the law of collinear imagery is not even approximately valid for the general case. Thus, when the general laws of optical image-formation were unknown, there was no alternative except to define the realities as deviations from the supposed ideal of collinear image-formation. Abbe preceded most others in this connexion and deserves most praise

for the present upsurge in optical techniques. The fact that this splendid progress was achieved without knowledge of the general laws of image-formation, is a result of the fact that what investigators were trying to achieve was precisely that axially-centred system which comes as close to the ideal of collinear imagery as possible, and that this can be solved by trigonometric methods, which work independently of the laws of image-formation. In other words, specifically-designed optical instruments, such as the modern photographic objective, come very close to the ideal of collinear imagery. But as yet we had no precise knowledge of the working of an optical system not built according to these construction principles. Moreover, for technical purposes it is sufficient to say that a good instrument behaves with a greater or lesser degree of accuracy, according to the laws of collinear image-formation and this is enough from the technical viewpoint. And science often draws its impetus from man's practical needs, and if technical optics had not required general laws of image-formation, it seems clear that science would not have found these laws. Such a need was strongly felt in ophthalmology and physiological optics.

Here the first requirement was for a knowledge of the general laws governing the focusing of light rays. When monochromatic light originating from a point and passing through an optical system, is not focused again to a point, how is the refracted ray built up, since it is not homocentric? Geometrical optics had answered this question from its own viewpoint, for the special case where the light-point is situated on the axis of an axially-centred system with spherical surfaces. The central ray of the refracted bundle coinciding with the axis is intersected by the adjoining rays, whatever their direction of travel, in one point, the focal point, and the course of the remaining rays is determined by the so-called spherical aberration. But already, in the case where the light-point does not lie on the axis of the system, this theory is erroneous. If we depict the rays which, in a normally centred system such as a telescope, pass from an eccentric object-point through the centre of the effective aperture, that is to say through the centre of the objective in the astronomical telescope and in the comparable and now common prismatic telescope, then we find that, after passing through the instrument, these rays generally intersect the adjoining rays in two separate focal points. The phenomenon known as astigmatism follows, and it will be readily understood that astigmatism represents the general case, and that its absence - anastigmatism - constitutes the special case, which is characterized by the fact that both focal points coincide.

The quest for knowledge of the general laws governing the focusing of light rays led us to a direct investigation of the constitution of astigmatic bundles of rays. As with anastigmatic bundles, the more nearly they can be considered to be homocentric, the smaller the iris aperture is relative to the distance of the focal point from the iris, so a type, the so-called Sturm conoid had been discovered, which was considered to represent an astigmatic bundle with a small aperture. It was consistently forgotten, however (and this omission gives a most striking example of the peculiarities of scientific psychology) that the Sturm conoid was derived under conditions where the iris aperture is infinitely small, not only compared with its distance from the two focal points, but also compared with that separating these points, the so-called focal range. But whereas in the case of astigmatism, in a usual centred optical system near the focal point the refracted ray bundle lies outside the axis, in an astigmatic eye the aperture of the ray bundle is as a rule greater than the focal range, practically never small in comparison with it. A simple investigation shows in confirmation of this, that the Sturm conoid cannot be used as a model for the narrow astigmatic ray bundles, in the case in which technical and physiological optics are most interested. Its role is in practice restricted to representing ray bundles of the type found in the laboratory.

A bundle which radiates from an object-point and is refracted in an optical system with single refracting media separated by continuous surfaces, has the property that one can construct a plane from any one point to any other (the so-called plane of balance) which is at right angles to the combined rays of the bundle. The investigation of the structure of ray bundles is thus the same as that of the structure of standard bundles. Such an investigation comes under the heading of differential geometry, in that the properties of the standard bundle are studied under the nearest conditions to a standard environment, just as in general, when the equations of surfaces cannot be expressed explicitly, the surfaces are studied under the conditions approximating most closely to a certain set or arbitrarily chosen point. In this study a closer knowledge of the bundle is obtained by taking differential quotients of a higher order in the equation of the surface. Now the Sturm conoid was derived by ignoring differential quotients of a higher order than the second, and therefore the first task I set myself was the investigation by differential geometry of astigmatic ray bundles, taking into account all the differential quotients of the third order, in the balance-plane equation. I found the quantities determining the structure of the bundle, and I also derived the formulae for calculating these quantities in optical systems of all types. By simple verifying

experiments I showed that the knowledge gained in this way concerning the structure of astigmatic rays is sufficient for practical purposes, with the apertures normally found in optical instruments. Laws were thus also obtained governing the occurrence, but not the essentials, of the so-called coma error. Up to now we had only been able to make calculations for the paraxial region, and thus not even for a ray bundle issuing from a point located a finite distance from the axis of a centred system; in other words in a centred system of spherical surfaces means were known of calculating coma error with an infinitely small angle of incidence, but not with a finite angle of incidence.

In this, the simplest case, when the optical system consists of centred spherical surfaces, and the equal rays of the ray bundle intersect the optical axis at a finite angle, the problem should also be of interest in design optics. Here the bundle is determined by two asymmetry values, i.e. to use the language of technical optics, there are two types of coma error in such a system. But when the representatives of geometrical optics started their investigations - they were unacquainted with mine - they first of all studied the first type of coma error, and then discovered one too many. The reason for this is that in geometrical optics it is generally considered that it is possible to proceed from a two-dimensional concept, while the problem here is three-dimensional and must be treated as such.

In considering simpler questions the normal eye can justifiably be considered as a centred optical system, but the ray that in the case of sharp reproduction goes through the centre point of the pupil, does not coincide with the axis but makes a finite angle with it. Relative to this ray, the so-called sight line, the refracted bundle is astigmatic with finite asymmetry values, or, putting it another way, it is subject to coma error. On revising Helmholtz' eye diagram in the light of my formulae, I obtained a figure for these asymmetry values, with the result that they appeared to be unarmful to vision; but the knowledge obtained in this way concerning the structure of the ray bundle refracted in the eye was insufficient, for without a knowledge of the laws governing aberration in the eye we cannot expect in physiological optics to use this knowledge in determining the nature of the accommodation mechanism.

I have just said that physiological optics occupied itself with the focusing of rays along the axis of a centred system, and expressed the deviations from homocentricity that occur with monochromatic light, as spherical aberration. This unfortunate expression was based on the fact that spherical surfaces only had been studied, and the aberration depends on the shape of the surfaces.

Helmholtz had already substituted for this term that of monochromatic aberration. The value for this, applicable in cases where the angular aperture is not too great, had long since been calculated along the axis in a centred instrument with spherical surfaces, and was given in textbooks on geometrical optics. But this particular case is inapplicable in relation to the eye, and it was thus necessary to derive a general theory of monochromatic aberrations, in order to know the basic characteristics of the focusing of the rays in the eye. To do this, it was necessary to take all the differential quotients up to the fourth power in the normal plane equation. I carried out this mathematical investigation in its entirety for the astigmatic ray bundle.

The difficulties were greater in the case of anastigmatic ray bundles, and I was unable in my early work to make a complete study of their structure and of the geometrical significance of the asymmetry values. This study in fact necessitates a detailed examination of a field of mathematics that has so far hardly been investigated, involving the problems of the so-called lines of principal curvature of single points, and the relation between the two caustic surfaces at common points of contact. It was only after carrying out such an investigation that I was able to find the knowledge necessary for dioptrics in

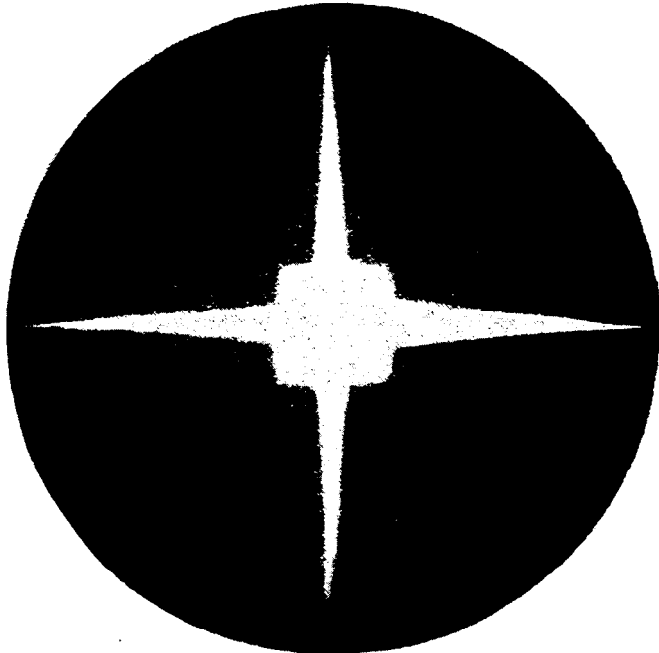


Fig. 1

general and in particular for the dioptics of the eye, concerning anastigmatic ray bundles, and astigmatic ray bundles in which the focal range is small in relation to the aperture; and only then was it possible to carry out a physiological examination of optical image-formation in the eye. The methods I developed for this purpose showed that on the one hand the aberrations in the ray bundle refracted in the eye are of a very complex and still unknown type, and on the other the radiant emission seen around light-points, e.g. fixed stars, is an expression of the individual character of the aberration. Thus one can reproduce experimentally this radiant emission round images of light-points, by designing the optical system so that the refracted bundle is characterized by the aberration values required therefor. Fig. 1 shows such an image of a light-point. I obtained it by photographing a greatly reduced image of the sun with an objective consisting simply of spherical and cylindrical glass lenses. The picture was produced by photomechanical reproduction straight from the original negative.

The physiological investigations on the eye carried out by means of the above-mentioned methods which I developed showed clearly that the importance usually ascribed to diffusion circles in the case of optical image-formation is exaggerated, because otherwise the eye, with the large disc of confusion found in it, would have nothing like the sharpness of vision that it in fact has. It has been supposed that the very thin cross-section of a ray bundle is of major importance in image-formation, but it is clear, both from physiological investigations carried out on the eye, and from physical experiments, that in image-formation the light distribution over the cross-section of the ray bundle is of primary importance and the size of the cross-section is only of secondary importance. Now, since the light intensity is greatest when rays running very close to each other converge together, and since the points in which such rays converge are located on the so-called caustic surfaces, it is clear that it is these surfaces, and the geometrical values which, on the basis of my previous investigations, characterize them, that are of central importance for the problem of image-formation.

At the same time as the diffusion circles lost their importance, it became necessary to study the effect of diaphragms from a new viewpoint. This had been studied mainly in relation to restriction of the ray bundle, an investigation which sufficed for the optical instruments where collinear imagery was realized more or less ideally. But in the case of image-formation in general another aspect of the function of the diaphragm comes to the fore, viz. the optical projection through the diaphragm centre or another selected projec-

tion centre in it. Just as it is possible to produce a more or less geometrical projection in a camera without a lens or by shadowplay, so an optical system can be inserted during the tests so as to preclude sharp image-formation approximating to optical projection. If we draw the rays that in the diaphragm of the optical system pass from the different points of an object through the projection centre, and study these rays on a screen, we find that each point of the object surface corresponds to a point on the screen; thus a point-by-point correspondence is produced through the optical projection. And if in addition the opening of the diaphragm is reduced so far as is possible without producing interference through diffraction, then, just as in a camera without a lens and with shadowplay, we get a picture which, while it is lacking in sharpness and does not geometrically resemble the object, does however give a recognizable image of the object.

Now optical image-formation can be distinguished from optical projection in that it involves focusing of the rays, and it can also be characterized mathematically on the basis that the convergence of the rays must be total to at least the first order. We already knew that optical point-by-point imagery does not take place in the general case, and that it does not occur even in a centred optical system in the case of excentrically-located object points. The Abbe school of investigators had overcome this difficulty by assuming two different collinear image-formations, but in this way they were only able to take into account the rays that run in the meridional plane and in the plane perpendicular to this, rays which together constitute a very small fraction of the light concerned in image-formation. Thus this fiction could have no justification except that the general laws were still unknown.

These general laws followed from my basic equation of optical image-formation, and they stated first and foremost that optical image-formation of lines generally exists. In any optical system, through the constants of the system and the position and shape of the object surface, there are two systems of reproducible lines running along it, which intersect each other at various points at finite angles and are reproduced with total focusing of the rays to at least the first order, each system being on a separate picture surface. No other optical image-formation takes place, and the mutual points of contact between the two surfaces of the picture are only point-by-point pictures of the individual points of the reproducible line system. Just as ideally we can popularize theories of collinear image-formation by saying that in the case of narrow diaphragm each ray emitted from an object passes through a corresponding picture-point, thus analogously in reality we can popularize theories

of optical image-formation by saying that in the case of narrow diaphragm each ray emitted from a reproducible object line passes through a corresponding picture line although with these lines point-by-point imagery does not take place. In a plane that lies perpendicular to the axis of a centred system, the reproducible lines comprise meridians and parallel circles, and the two surfaces of the picture meet at the points of intersection with the axis. In a plane passing through this point perpendicular to the axis, a more or less point-by-point imagery is found in the centre, while generally at the periphery optical projection only takes place and a reproduction of the one line system, usually meridian lines, may be found in the intermediate zone.

Only after this study of the general optical image-formation had enabled me to ascertain its character and fundamental equation was it possible with any prospect of progress to come to grips with the problem of image-formation in heterogeneous media and particularly the eye lens. The refractive index, i.e. the factor which at a certain angle of incidence determines the direction of the light when it passes from one medium to another, varies in heterogeneous media from one point to the next and the result of this is primarily that the path of the light in such a medium is not a straight line. Instead of travelling in straight lines in common media (the light rays), light follows curvilinear paths (trajectories as they are termed) in heterogeneous media of continually variable refractive index; the shadow thus never lies in the same straight line as the object and the light source. One such medium is the earth's atmosphere and as a consequence a star that has just appeared to rise above the horizon has in fact still not passed it. Astronomers and physicists had accordingly studied the phenomenon known as terrestrial or astronomical refraction but confined themselves to determining the shape of the trajectory so that the problem of image-formation starts at the very point where these studies cease. On the other hand the situation in the eye-lens had given rise to physical and physiological research which has however, owing to the wrong methods being used, yielded mainly incorrect results.

I first showed by means of a general mathematical study of such media that the fundamental equation and hence the laws of image-formation governing normal homogeneous media also apply in media with a continuously variable refractive index and for the passage of light between different such media as well as between one such medium on the one hand and a homogeneous medium on the other. After I had also deduced the formulae required for calculating the image-formation and aberration, I was in possession of the mathematical tools which are necessary and, in conjunction with physiolog-

ical examinations, adequate for gaining a detailed knowledge of the image formation in the eye and of the intracapsular accommodation mechanism.

For these physiological examinations, however, an accurate knowledge was required of the surfaces and thickness of the cornea. By and large, research workers had been content to ignore the effect of the posterior surface since the difference in refractive index between the corneal substance and the aqueous humour is relatively small. They then had only the anterior surface to consider and this was sufficiently well known. However, the radius of the posterior corneal surface had been determined, albeit by unreliable methods, and was at least enough to show that for certain examinations it was inadmissible to neglect the refraction at this surface. I had therefore to repeat these examinations with new, precise methods before I could proceed further. The extent to which this was necessary can be appreciated most readily from the fact that the thickness of the cornea at its top has generally been estimated as about 1 mm, whereas my studies showed that in round figures it is only half a millimetre, a result moreover, which had been obtained earlier by Blix and to which inadequate attention was paid.

To compute the refraction of a lens which is a heterogeneous medium, it is advisable to take special account of the change in convergence of the light which occurs during passage through the heterogeneous medium. This change is wholly analogous to the diffraction in an optical system, and therefore the substance of the lens can be treated as an optical system in its own right, the "core lens" as it is known. To calculate its effect on the transient light the law governing the variations in refractive index needs to be known - in other words an indicial equation is required. Such an equation has been established by the physicist Matthiessen and in deriving it he only took account of up to second-order differential quotients. The refractive-index determinations that have been carried out have shown this law to be sufficiently accurate in itself, provided however that it does not clash with known mathematical or physical facts. It has been used for integration in the same way as if completely accurate and has yielded, inter alia, a simple formula for the so-called total index of the lens. This latter is an imaginary refractive index for a homogeneous lens which, for the same surfaces, has the same refraction as the eye-lens. According to Matthiessen's law the total index exceeds the refractive index at the centre by the same amount as the latter exceeds the refractive index at the surface.

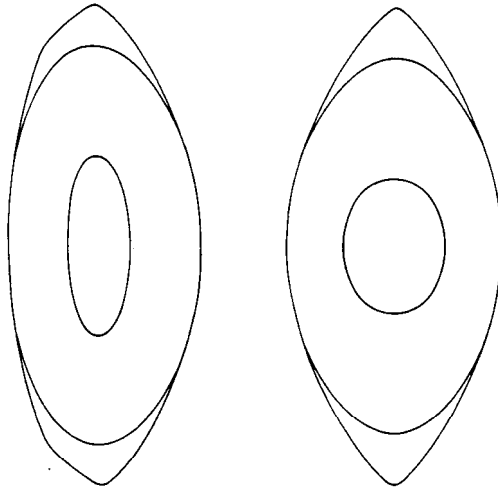
Yet this Matthiessen indicial equation is so hopelessly at variance with facts that it immediately proved necessary to include all the differential quotients

of up to the fourth order to obtain a sufficiently exact indicial equation. This then contains seven constants which remained to be determined. Were the eye-lens of the same size as the object-lens in a telescope, these constants could be found by determining the refractive index at a suitable number of points using the refractometer. But owing to the small distances in the eye-lens and the relatively insignificant differences in the refractive indices, not more than three sufficiently reliable equations could be derived in this way: it could be assumed that the values at the centre, the poles and the edges had been determined with sufficient accuracy. I derived a further two equations from the curvature of the surfaces. If all the points in the lens substance are found at which the refractive index has the same value, together they form an iso-indicial surface. The anatomical structure of the lens lends definite support to the assumption that at both poles the isoindicial surfaces have the same radius of curvature as the lens surfaces, and from there these equations follow. One equation is also derived from the loss of refraction sustained by the eye on extraction of the lens and here too the exact values for the corneal system have to be used and the aberration along the eye's axis as measured by direct experiment has also to be included in the calculation. The refraction of the "core lens" from which the total index of the lens follows, is determined in this way. This is not determined by Matthiessen's law when differential quotients of higher than the second order are included in the indicial equation. I was unable to find any reliable physiological method to derive the seventh and last equation but I have shown that if this equation is derived by assuming Matthiessen's indicial equation to be valid along the axis, no inadmissible approximation is made. On the one hand it has previously been found that this equation agrees so closely with the observations that it can be applied in every case where it does not conflict with fact (which does not apply here), and on the other hand I have been able to demonstrate that discrepancies as regards the variation in index along the axis have no significant effect on the result, even when they become so large that they certainly lie outside the bounds of possibility.

After thus finding the indicial equation for the lens at accommodation rest I was able, using the formulae I had previously derived, to work out fully its optical system. The same task then remained in respect of the accommodating lens. Following Helmholtz' example, repeated measurements had been made of the changes undergone by the lens during accommodation but precise details were lacking of the degree of accommodation corresponding to a given degree of change in the shape of the lens. It is well known that it is mainly the

anterior lens surface which increases in curvature during accommodation and at the same time moves slightly forward, although so far nothing is known for certain about an accommodative dislocation of the posterior lens surface, the curvature of which changes only slightly during accommodation. Hence there was a need to measure by means of a new and exact method the radius of the anterior lens surface in the same eye, both at rest and during accommodation for an accurately measured minimum distance. In this way the refraction of the core lens is obtained for the state of accommodation which is determined by the radius of the anterior lens surface. Furthermore I introduced the two conditions which follow from the anatomical structure of the lens, namely that no compression can occur in the centre when the shape changes, and that the volume limited by the largest closed isoindicial surface cannot undergo any change either. I then had all the data which, over and above knowing the thickness of the lens and the radius of curvature of its surface, are required to find the indicial equation of the accommodating lens and then calculate from that its optical system.

Here I have a diagrammatic meridional section of the lens firstly at rest and secondly at maximum accommodation, at about the age of twenty (Figs.2 and 3). In both diagrams there are three continuous lines, the outermost of which represents the section through the lens surface, the other two being meridional sections of two isoindicial surfaces. The refractive index of the section passing through the poles of the lens is 1.386, so falling short of the re-



Figs.2 and 3

fractive index in the centre, 1.406, by two units of the second decimal. The line at the centre represents the isoindicial surface where the refractive index is only two units of the third decimal less than in the centre. The distance between these curves illustrates the fact that from the surface towards the centre the refractive index increases initially at a relatively fast rate which rate then decreases progressively towards the centre.

I obtained the cross-section of the isoindicial surfaces by computing the coordinates point by point from the indicial equations.

Their shapes are therefore quite correct, with the sole reservation that it is possible, although so far unproved, that the accommodating core lens may exhibit a slight degree of asymmetry. I only wish to add that provided an arbitrary difference between the radii of curvature within the limits specified by measurements carried out hitherto is introduced into the calculation, the resulting asymmetry of the core lens will not be significant and in any case will have absolutely no effect on the result I will outline.

Owing to our defective knowledge, the shape of the cross-section of the lens surfaces is drawn in a more arbitrarily schematized manner. As far as possible I have drawn them as parabolas - which seems most closely to agree with the present state of our knowledge - and connected the ends of the parabolas by arbitrary curves, approximately ensuring that the volume contained between the lens surfaces and the largest continuous isoindicial surface remains practically unchanged during accommodation. For simplicity's sake I thus drew the whole accommodating lens symmetrically round the equatorial plane, notwithstanding that very probably such is not the case. For example, the anterior lens surface could be hyperbolic with constant top radius and thus the lens would be of asymmetrical shape with symmetrical isoindicial surfaces. The manner in which I have drawn the cross-section of these lens surfaces thus makes no claim to represent the actual situation, all the less so as this situation is unknown to us in such detail, and it only seeks to illustrate schematically the essential features of the change in lens shape during accommodation. The conclusions I draw regarding the intracapsular accommodation mechanism will therefore not differ from those obtainable solely from the exactly calculated change in shape of the isoindicial surfaces as well as from the ophthalmometrically determined changes in lens thickness and in the top radii of the lens surfaces. The former increases by about 11% during accommodation, while the curvature of the anterior lens surface increases by 87% in round numbers, against which that of the posterior lens surface increases by only 12.5%.

The most notable feature to emerge from a comparison of these two diagrams is the strikingly large change in shape undergone by the innermost of the two drawn isoindicial surfaces. These two surfaces change and tend to become spherical, but the inner surface changes most. As shown by a comparison of the two indicial equations, this phenomenon in the drawings is an expression of the fact that the accommodative change in shape of the isoindicial surfaces increases with their proximity to the centre of the lens. On the other hand it follows from the mathematical analysis that this condition corresponds to an accommodative increase in refraction greater than the one that would be brought about by the change in shape itself if the lens were homogeneous. Since the refraction of a homogeneous lens of particular shape is given by the refractive index, it follows that if a lens is made having the same shape as that of the eye, firstly at rest and secondly at maximum accommodation with the refractive index in both cases chosen so that the refraction of the homogeneous lens is the same as that of the eye lens, the refractive index of the homogeneous lens corresponding to the state of accommodation must be made larger than that of the lens corresponding to rest. But it is this same imaginary refractive index which, as I have previously mentioned, has been termed the total index of the eye lens. Thus in the eye the total index of the lens increases during accommodation, a truly remarkable situation although as we have seen, the total index is not a physical refractive index but an imaginary concept. It is not necessary to know the dioptrics of the lens to prove this. The length of the eye and the refraction of the lens during accommodation can be found from the constants of the corneal system, which can be measured directly, and from the loss of refraction when the lens is extracted, this factor being known from satisfactorily precise examinations. Together with the change in refraction observed for a given measured change in the curvature of the anterior lens surface these values indicate the contribution of the lens to the refraction during accommodation and hence the accommodative change of the total index. I introduced these values of the lens refraction when calculating the indicial equations and it was only by means of these equations that the accommodative change in the total index of the lens was proved to be governed anatomically by the fact that the accommodative change in shape of the isoindicial surfaces of the lens increases with their proximity to the centre of the lens. I purposely say anatomically because the displacement liable to occur between adjacent lens fibres can only be measured on the microscopical scale. It thus follows directly from these two diagrams that within the closed isoindicial surfaces the axipetal displacement of the lens

tissue constituents in the equatorial plane which occurs during accommodation increases with their proximity to the axis. This condition is one of the essential characteristics of the intracapsular accommodation mechanism. The importance of the accommodative change in the total index of the lens for the dioptics of the eye is best brought out by the fact that unless it is known it is simply impossible to derive a scheme for the accommodating eye that is not in sharp contrast with the remaining known facts.

On the lens at rest I have marked by means of a rounded corner the point where the suspensory ligament of the lens, the zonule, is attached at the front, not far from the equator. A glance at the two figures is sufficient to realize that the lens particles within the largest closed isoindicial surface nearest this point are displaced towards the lens axis during accommodation. This is the second important characteristic of the intracapsular accommodation mechanism. Owing to the nearness to the zonule attachment it hence follows that the anterior zonule attachment must also approach the axis during accommodation. In other words, the intracapsular accommodation mechanism leads of necessity to the requirement that the extracapsular accommodation mechanism must result in an accommodatively reduced tension of the zonule. This was Helmholtz' opinion of the extracapsular accommodation mechanism but this opinion has been exposed to such unbridled attacks that the proof of its mathematical necessity as supplied by the intracapsular mechanism ought not to be underrated, notwithstanding that Hess in Würzburg, who was unaware of the intracapsular mechanism, proved the correctness of Helmholtz' view in such a way that anyone willing and able to see the truth in physiological experiments had to acknowledge the proof as conclusive.

One further conclusion can be drawn from these figures and the fact that the lens particles are neither compressible nor freely displaceable. It follows that when a change in shape occurs the volume enclosed within an isoindicial surface must remain approximately constant. But during the considerable changes of shape which the isoindicial surface undergoes, their area cannot remain constant provided they remain surfaces of rotation. A glance at the inner line in both figures is sufficient to prove this. The result once again is that some process similar to a radial folding of the isoindicial surfaces must follow the change in shape. I have previously pointed out that the rays which we see round a luminous point or a fixed star are determined by the nature of the aberration. The corresponding property in the case of a wave surface is obtained during the passage of the light through the lens. As revealed by mathematical analysis, this characteristic of the wave surface can only occur

owing to a structure of the isoindicial surfaces that can most readily be visualized as shallow, radial, folded structures becoming more indefinite towards the centre, and such structures also occur in the normal eye at rest. Tests using the subjective stigmatoscope developed by me also show plainly that the visible ray formations alter their character during accommodation which signifies a change in the radial folded structures of the isoindicial surfaces. It will perhaps be objected here that in the presence of such structures of the isoindicial surfaces it was inadmissible to treat them as surfaces of rotation in the mathematical examination in the way I did. The fact is, however, from what is to be inferred from the results obtained using the subjective stigmatoscope, that the broken wave surface of the fascicle in the eye - here I must use mathematical language - has a complete contact of the fourth order with a surface of rotation and it is this surface which is the object of the mathematical examinations of the lens dioptrics.

We have thus found the intracapsular accommodation mechanism characterized mainly by the fact that during the accommodation the particles in the equatorial plane are displaced in the axipetal direction, the extent increasing with their proximity to the axis, further by the fact that the zonule attachment on the anterior lens surface is displaced in the axipetal direction, and finally by the fact that displacement occurs to different extents along various radii of the lens. I shall now demonstrate that this mechanism corresponds so accurately to what we know of the lens structure that it should have been possible to forecast it completely. I have mentioned that the lens consists throughout of microscopically fine fibres in the form of loops aligned towards the equator. Consequently, the equatorial plane contains only cross-sections of these fibres. They are intersected at almost a right angle and are so tightly packed that they have assumed hexagonal shape. It is now quite obvious that when a centripetal movement occurs where during unit time the same surface area of the cross-section must pass through the circles having the lens centre as their centre, the amount of displacement must increase with decreasing size of the circle's periphery, i.e. with proximity to the axis. Furthermore, it is also quite clear that in the more central parts of the equatorial plane, where the displacement is large, not all the cross-sections in the circle can move towards the centre to the same extent because they do not have the room within the smaller circle that they occupy after complete displacement. The displacement must therefore necessarily take place to varying degrees according to the radii in the equatorial plane. And finally: because the whole lens consists of packed fibres, which intersect the equatorial plane at almost

a right angle to form a loop aligned towards the equator while they are attached at the front and back and cannot be displaced towards each other, the lens cannot become thicker in any other way than that these loops stretch, whereupon some part of them must move axipetally. Since furthermore when the lens thickens, the curvature of the anterior lens surface greatly increases at its pole, this can occur in no other way than that the peripheral parts of the fibres running along the anterior lens surface participate in this axipetal movement. For the same reasons it is very probable that identical behaviour applies to the parts of the lens fibre loops lying in the equatorial plane and along the peripheral parts of the posterior lens surface, but this could not be concluded with certainty since the increase in its curvature at the pole is so insignificant and since it is not known whether this can be succeeded by an accommodative flattening. It need only be known that during accommodation the anterior zonule attachment moves towards the axis.

It will be appreciated that in view of the lens structure and of the way in which the lens alters shape during accommodation, the intracapsular accommodation mechanism simply cannot be any other than the one which follows from my studies of the lens dioptrics. It ought therefore to have been possible to find it from what we knew before I initiated my studies, it ought to have been possible to foresee, *inter alia*, that the total index of the lens must increase during accommodation, and that the Helmholtz accommodation theory must essentially be correct, even though the physiological experiments contradicted the fact. But no one thought of it. It must also be admitted that it would have been a bold thought before definite proof was available. And hence the intracapsular accommodation mechanism would still have remained unknown had it not been necessary to study the dioptrics of heterogeneous media to discover precise details of image-formation in the eye.