There is a wide variety of optical instruments with which the human eye forms an integral part of the overall system. This book provides a comprehensive description of the construction and image formation in such visual optical instruments, ranging from simple magnifiers, through microscopes and telescopes, to more sophisticated interferometric and diffractive devices. Throughout, details of the eye's interaction with a particular optical instrument, the visual ergonomics of the system, are emphasised.

The book begins with a section on the general theory of image formation and a description of basic optical components. The various optical instruments that can be adequately described using geometrical optics are then discussed, followed by a section on diffraction and interference and the instruments based on these effects. There are separate sections devoted to ophthalmic instruments and aberration theory, with a final section covering visual ergonomics in depth.

Dealing with basic physical principles, as well as engineering and design issues, and containing many problems and solutions, this book will be of great use to undergraduate and graduate students of optometry, optical design, optical engineering, and visual science, and to professionals working in these and related fields.

The eye and visual optical instruments

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Preface

The purpose of this book is to present a thorough description of the construction and image formation of visual optical instruments, ranging from simple magnifiers, through microscopes and telescopes, to the more sophisticated instruments based upon interference and diffraction. There are many other types of optical instruments, such as spectrophotometers and laser systems, but these are not visual optical instruments; that is, they are not used with the eye as an essential component in the imaging process. The only instrument that we include in this book that may not be regarded as a visual optical instrument is the camera. However, we have included the camera, because while one can take a photograph without any "eye" input, the eye is often used to aim the camera and the final image is usually viewed by the eye, either directly or with a projection system.

There are many other textbooks on optics but most of these only briefly discuss visual optical instruments and even more briefly discuss any visual ergonomic aspects of these instruments. We believe that the major strength of this book is its emphasis on the detail of the construction and image formation and most importantly the visual ergonomic aspects. Visual ergonomics is the study or application of the properties of the eye to human performance. In this context, visual ergonomics involves the following factors that may affect vision through an optical instrument: the aberrations of the eye, depth-of-field of the eye, the role of the pupil of the eye, the amplitude of accommodation, refractive errors, visual acuity and the coordination of the two eyes in binocular vision.

Apart from a more comprehensive treatment of visual optical instruments and the inclusion of visual ergonomics, this book includes other topics not normally covered in standard texts. Perhaps the most important is a discussion (Chapter 10) on defocus and focussing techniques.

The book is divided into six parts and a set of appendices, with the chapters in each part having a common theme. Part I covers the general theory of image formation and the description of the optical components that make up a system. Part II is dedicated to individual optical instruments that can be adequately described using geometrical optics, usually with one instrument per chapter. Part III describes two important aspects of physical optics (interference and diffraction), some interesting visual optical instruments based upon these effects and the importance of diffraction to image formation. Part IV is set aside for specific ophthalmic instruments. Part V covers general aberration and image quality theory as well as the aberrations and image quality of the eye. Part VI is dedicated to the visual ergonomics of visual optical instruments.

Various professionals – vision scientists, optometrists, ophthalmologists, microscopists, astronomers and those in surveillance professions such as the police and military – regularly use visual optical instruments. This book will be useful to these professionals, particularly those who need to understand the workings of these instruments in order to understand their limitations. However, visual optical instruments have a wider range of uses and by a wider community.

Some typical instrument uses are listed in the following table:

Instrument	Chapter No.	Uses
Ophthalmic lenses	14	correction of refractive errors of the eye
Simple magnifiers and eyepieces	15	inspection of fine detail, down to about 0.01 mm in size, fine mechanisms, e.g. watches, electronic components low vision magnifiers
Microscopes	16	inspection of very fine detail from about 0.1 mm down to the wavelength of light which is approximately 0.0005 mm components in other instruments such as the slit lamp or the bio-microscope
Telescopes	17	magnification of distant objects (e.g. astronomical bodies) components in many other instruments such as binoculars, spectrometers, focimeters low vision magnifiers or field expanders viewfinders (usually Galilean) in cameras and security doors
Macroscopes	18	magnification of objects at a close distance, but not so close that a microscope can be used
Relay systems, e.g. periscopes, endoscopes and fibrescopes	19	transmission of images over some distances and around corners, e.g. inspection of internal organs and inside machines
Angle and distance measuring instruments (e.g. sextants and rangefinders)	20	measurement of angular distance measurement or estimate of distance
Cameras	21	recording of scenes on photographic material or for electronic recording, e.g. video camera
Projection systems	22	projection of photographic slides or other suitable objects, usually at a high magnification
Collimators	23	production of images at optical infinity, i.e. simulation of very distant scenes or targets checking of infinity settings on many instruments such as in eyepieces, telescopes and camera lenses
Photometers and colorimeters	24	measurement of the light level or colour of a target
Interferometers	25	testing of visual acuity by producing sinusoidal fringes on the retina that by-pass the optics
Diffraction and diffractive devices	26	Fresnel zone plate forms of bifocal ophthalmic lenses speckle patterns for the measurement of refractive error effect of diffraction on image quality
Focimeters	27	measurement of the vertex power of ophthalmic lenses
Radiuscopes and keratometers	28	measurement of the radius of curvature of surfaces
Ophthalmoscopes	29	detailed inspection of the retina
The Badal optometer	30	presentation of stimuli of constant size at different distances
Optometers	31	measurement of the level of accommodation or refractive error
Binocular vision testing instruments	32	measurement of binocular vision

We have included worked examples in the book for two reasons. One is that worked examples help to give some concrete interpretation to what may at first appear to be abstract quantities. The other reason is that many calculations, such as ray tracing, can be done by computer. The worked examples can be used to check the computer program.

Acknowledgements

This book was started by George Smith, who owes his interest in optics to Professor H. H. Hopkins FRS (deceased), his doctorate supervisor while at the Reading University (1968–1972). In those early days of the book, before being joined by David Atchison, he was also encouraged by Professor V. V. Rao (deceased) at the Physics Department of the Regional Engineering College, Warangal, Andra Pradesh, India.

Symbols, signs and other conventions

Symbols

The following is a list of general symbols used in this book. A list of other symbols specific to each chapter is given at the end of the chapter. Where possible the lower case (small) characters are used for distance and the upper case (capitals) are used for the corresponding reciprocals. The most common exceptions are the radius of curvature of a surface and the diameter of the pupil. The surface curvature is denoted by C not R and the pupil diameter is denoted by the symbol D.

As a general rule, a symbol that is not followed by a prime symbol (′) indicates an object space quantity and a symbol followed by a prime symbol indicates an image space quantity.

λ	wavelength in vacuum
λ_d	= 587.6 nm: wavelength of the helium yellow spectral line
λ_F	= 486.1 nm: wavelength of the hydrogen blue spectral line
λ_C	= 656.3 nm: wavelength of the hydrogen red spectral line
r	radius of curvature
C	surface curvature ($C = 1/r$)
F	equivalent power of a system

Object and image space quantities (Note that symbols for points are written in the *Poetica Chancery* font)

$\mathcal{O}, \mathcal{O}'$	object and image positions (axial case)
$\mathcal{Q}, \mathcal{Q}'$	object and image positions (off-axis case)
$\mathcal{F}, \mathcal{F}'$	front and back focal points
$\mathcal{P}, \mathcal{P}'$	front and back principal points
$\mathcal{N}, \mathcal{N}'$	front and back nodal points
$\mathcal{V}, \mathcal{V}'$	front and back vertex points
$\mathcal{E}, \mathcal{E}'$	centres of entrance and exit pupils
l, l'	object and image distances from respective principal planes
L, L'	corresponding (reduced) vergences
l, l'_v	object and image distances from respective vertex planes
x, x'	object and image distances from respective focal points
$\bar{l}, \bar{l}'$	distances of pupils from respective principal planes
$\bar{L}, \bar{L}'$	corresponding vergences
$\bar{l}_v, \bar{l}'_v$	distances of pupils from respective surface vertices
$\bar{L}_v, \bar{L}'_v$	corresponding vergences
η, η'	object and image sizes
$\bar{\rho}, \bar{\rho}'$	radii of entrance and exit pupils
D, D'	diameters of entrance and exit pupils
u, u'	paraxial ray angles (also angles of paraxial marginal ray)
h, h'	paraxial ray heights (also heights for paraxial marginal ray)
$\bar{u}, \bar{u}'$	paraxial pupil ray angles
$\bar{h}, \bar{h}'$	paraxial pupil ray heights

Greek alphabet

α A	alpha	η H	eta	ν N	nu	τ T	tau
β B	beta	$\theta\Theta$	theta	$\xi\Xi$	xi	$\upsilon\Upsilon$	upsilon
$\gamma\Gamma$	gamma	ι I	iota	o O	omicron	$\phi\Phi$	phi
$\delta\Delta$	delta	κ K	kappa	$\pi\Pi$	pi	χX	chi
ϵ E	epsilon	$\lambda\Lambda$	lamda	ρ P	rho	$\psi\Psi$	psi
ζ Z	zeta	μ M	mu	$\sigma\Sigma$	sigma	$\omega\Omega$	omega

Sign convention

The mathematical theory of optical systems requires a sign convention, particularly for ray tracing. The choice of a sign convention is arbitrary but it must be consistent. In this book we use the standard cartesian and trigonometric sign conventions. That is, distances to the left of a surface or lens or below the optical axis are negative and those to the right or above are positive. Angles which are due to an anti-clockwise rotation of the ray from the optical axis are positive and those due to a clockwise rotation are negative. This sign convention is explained more fully in Chapter 2.

Distance notation and sign of distance

Distances are denoted by either a single lower case letter such as l or two upper case letters, e.g. $\mathcal{VF}$. In this example, $\mathcal{V}$ and $\mathcal{F}$ are both points, usually on the optical axis, and thus $\mathcal{VF}$ denotes the distance from $\mathcal{V}$ to $\mathcal{F}$. If $\mathcal{F}$ is to the right of $\mathcal{V}$, this distance is positive, and if $\mathcal{F}$ is to the left of $\mathcal{V}$, then the distance is negative.

Notation for refractive index on diagrams

The refractive indices are denoted by the symbol n, n', μ or a number written inside a circle or ellipse.

Units and their abbreviations

metre	m
centimetre	cm
millimetre	mm
micrometre	μm
nanometre	nm
second	s
prism dioptre	Δ
hertz	Hz
Kelvin	K
radian	rad
degrees	°
cycles per degree	c/deg
cycles per radian	c/rad
Joule	J
exposure	lux.s
lumen	lm

lux (lumens per squared metre)	lm/m^2
candela	cd
candelas per squared metre	cd/m^2
steradian	st
Watt	W
Joule-seconds	J.s

References and bibliography

From time to time in various chapters, we have cited other published work, and this material is fully referenced at the end of the respective chapter. In some chapters we have also supplied references for alternative or background reading. The cited material is marked with an asterisk (*).