Introduction to Classical and Modern Optics

THIRD EDITION

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Preface

THE PURPOSE AND EMPHASIS in this third edition remain the same: to provide a concise, and still readable, *Introduction to Classical and Modern Optics,* written for advanced undergraduates and for a course spanning two semesters or the equivalent. I have made the text as self-contained as practical, set out the motivation for each step, and avoided shortcuts of the it-can-be-shown-that type.

Compared with the earlier editions, I have again made major changes. I continue using the rational *Cartesian sign convention,* long familiar from ray tracing and from ophthalmic optics but until recently somewhat slighted in physics. This convention is essential for the concept of *vergence* and mandatory in any *computer-aided lens design.* This dual connection identifies the two groups of readers to which this *Introduction to Optics* is addressed in particular: those interested in the *scientific and engineering applications of optics* and those preparing for the *ophthalmic professions.*

Virtually every chapter on *geometrical optics* opens with the same triplet combination of lenses. Each time, the light progresses a little further, showing the logic in the sequence of topics: from thin lenses to a combination of lenses, to stops and pupils, to ray tracing, to aberrations, and to computer-aided lens design (CALD).

Many chapters have been rewritten, most extensively the chapters on the propagation of light, ray tracing, gradient-index and fiber optics, systems evaluation, interference, coherence, optical data processing, atomic spectra, and lasers. Completely new are the chapters on CALD and on Light Sources and Detectors.

As before, ample space has been allocated to classical topics such as thin lenses, optical systems, and polarization. But modern subjects such as holography, and of course lasers and laser safety, as well as Fourier transform spectroscopy and radiometry and photometry, are also presented in reasonable detail. Relativistic optics, likely to play an important part in celestial navigation, is fun to read, aside from its utilitarian aspect.

As a prerequisite, all that is needed is a good background in general physics and a working knowledge of how to use a calculator. A concurrent course in calculus, and some knowledge of a computer language, are desirable though not essential.

Numerous worked-out *examples*, from penumbras to relativistic reflection, are interspersed throughout the text. *Problems*, ranging from easy to difficult, are found at the end of each chapter, following the *Suggestions for Further Reading*. Most of the examples and problems are new. All have been use-tested and modified where needed. (Answers to the odd-numbered problems are found in the back of the book.) None of the problems is intended as "busy work"; all are realistic and apply to practical situations; some, in fact, were drawn from consulting work I do from time to time. *Lecture demonstrations* are referred to on occasion. A great many *historical footnotes* have been included to reveal the human side of optics' great masters, adding color to the description of their accomplishments. (For the statistical-minded, there are 30 chapters, 344 illustrations, 89 examples, 7 computer programs, 121 historical footnotes, 549 problems, and 154 Suggestions for Further Reading.)

I have enjoyed writing this new edition. It took hundreds of hours of lecturing. It also took the patience of a great many students, questioning, challenging, attentive, and at times not so attentive, for me to discover—often by trial and error—how to get a concept across. How do I best present the idea of principal planes, the vector form of Snell's law, the use of Cornu's spiral, the theory of stimulated emission? How do I present the fantastically wide field of optics at a reasonable level and within a reasonable length of time? There is no final answer to that, just steps of successive improvement.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the assistance I have received from others. Many of my colleagues have helped, in ways large and small, with the preparation and revision of this new edition. Much appreciation also goes to my students. But comments, both laudatory and critical, have come also from readers I have never met. In particular, I wish to thank Thomas B. Greenslade, Jr., David A. Cantley, and Peter A. Barnes (geometrical optics), Silverio P. Almeida and Michael E. Mickelson (physical and modern optics), Laurel Gregory, and Patricia R. Wakeling *(Applied Optics)*. I also express my gratitude to the editorial and production staff of Prentice Hall, especially to Holly Hodder, acquisitions editor, and to Kathleen Lafferty, production editor; because of them my manuscript became the book it now is.

Jurgen R. Meyer-Arendt

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PART 3 WAVE OPTICS

Introduction

I BEGIN THIS INTRODUCTION TO OPTICS by presenting right away a complex practical problem. Look at Figure 0-1. This is a combination of lenses, a lens *system,* containing a positive lens in front (on the left), a negative lens behind it, and another positive lens in the back (on the right). These lenses have certain surface characteristics, they have certain thicknesses, and they are certain distances apart. Probably, they are made out of different types of glass. By choosing these parameters correctly, we can obtain a system of superior performance. In fact, the system shown is the basis for some of the best, and best known, photographic camera lenses.

How does the system work? Why are the lenses of the type shown preferable to other lenses? Why is this system superior to other systems? These are questions that we are not yet ready to answer. We will use this system as an example and a guide to introduce many of the concepts of optics.

More specifically, we will use this model to introduce *geometrical optics.* Geometrical

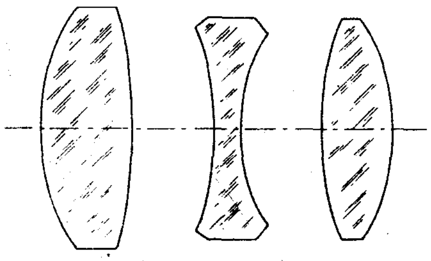

Figure 0-1 Combination of three lenses, used for introducing various aspects of geometrical optics.

optics is that part of optics where the wave-nature of light can be neglected. *Physical optics* is more inclusive: it is the branch of optics concerned with the wave properties of light, the superposition of waves *(interference)*, and the deviation of light from its rectilinear propagation by means other than geometrical optics *(diffraction)*. Physical optics also includes the concept of *transformation*, which is fundamental to optical data processing, pattern recognition, and holography. In *quantum optics* we discuss light sources and detectors, spectra, absorption, and the ubiquitous laser. *Relativistic optics* points to the future.

Some phenomena in optics are easy to see. Others are very subtle. Look at a street lamp through the fabric of an open umbrella. You will see light *fans*, extending in various directions. These are due to diffraction. Or look at a fairly bright star (without the umbrella). You may see light fans or "points" that seem to emanate from the star. In reality, there are no such points. They are merely due to occasional straight segments in the otherwise round pupil of the eye caused by a hardening of the smallest arteries, arteriolosclerosis.

And so, in the art of all ages, stars have traditionally been represented as objects with a multitude of points. However, a star with an odd number of points, as shown in Figure 0-2, is wave-optically impossible because the light fans must, by necessity, always occur in pairs.

Figure 0-2 Artist's conception of a star. Stained-glass window in St. John's Church, Herford, Germany, fourteenth century.

Optics is a field of science that is particularly lucid, logical, challenging, and beautiful. Most of our appreciation of the outside world—nature, art—comes to us through light. We will now proceed to discuss its many aspects.

A BIBLIOGRAPHY ON OPTICS

E. HECHT, *Optics*, 2nd edition (Reading, MA: Addison-Wesley Publishing Company, Inc., 1987).

F. A. JENKINS and H. E. WHITE, *Fundamentals of Optics*, 4th edition (New York: McGraw-Hill Book Company, 1976).

M. YOUNG, *Optics and Lasers*, 3rd edition (New York: Springer-Verlag New York, Inc., 1986).

W. H. A. FINCHAM and M. H. FREEMAN, *Optics*, 9th edition (Woburn, MA: Butterworth Publishers, Inc., 1980).

If you want to work on some research project in optics, you should consult, in addition,

M. BORN and E. WOLF, *Principles of Optics*, 6th edition (Elmsford, NY: Pergamon Press, Inc., 1980).

R. S. LONGHURST, *Geometrical and Physical Optics*, 3rd edition (New York: Longman, Inc., 1974).

M. V. KLEIN and TH. E. FURTAK, *Optics*, 2nd edition (New York: John Wiley & Sons, Inc., 1986).

H. HAFERKORN, *Optik*, 2nd edition (Berlin: VEB Deutscher Verlag der Wissenschaften, 1984).

You should also read, at least, the following journals:

Applied Optics
Journal of the Optical Society of America
Scientific American

1.1

The Propagation of Light

THE FIELD OF OPTICS IS OFTEN DIVIDED into Geometrical Optics and Physical Optics, as if there were a dichotomy, a division of optics into separate entities. But, take the example of image formation, a topic that surely pervades much of optics. Both geometrical optics and physical optics discuss image formation, albeit at different levels of sophistication. The more elementary approach is by geometrical optics. Much more comprehensive is to discuss it in terms of diffraction and optical transformation.

Let us begin with the *propagation* of light. Look at sunlight that, on a misty morning, breaks through the dense foliage of a tree. The light, made visible by the moisture in the air, travels along straight lines called *rays*. Rays follow the law of *rectilinear propagation*. But, why are the rays in Figure 1.1-1 diverging? That is merely an illusion; in reality, the rays are parallel, just as railroad tracks are parallel extending to the horizon; they only *seem* to be converging.

CHARACTERISTICS OF LIGHT

Under certain conditions, light behaves like a sequence of *waves*. If we set a rope in oscillatory motion, waves will propagate along the rope. Actually, the rope moves only up and down. It does not move forward. What moves forward is the *wave configuration*. Wave configurations can move along in one, two, or three dimensions. In a rope, the wave moves along in one dimension. Surface ripples on a pond expand in two dimensions. Sound and

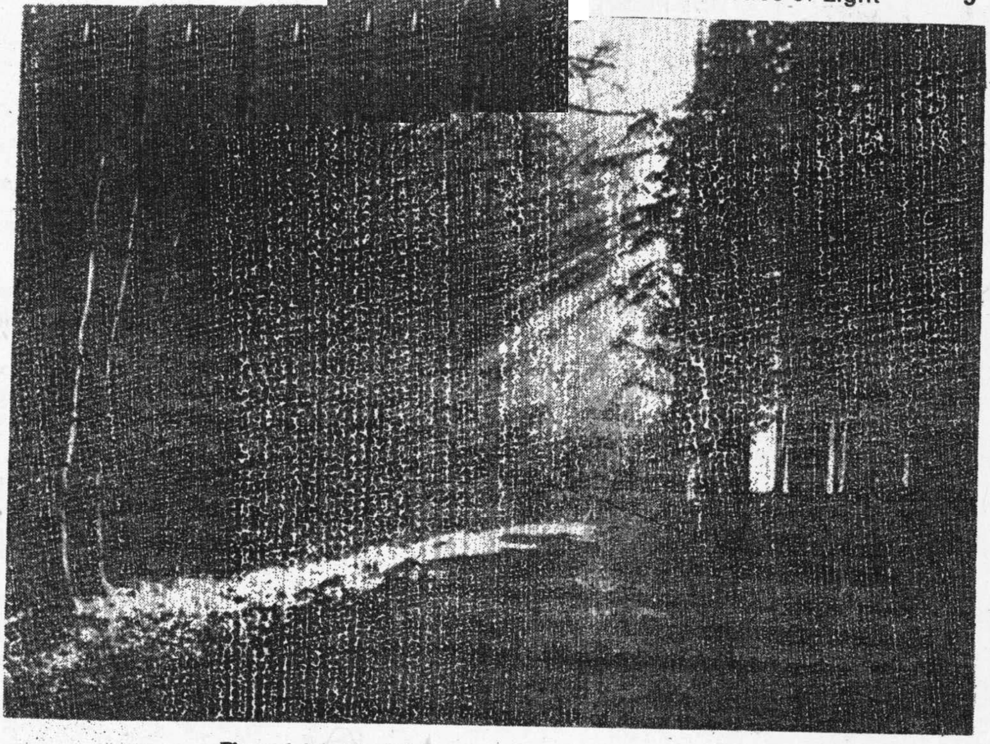

Figure 1.1-1 Sunlight passing through the foliage of a tree.

light propagate through space in three dimensions. Terms we need to know in this context are the following·

Amplitude, A, is the *height* of the wave above the average. Amplitudes vary between a maximum of +A and a maximum of −A (Figure 1.1-2).

Wavelength, λ, is a measure of *length.* It is the length of a full wave, from peak to peak. Wavelengths are measured in the same units as length in general. The basic unit of length in the Système International d'Unités, the International System of Units, SI, is the meter, m. But since the wavelength of light is rather small, fractional units of a meter are needed. These are

1 millimeter, mm, 10^{-3} m.

1 mi′crometer, μm, 10^{-6} m, 1/1000 of a millimeter. The prefix μ alone must not be used. (Do not confuse with micro′meter, accent on the *o*, which is an instrument for measuring small distances.)

1 nanometer, nm, 10^{-9}. This is the *preferred unit of wavelength of light* (in the visible part of the spectrum).

1 Ångström, Å, 10^{-10} m.*

*Named for Anders Jonas Ångström (1814-1874), Swedish spectroscopist and professor of physics and astronomy at the University of Uppsala. Ångström found that a cold gas absorbs the same wavelengths of light that it emits when hot, discovered hydrogen in the spectrum of the sun, carefully determined the wavelengths of all other lines he could see, and published the results in *Recherches sur le spectra solaire* (Uppsala, 1869).