SCIENTIFIC INSTRUMENTS

VOLUME ONE

SCIENTIFIC INSTRUMENTS

Described by Specialists
under the Editorship of

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PREFACE

The complexity of modern science and the enormous range of modern knowledge have sometimes unfortunate consequences. One of these is specialisation, a result of which is that one group of scientists does not know how another group works. It often happens that one scientist would like to know something of the fundamental principles and uses of the instruments used by his colleagues, possibly in the hope that they may be helpful to him—or just to satisfy a commendable curiosity; this book is an attempt to meet this desire.

Scientific instruments are here described in a way that may be understood by the non-specialist so that the worker in one field may get a useful idea of the instruments used in another. The book does not set out to tell the specialist about his own equipment but about the other man's. The surveyor will not learn from it all that he ought to know about the theodolite and its use, but he may gather some useful information about calculating machines and lenses, while the mathematician and the optician may well like to know something about the theodolite or the mariner's compass which this book can tell them, though it will not tell them *anything* that as specialists they should know already about the slide rule and lenses, respectively. But how many of the vast numbers of people who every day use optical instruments—whether cameras or spectacles—understand the functioning of a lens?

The book is in no sense meant to be an exhaustive treatise on instruments, but it is hoped that it will be valuable to the student and to the research worker, as well as to many people who are using scientific instruments and require a working knowledge of them without going into the details of design.

As shown in the contents list, the book is divided into five sections of broad types of instruments and each section contains a chapter on various specific classes; thus Section 1, on optical instruments, has chapters on lenses, on microscopes and spectroscopes, etc.

Inevitably, selection and division of sections and chapters are somewhat arbitrary; thus the theodolite and sextant are described as surveying and navigational instruments but might have been included as optical, as indeed could the majority of scientific instruments. Any suggestions for rearrangement and indeed for any improvement in future editions will be welcome and careful consideration given to them. The Editor and Publishers are of course well aware that the book is very far from being exhaustive in the number of instruments it describes, but it is hoped that future volumes and editions will be justified by the reception accorded to this first effort.

Gratitude is expressed to all who have co-operated in giving advice and assistance, and to those specialists who have so kindly and carefully revised portions of the MS. and made valuable suggestions. The Editor feels particularly indebted to Mr. W. H. Johnson who first suggested the book and whose advice and assistance have been freely given throughout its preparation. Appreciation should also be expressed of the way in which the various authors have co-operated and helped each other.

So many firms and organizations have helped in providing information and illustrations that a separate list is appended, and to these also thanks must be expressed, for without their help the book would hardly have been possible.

January, 1946. HERBERT J. COOPER.

PREFACE TO SECOND EDITION

In preparing this second edition for press the opportunity has been taken to correct a few minor errors that crept into the first printing and an index has been added which it is hoped will very much increase ease of reference and the practical utility of the book.

Thanks are given to readers who have written expressing their appreciation of the book and to those who have made suggestions. All readers will, it is believed, be glad to know that a sequel to this book under the title *Scientific Instruments II* is now in the press and will be published shortly. The new book is on similar lines to the present but, although elaborating one or two subjects dealt with in this first book, it is devoted in the main to entirely different instruments.

H. J. C.

June, 1948.

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Thanks are expressed to the following who have co-operated in the production of this book, in most instances by the loan of illustrations and in some cases by supplying useful information. Without their co-operation some chapters could not have been written but it should be emphasized that none of those mentioned is in any way responsible for the accuracy of any of the matter in the book.

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Chapter IX

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SECTION 1

OPTICAL INSTRUMENTS

CHAPTER I

LENSES

A lens is, in general terms, a piece of transparent refracting material designed to form images of objects placed so that pencils of light diverging from points of the object are, after refraction by the lens, made to converge toward or diverge from the corresponding point of the image. The relative distances and the relative sizes of the object and image are related to the focal length of the lens by simple formulae, and the focal length is related to the radii of curvature of the lens surfaces and the refractive index of the material. The lens surfaces are generally parts of spheres, but they may be aspherical or cylindrical and the lens itself is most commonly made of glass of optical quality, but progress is being made in the use of plastic materials with characteristics similar to glass. Lenses, either by themselves, or in combination with other lenses, prisms, mirrors, etc., are used in large numbers of scientific instruments and they are, of course, essential to most optical instruments. In this chapter it is proposed to describe briefly the various forms which lenses take and to discuss the defects to which they are subject so that the application of lenses to scientific instruments in general may be properly understood.

Historical

In very ancient times glass globes filled with water were apparently known, and the early development of lenses is shrouded in mystery, but they were mentioned as early as the 13th century in the writings of Roger Bacon. Their first use was, as far as can be ascertained, as burning glasses and later for spectacles and magnifying glasses, but their image forming properties must have been observed at an early date, and, in his *Magia Naturalis*, published in 1558, Giambattista della Porta mentions the camera obscura and the uses of mirrors and lenses. In 1608 Hans Lippershey, a Dutch spectacle maker, described a telescope which was also invented at about the same time by Galileo. In 1758 Dolland of London was the first to construct an achromatic telescope objective using a combination of two lenses of crown and flint glass. Since that time progress in the design and manufacture of lenses of all kinds has been comparatively rapid. Camera lenses became necessary from 1840 onwards, and because of the new problems arising from wide fields of view, it was at this time that most progress in the theory of lenses was made. Much theoretical work on lenses and the formation of images was done by Airy, Coddington and other British scientists but the first really co-ordinated system of geometrical optics was due to Gauss, who described the formation of images in optical instruments, and to von Seidel, who discussed the defects of the image. It is to Germany also that we must give the credit for the development of optical glass of types specially intended for lenses, although it can safely be said that British optical glass and British design work are the best in the world.

Raw Materials and Manufacture

The manufacture of optical glass is a highly-specialised trade involving the careful selection of materials and regulation of temperatures. The glass itself is usually made in "pots" of fireclay, each pot furnishing a so-called "melt" with definite characteristics as regards refractive index and dispersion. Glasses are described according to their types as Crown, Flint, Barium Crowns and Flints, Borosilicate Crown, Extra Dense Flint, etc., and are listed according to their refractive index and dispersion. The following table shows some characteristic types, and it will be noticed that in the "old" glasses the V-value, which is the reciprocal of the dispersive power, decreases as the refractive index increases, while in the "new" glasses we have types in which the high refractive index corresponds to a high V-value or low dispersion. This important distinction has considerable bearing on the design of lenses, and it was these "new" glasses which were originally developed at Jena in Germany.

Table

Representative Types of Old and New Glasses

Old Glasses	*N*	*V*	*V/N*
Hard Crown	1.5175	60.5	39.9
Extra Light Flint ..	1.5290	51.6	33.8
Light Flint	1.5746	41.4	26.2
Dense Flint	1.6041	37.8	23.5
Extra Dense Flint ..	1.7402	28.4	16.3
New Glasses			
Barium Flint	1.6530	43.2	27.9
Light Flint	1.5674	43.6	27.9
Dense Barium Crown ..	1.6098	53.3	33.1
Extra Light Flint ..	1.5290	51.6	33.8
Dense Barium Crown ..	1.6016	59.9	37.3
Telescope Flint	1.5151	56.4	37.2

The glass from the pots is allowed to cool slowly and is then broken up into lumps from which are moulded the lens blanks supplied to manufacturers. The lens blanks are made as nearly as possible to the size and weight required by the lens manufacturer so that the amount of "roughing" necessary will be reduced to a minimum. The lenses are ground to shape on special machines, on tools of many types, usually spherical cups, using emery of fine grades and finally rouge for polishing. The accuracy of the surfaces so obtained is tested by placing the newly-made surface in contact with a glass test plate whose curvature is accurately known and the discrepancies noted by the appearance of the interference fringes known as Newton's Rings. In optical instruments the lenses are carefully mounted and centred, the distances between the components being an important part of the design. On this account it is most unwise to take an optical instrument to pieces for cleaning unless it is certain that it can be reassembled exactly. The surfaces of lenses should not be touched by the fingers as the grease marks left are difficult to remove. Excessive rubbing must be avoided and soft-boiled linen is the best material to use for cleaning, moistened only with a little benzol or methylated spirit.

Types of Lenses

Simple lenses and the simple components of compound lenses are found in a variety of shapes which are illustrated in Fig. I. 1, the dotted pairs of lines in each diagram show roughly the position of the so-called principal planes. The principal foci of the lens are situated at equal distances from these planes when the lens is in air, and in calculating the distances of object and image by the elementary Gaussian formulae these distances must be measured from these planes. If the lens is considered as "thin" the two planes coincide.

For most purposes, other than in spectacles, lenses are not used singly but in combination with other lenses to form compound systems. Sometimes they are balsamed together to form doublets or triplets or they are spaced in mounts and are invariably associated with a stop or diaphragm which plays an important part in the construction. The reason for the use of these complex lens systems will be at once apparent if an attempt is made to use a single lens say as a telescope objective or eyepiece, or as a microscope objective, or a camera lens; the image formed will be found to be so defective as to be quite useless. The defects of the image are due to the aberrations resulting from the refractions at the lens surfaces. It is most instructive to study the aberrations by examining the image formed by a simple bi-convex lens, using as object a grid of lines in two directions forming a series of squares or any convenient light source. For the lens a spectacle lens will serve provided it is of reasonably short focal length, and the image should be examined on a white card.

Defects of the Image

When an attempt is made to form an image with the object situated exactly on the axis it will be found difficult to decide where the best definition is obtained; the image will be slightly fuzzy and surrounded by a sort of halo. This defect is due to *Spherical Aberration*, which can be defined as the failure of the light passing through the outer zones of the lens to come to the same focus as the light passing through the central zones. It will be found that the image can be made sharper by stopping down the lens so as to reduce the aperture, but no difference will result from moving the stop along the axis. It will also be noticed that the image will be coloured. As the screen is moved farther away from the lens there may be a red central dot surrounded by a greenish fringe edged with violet, and as the screen is moved towards the lens the centre becomes violet and the fringe reddish. This axial colour effect is due to *Chromatic Aberration* and is caused by the differences of the refractive index of the glass for different colours. In general the violet light is bent much more than the red light so that the image of a point source on the axis will be in the form of a spectrum with the violet end nearest the centre of the lens.

The spherical aberration and the chromatic aberration of a concave lens are in the opposite sense to those occurring with a convex lens, so by using two types of glass in combination it is usually possible to construct a lens consisting of convex and concave elements such that the spherical aberration and the chromatic aberration are removed for any given zone of the lens and for any given pair of colours, and very much

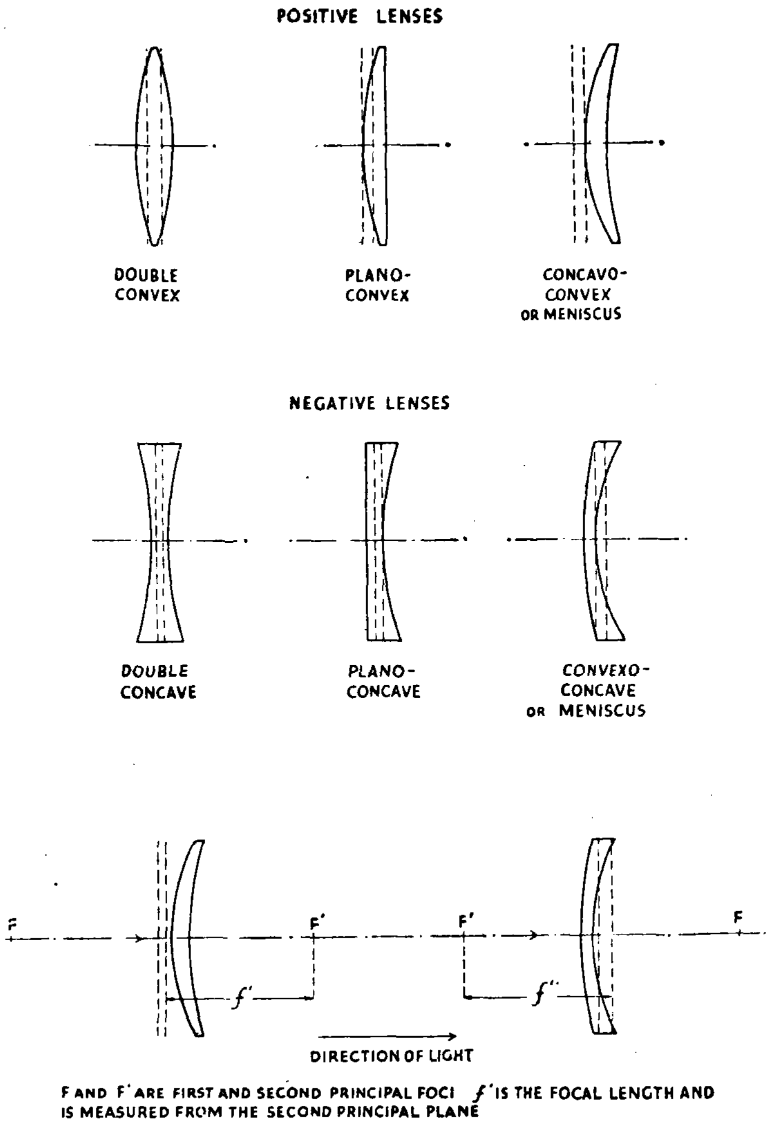

Fig. I. 1. Forms of lenses. The dotted lines indicate the positions of the principal planes.

reduced in general over the whole lens. Such a corrected lens is known as an achromatic doublet.

If now the lens is slightly tilted so that the object is no longer on the axis it will be found almost impossible to form any semblance of an image. The complex appearance which the image will take is caused by a combination of a number of aberrations, which, for convenience of study are known as *Coma*, *Astigmatism* and *Transverse Chromatic Aberration.* It will be found that these transverse aberrations are very sensitive to the position of the stop and the shape and position of the image will change as the stop is moved along the lens axis.

In an attempt to form an image by moving the screen to and fro, it will be seen that when the screen is nearer the lens the image will be drawn out into an elongated form tangential to an imaginary circle drawn about the lens axis and that lines in the object in this direction are reasonably sharp, but much elongated. As the screen is moved away from the lens the image will contract in length and fatten out until it is roughly circular but very fuzzy and on still further withdrawing the screen the image will again be elongated but this time in a radial direction. This defect is due to *astigmatism,* which simply means the failure of the light to form a point image. Stopping the lens down has no effect on the distance between these two elongated images, but moving the stop has, and if lenses of different shapes are tried it will be found that the amount of the astigmatism will change. All the astigmatic images which have been examined will have been found to be associated with a halo or fuzz in one direction, rather like a brush or the tail of a comet, which will be reduced by stopping down and also by moving the stop. This defect is *Coma,* which is defined as the failure of the lens to form an image of the calculated size for all zones of the lens. In an achromatic doublet the coma can be reduced by a careful choice of glasses, and a coma-free doublet is often spoken of as an *aplanat.* Telescope objectives are an important example of a type of lens which is designed to be as free as possible from spherical aberration, chromatic aberration and coma. When the astigmatism is corrected as in photographic lenses the lens is frequently called an *anastigmat.*

No mention has yet been made of transverse chromatic aberration or chromatic difference of magnification as it is frequently called, but this defect is almost self-explanatory and is noticed as a colour fringe particularly when examining an object with a magnifying glass; it is simply caused by the failure of the lens to form images of the same size for each colour of light.

In addition to the aberrations which have been described it will be found, if an extended object is used, that it will be generally impossible to find a position of the screen for which the whole image will be in focus; this is of course due to *curvature* of the image. Assuming that the best image will be formed at the point between the two astigmatic line images where the circular patch was found, it is obvious that the only way to alter the curvature will be by altering the astigmatism, but even if the astigmatism could be entirely removed the best images will still be formed on a curved surface, and moreover, no changes in the shape of the lens will in any way reduce this inherent curvature which depends only on the focal length and the refractive index of the glass. This inherent curvature is called the *Petzval curvature* of the lens, but the best image will only be formed on this Petzval surface if there is no astigmatism. Finally, it will generally be found that the image also suffers from *distortion,* a defect which is very sensitive to the position of the stop. In photographic lenses the elimination of distortion is considered of the utmost importance, for otherwise it would be quite impossible to obtain good photographs of buildings and in fact, cheap cameras, in which single lenses are used, have so much distortion that architectural subjects cannot be photographed with any real success.

From the foregoing it should be quite obvious that the design of lenses for optical instruments is no simple matter, and lens design, in fact, is a highly-specialised business. The elementary formulæ found in text books on light are of no value whatever and unfortunately there is no compact and logical algebra available to the designer. The work consists in gaining experience from successful attempts and the laborious tracing of rays by trigonometrical computation, repeated trial and error and a final compromise. The possible combinations of curves, air spaces and glasses is almost infinite, but rough guides and experience can be used to curtail to some extent the early parts of design work. In the following paragraphs will be found a short description of some of the actual forms of simple and compound lenses.

Spectacles

The lenses used in spectacles for the correction of defective eyesight form a good example of the use of thin single uncorrected lenses, but even in spectacles the shape is of importance and in recent years contact lenses have been produced which are fitted directly to the front of the eye. Convex lenses are used for the correction of long sightedness, concave lenses for short sight, cylinders for astigmatic eyes and prisms to correct any lack of parallelism in the eyes. Spectacle makers usually stock large quantities of half-finished lenses, ground to various shapes on one side and with the other side ready for finishing to any curve, cylinder or prism, according to the optician's prescription. The power of spectacle lenses is always quoted in *dioptres*, one dioptre being the power of a lens of one metre or forty inches focal length, and power being defined as the reciprocal of the focal length. Thus the power of a lens in dioptres is equal to 40 divided by the focal length in inches. Spectacle lenses may be double convex or plano convex in shape, but it is more usual and better to fit "periscopic" or meniscus lenses to spectacles because the correction is then better over a wide field. Meniscus lenses are shown in Fig. I. 1, and the periscopic type are of shallow meniscus form, the curvatures being standardised for ease of production.

Magnifying Glasses

The simple magnifying glass or reading glass of moderate power is so familiar that no description is necessary, but where more power is required for greater magnification it is soon found that the simple lens is no longer adequate. Distortion and chromatic effects are the two main defects which become apparent as soon as high degrees of magnification are used. Ordinary high power magnifiers for dissecting work and other special purposes are often sold in the form of achromatic doublets of plano convex shape and such lenses should be held with the plano side nearest the object if the eye is far away from the lens, but with the convex side nearest the object if the eye is held close to the lens. The inconvenience of having to turn the lens over to find the correct way of using it is removed by the use of an achromatic triplet first made

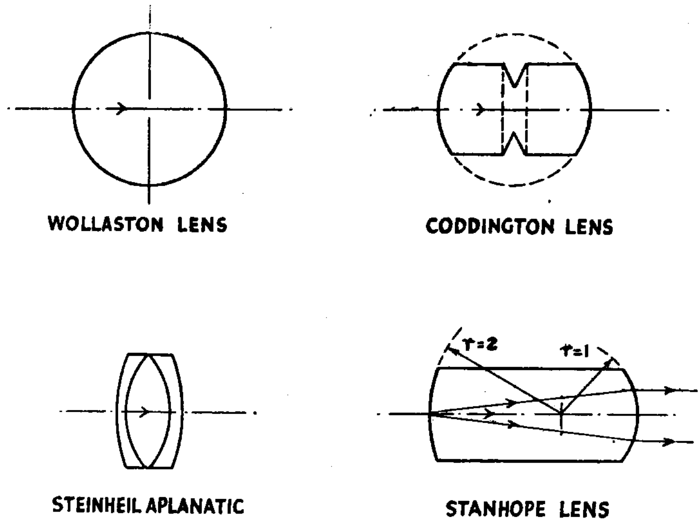

Fig. I. 2. Magnifying glasses. Some special forms of magnifying glasses. Simple lenses are also used for this purpose.

by Steinheil and shown in Fig. I. 2. The Wollaston and Coddington lenses were attempts to eliminate colour effects with the use of only one glass but they have curved fields which are troublesome. The Stanhope lens is much used in very minute form in which a picture, usually advertising some resort, is transferred on the less curved surface and is seen highly magnified when the eye is placed close to the other side.

The magnifying power of a lens is usually defined as the ratio of the size of an image formed by the lens at the least distance of distinct vision (10 inches) to the actual size of the object and the magnifying power is thus equal to 10 divided by the focal length in inches, or the power in dioptres divided by 4.

Telescope Objectives

It has already been said that for a telescope objective to be of any value it must be achromatic and free from spherical aberration and coma. For small telescopes, up to about 2 inches in diameter, these conditions can be reasonably easily fulfilled by a cemented doublet consisting of a hard crown and a dense flint glass, but where larger diameters are required the pair of lenses forming the doublet are seldom cemented and may be of the type shown as the Fraunhoffer objective in Fig. I. 3. The Gauss type of telescope objective, frequently fitted in large theodolites, is designed to be free from spherical aberration for two colours, thus giving very good definition for very small objects on the axis. For astrographic purposes, where it is important to be able to focus visually and then to photograph a star, the Cooke photo-visual objective is invaluable and for general astronomical photography where a comparatively large field is required, a photographic objective such as the Tessar type is often used.