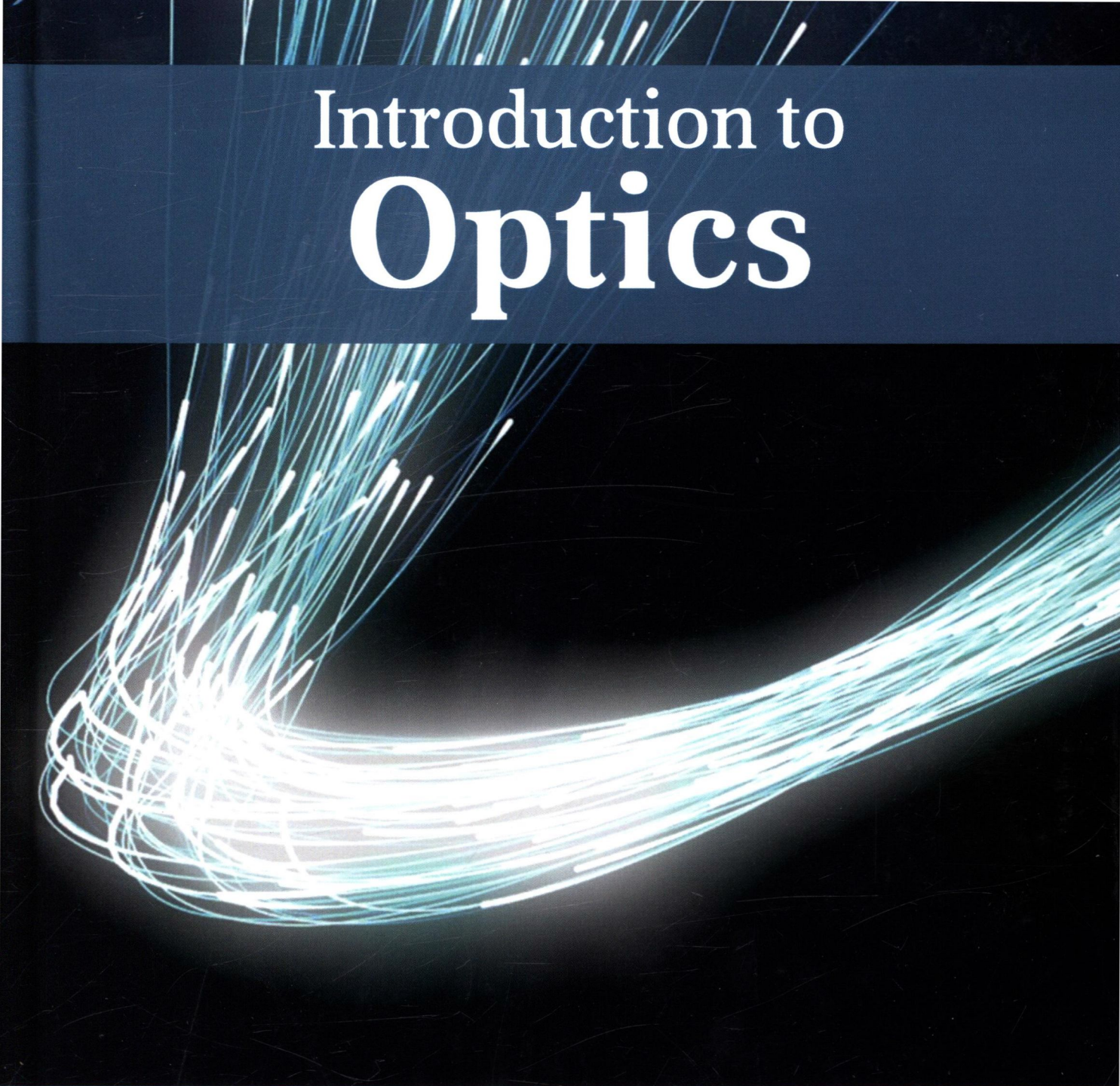


An abstract graphic showing a dense bundle of light rays, primarily in shades of cyan and white, curving from the top left towards the bottom right against a black background. The rays appear to originate from a point and fan out as they move, creating a sense of motion and depth.

Introduction to Optics

Albie Reid

 **Larsen & Keller**

Introduction to Optics

This book provides comprehensive insights into the field of optics. It provides detailed information about the various advancements within this field. Optics is the study of light. It also discusses the design and manufacture of technology related to the manipulation and control of sources of light. It is used in many fields like photography, astronomy, optometry, ophthalmology and many other engineering fields. The aim of this textbook is to provide thorough insights to readers about this subject. Most of the topics introduced in it cover fundamentals techniques and the applications of optics. This book, with its detailed analyses and data, will prove immensely beneficial students involved in this area at various levels.

Albie Reid pursued his Master of Science in Optics and Photonics from University of Central Florida College of Optics and Photonics, United States. He is an active member of several scientific and technical societies, where he continues to share his expertise and knowledge in the field of the electromagnetic wave, physical optics and fiber optics. Reid has been awarded the "Distinguished Teacher of the Year" award for his excellence in guiding students. Today, he is a veteran in the field of optical engineering with numerous revolutionizing texts, articles and research papers to his credit.

 **Larsen & Keller**
www.larsen-keller.com

ISBN 978-1-63549-208-8



OBS-BN



09L1471647

Reid Introduction to Optics

H. L. Larsen & Keller

Introduction to Optics

Edited by
Albie Reid

Introduction to Optics
Edited by Albie Reid
ISBN: 978-1-63549-208-8 (Hardback)

© 2017 Larsen & Keller



Published by Larsen and Keller Education,
5 Penn Plaza,
19th Floor,
New York, NY 10001, USA

Cataloging-in-Publication Data

Introduction to optics / edited by Albie Reid.

p. cm.

Includes bibliographical references and index.

ISBN 978-1-63549-208-8

1. Optics. 2. Optical instruments. 3. Optics--History.

4. Optical engineering. I. Reid, Albie.

QC355.3 .I58 2017

535--dc23

This book contains information obtained from authentic and highly regarded sources. All chapters are published with permission under the Creative Commons Attribution Share Alike License or equivalent. A wide variety of references are listed. Permissions and sources are indicated; for detailed attributions, please refer to the permissions page. Reasonable efforts have been made to publish reliable data and information, but the authors, editors and publisher cannot assume any responsibility for the validity of all materials or the consequences of their use.

Trademark Notice: All trademarks used herein are the property of their respective owners. The use of any trademark in this text does not vest in the author or publisher any trademark ownership rights in such trademarks, nor does the use of such trademarks imply any affiliation with or endorsement of this book by such owners.

The publisher's policy is to use permanent paper from mills that operate a sustainable forestry policy. Furthermore, the publisher ensures that the text paper and cover boards used have met acceptable environmental accreditation standards.

Printed and bound in China.

For more information regarding Larsen and Keller Education and its products, please visit the publisher's website www.larsen-keller.com

Preface

This book provides comprehensive insights into the field of optics. It provides detailed information about the various advancements within this field. Optics is the study of light. It also discusses the design and manufacture of technology related to the manipulation and control of sources of light. It is used in many fields like photography, astronomy, optometry, ophthalmology and many other engineering fields. The aim of this textbook is to provide thorough insights to readers about this subject. Most of the topics introduced in it cover fundamentals techniques and the applications of optics. This book, with its detailed analyses and data, will prove immensely beneficial students involved in this area at various levels.

A detailed account of the significant topics covered in this book is provided below:

Chapter 1- The branch of physics that involves light, its properties and its interaction with matter is known as optics. Optics as a subject concentrates on the behavior of visible, ultraviolet and infrared light. The chapter on optics offers an insightful focus, keeping in mind the subject matter.

Chapter 2- Optics evolved from the development of lenses. The history of optics is divided into two halves, classical optics and modern optics. Modern optics has developed in the 20th century and covers topics such as wave optics and quantum optics. The following section will not only provide an overview, it will delve deep into the topics related to it.

Chapter 3- The branches of optics discussed in this section are geometrical optics, physical optics, quantum optics, nonimaging optics and nonlinear optics. Geometrical optics defines light propagation in terms of rays whereas physics optics is a branch of optics that concerns itself with diffraction and polarization. This chapter is a compilation of the various branches of optics that form an integral part of the broader subject matter.

Chapter 4- The significant topics of optics explained in this section are optical instruments and optical engineering. An optical instrument processes light waves to improve an image for viewing and optical engineering is the study of optics. The section strategically encompasses and incorporates the major components and significant topics of optics, providing a complete understanding.

Chapter 5- The concepts of optics explained in the following text are photometry, exposure, atmospheric optics, optical vortex, focus and dispersion. Photometry is the study of measuring light; there is a difference between photometry and radiometry. Photometry mainly studies the sensitivity of visible light on the human eye; it measures this by calculating the power of each wavelength by representing the sensitivity of eye at that particular wavelength. This section elucidates the crucial theories of optics.

Chapter 6- Optics is used for scientific and commercial use. Fiber- optic communication is the technique of conveying information from one place to another. This is done by sending pulses of light through an optical fiber. Alternatively the other uses of optics are electromagnetically

induced transparency, superlens, optical fiber, spectrometer and optical computing. This section has been carefully written to provide an easy understanding of the theory of optics.

It gives me an immense pleasure to thank our entire team for their efforts. Finally in the end, I would like to thank my family and colleagues who have been a great source of inspiration and support.

Editor

Table of Contents

Preface	VII
Chapter 1 Introduction to Optics in Engineering	1
Chapter 2 Evolution of Optics	31
Chapter 3 Branches of Optics	41
a. Geometrical Optics	41
b. Physical Optics	47
c. Quantum Optics	48
d. Nonimaging Optics	50
e. Nonlinear Optics	64
f. Crystal Optics	76
g. Near-field Optics	78
h. Lens (Optics)	79
Chapter 4 Significant Topics of Optics	94
a. Optical Instrument	94
b. Optical Engineering	95
Chapter 5 Concepts of Optics	97
a. Photometry (Optics)	97
b. Exposure (Photography)	105
c. Atmospheric Optics	118
d. Wave-particle Duality	129
e. Optical Vortex	141
f. Focus (Optics)	144
g. Dispersion (Optics)	146
h. Opacity (Optics)	152
i. Fourier optics	154
j. Fermat's Principle	172
Chapter 6 Applications of Optics	177
a. Fiber-optic Communication	177
b. Electromagnetically Induced Transparency	190
c. Superlens	193
d. Optical Fiber	211
e. Spectrometer	234

f. Light-emitting diode	236
g. Photonic Integrated Circuit	268
h. Optical Computing	269

Permissions

Index

Introduction to Optics in Engineering

The branch of physics that involves light, its properties and its interaction with matter is known as optics. Optics as a subject concentrates on the behavior of visible, ultraviolet and infrared light. The chapter on optics offers an insightful focus, keeping in mind the subject matter.

Optics is the branch of physics which involves the behaviour and properties of light, including its interactions with matter and the construction of instruments that use or detect it. Optics usually describes the behaviour of visible, ultraviolet, and infrared light. Because light is an electromagnetic wave, other forms of electromagnetic radiation such as X-rays, microwaves, and radio waves exhibit similar properties.



Optics includes study of dispersion of light.

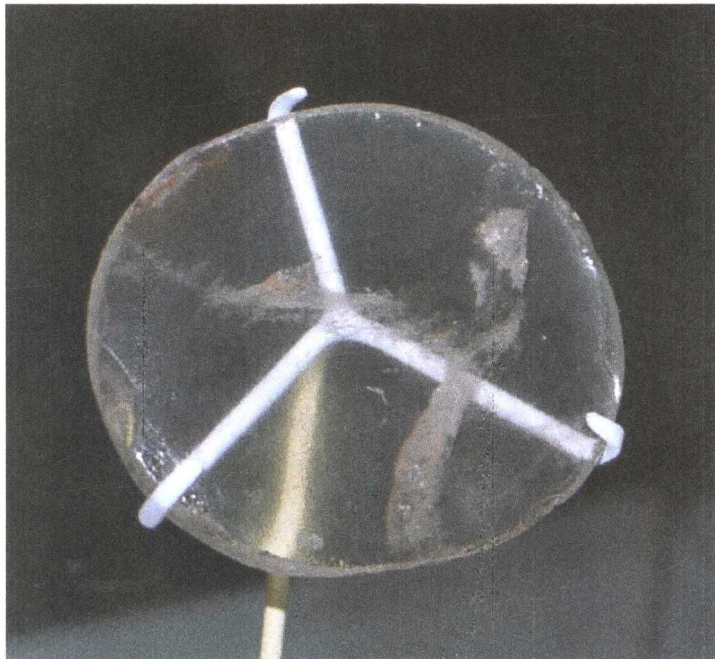
Most optical phenomena can be accounted for using the classical electromagnetic description of light. Complete electromagnetic descriptions of light are, however, often difficult to apply in practice. Practical optics is usually done using simplified models. The most common of these, geometric optics, treats light as a collection of rays that travel in straight lines and bend when they pass through or reflect from surfaces. Physical optics is a more comprehensive model of light, which includes wave effects such as diffraction and interference that cannot be accounted for in geometric optics. Historically, the ray-based model of light was developed first, followed by the wave model of light. Progress in electromagnetic theory in the 19th century led to the discovery that light waves were in fact electromagnetic radiation.

Some phenomena depend on the fact that light has both wave-like and particle-like properties.

Explanation of these effects requires quantum mechanics. When considering light's particle-like properties, the light is modelled as a collection of particles called “photons”. Quantum optics deals with the application of quantum mechanics to optical systems.

Optical science is relevant to and studied in many related disciplines including astronomy, various engineering fields, photography, and medicine (particularly ophthalmology and optometry). Practical applications of optics are found in a variety of technologies and everyday objects, including mirrors, lenses, telescopes, microscopes, lasers, and fibre optics.

History



The Nimrud lens

Optics began with the development of lenses by the ancient Egyptians and Mesopotamians. The earliest known lenses, made from polished crystal, often quartz, date from as early as 700 BC for Assyrian lenses such as the Layard/Nimrud lens. The ancient Romans and Greeks filled glass spheres with water to make lenses. These practical developments were followed by the development of theories of light and vision by ancient Greek and Indian philosophers, and the development of geometrical optics in the Greco-Roman world. The word *optics* comes from the ancient Greek word *πτική* (*optikē*), meaning “appearance, look”.

Greek philosophy on optics broke down into two opposing theories on how vision worked, the “intromission theory” and the “emission theory”. The intromission approach saw vision as coming from objects casting off copies of themselves (called *eidola*) that were captured by the eye. With many propagators including Democritus, Epicurus, Aristotle and their followers, this theory seems to have some contact with modern theories of what vision really is, but it remained only speculation lacking any experimental foundation.

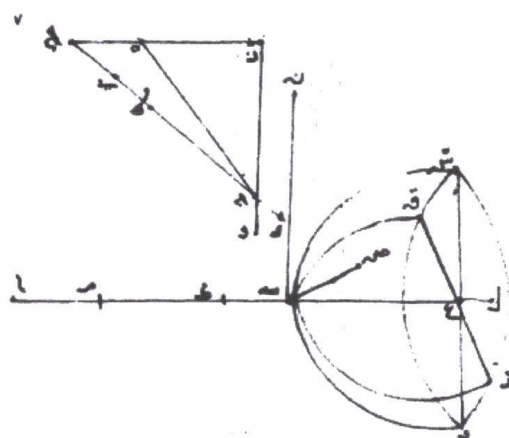
Plato first articulated the emission theory, the idea that visual perception is accomplished by rays emitted by the eyes. He also commented on the parity reversal of mirrors in *Timaeus*. Some hundred years later, Euclid wrote a treatise entitled *Optics* where he linked vision to geometry, cre-

ating *geometrical optics*. He based his work on Plato's emission theory wherein he described the mathematical rules of perspective and described the effects of refraction qualitatively, although he questioned that a beam of light from the eye could instantaneously light up the stars every time someone blinked. Ptolemy, in his treatise *Optics*, held an extramission-intromission theory of vision: the rays (or flux) from the eye formed a cone, the vertex being within the eye, and the base defining the visual field. The rays were sensitive, and conveyed information back to the observer's intellect about the distance and orientation of surfaces. He summarised much of Euclid and went on to describe a way to measure the angle of refraction, though he failed to notice the empirical relationship between it and the angle of incidence.



Alhazen (Ibn al-Haytham), "the father of Optics"

During the Middle Ages, Greek ideas about optics were resurrected and extended by writers in the Muslim world. One of the earliest of these was Al-Kindi (c. 801–73) who wrote on the merits of Aristotelian and Euclidean ideas of optics, favouring the emission theory since it could better quantify optical phenomenon. In 984, the Persian mathematician Ibn Sahl wrote the treatise "On burning mirrors and lenses", correctly describing a law of refraction equivalent to Snell's law. He used this law to compute optimum shapes for lenses and curved mirrors. In the early 11th century, Alhazen (Ibn al-Haytham) wrote the *Book of Optics* (*Kitab al-manazir*) in which he explored reflection and refraction and proposed a new system for explaining vision and light based on observation and experiment. He rejected the "emission theory" of Ptolemaic optics with its rays being emitted by the eye, and instead put forward the idea that light reflected in all directions in straight lines from all points of the objects being viewed and then entered the eye, although he was unable to correctly explain how the eye captured the rays. Alhazen's work was largely ignored in the Arabic world but it was anonymously translated into Latin around 1200 A.D. and further summarised and expanded on by the Polish monk Witelo making it a standard text on optics in Europe for the next 400 years.



لانه انما تراه عليها سطح مستوي غيره فلان هذا السطح يقطع سطح بصر
 على نقطة ت فلا بد من ان يقطع احد خطي ب ن بصر فليكن ذلك
 الخط بصر والفصل المشترك بين هذا السطح وبين سطح قطع ق ر
 خط مستقيم فلان هذا السطح ياتر مسيطر على نقطة ت لخط
 ب ت يطرئ على سطح ق ر بصر على نقطة ت وكذلك خط بصر وفصل
 فلا ياتر مسيطر على نقطة ت سطح مستوي غير سطح ب ن ص ٥

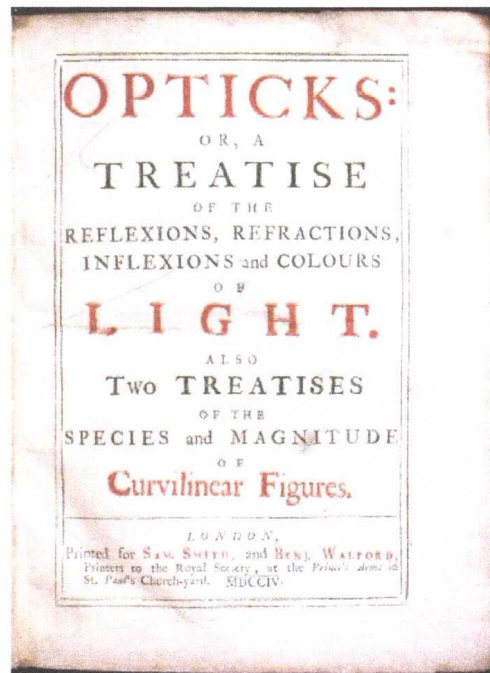
Reproduction of a page of Ibn Sahl's manuscript showing his knowledge of the law of refraction.

In the 13th century in medieval Europe, English bishop Robert Grosseteste wrote on a wide range of scientific topics, and discussed light from four different perspectives: an epistemology of light, a metaphysics or cosmogony of light, an etiology or physics of light, and a theology of light, basing it on the works Aristotle and Platonism. Grosseteste's most famous disciple, Roger Bacon, wrote works citing a wide range of recently translated optical and philosophical works, including those of Alhazen, Aristotle, Avicenna, Averroes, Euclid, al-Kindi, Ptolemy, Tideus, and Constantine the African. Bacon was able to use parts of glass spheres as magnifying glasses to demonstrate that light reflects from objects rather than being released from them.

The first wearable eyeglasses were invented in Italy around 1286. This was the start of the optical industry of grinding and polishing lenses for these "spectacles", first in Venice and Florence in the thirteenth century, and later in the spectacle making centres in both the Netherlands and Germany. Spectacle makers created improved types of lenses for the correction of vision based more on empirical knowledge gained from observing the effects of the lenses rather than using the rudimentary optical theory of the day (theory which for the most part could not even adequately explain how spectacles worked). This practical development, mastery, and experimentation with lenses led directly to the invention of the compound optical microscope around 1595, and the refracting telescope in 1608, both of which appeared in the spectacle making centres in the Netherlands.

In the early 17th century Johannes Kepler expanded on geometric optics in his writings, covering lenses, reflection by flat and curved mirrors, the principles of pinhole cameras, inverse-square law governing the intensity of light, and the optical explanations of astronomical phenomena such as lunar and solar eclipses and astronomical parallax. He was also able to correctly deduce the role of the retina as the actual organ that recorded images, finally being able to scientifically quantify the effects of different types of lenses that spectacle makers had been observing over the previous 300

years. After the invention of the telescope Kepler set out the theoretical basis on how they worked and described an improved version, known as the *Keplerian telescope*, using two convex lenses to produce higher magnification.



Cover of the first edition of Newton's *Opticks*

Optical theory progressed in the mid-17th century with treatises written by philosopher René Descartes, which explained a variety of optical phenomena including reflection and refraction by assuming that light was emitted by objects which produced it. This differed substantively from the ancient Greek emission theory. In the late 1660s and early 1670s, Isaac Newton expanded Descartes' ideas into a corpuscle theory of light, famously determining that white light was a mix of colours which can be separated into its component parts with a prism. In 1690, Christiaan Huygens proposed a wave theory for light based on suggestions that had been made by Robert Hooke in 1664. Hooke himself publicly criticised Newton's theories of light and the feud between the two lasted until Hooke's death. In 1704, Newton published *Opticks* and, at the time, partly because of his success in other areas of physics, he was generally considered to be the victor in the debate over the nature of light.

Newtonian optics was generally accepted until the early 19th century when Thomas Young and Augustin-Jean Fresnel conducted experiments on the interference of light that firmly established light's wave nature. Young's famous double slit experiment showed that light followed the law of superposition, which is a wave-like property not predicted by Newton's corpuscle theory. This work led to a theory of diffraction for light and opened an entire area of study in physical optics. Wave optics was successfully unified with electromagnetic theory by James Clerk Maxwell in the 1860s.

The next development in optical theory came in 1899 when Max Planck correctly modelled black-body radiation by assuming that the exchange of energy between light and matter only occurred in discrete amounts he called *quanta*. In 1905 Albert Einstein published the theory of the photo-electric effect that firmly established the quantization of light itself. In 1913 Niels Bohr showed

that atoms could only emit discrete amounts of energy, thus explaining the discrete lines seen in emission and absorption spectra. The understanding of the interaction between light and matter which followed from these developments not only formed the basis of quantum optics but also was crucial for the development of quantum mechanics as a whole. The ultimate culmination, the theory of quantum electrodynamics, explains all optics and electromagnetic processes in general as the result of the exchange of real and virtual photons.

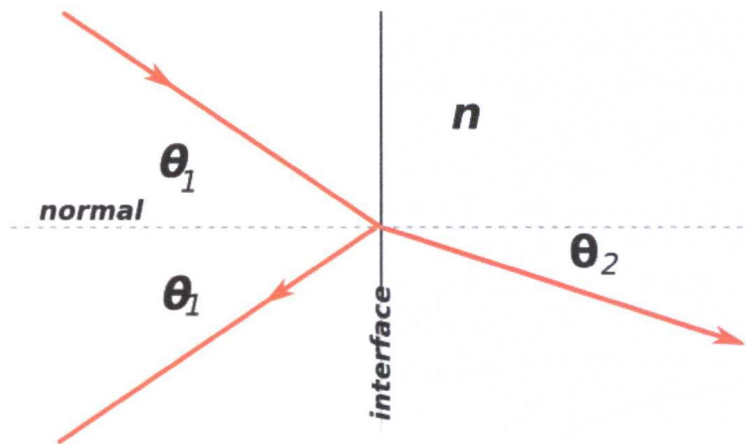
Quantum optics gained practical importance with the inventions of the maser in 1953 and of the laser in 1960. Following the work of Paul Dirac in quantum field theory, George Sudarshan, Roy J. Glauber, and Leonard Mandel applied quantum theory to the electromagnetic field in the 1950s and 1960s to gain a more detailed understanding of photodetection and the statistics of light.

Classical Optics

Classical optics is divided into two main branches: geometrical (or ray) optics and physical (or wave) optics. In geometrical optics, light is considered to travel in straight lines, while in physical optics, light is considered as an electromagnetic wave.

Geometrical optics can be viewed as an approximation of physical optics that applies when the wavelength of the light used is much smaller than the size of the optical elements in the system being modelled.

Geometrical Optics



Geometry of reflection and refraction of light rays

Geometrical optics, or *ray optics*, describes the propagation of light in terms of “rays” which travel in straight lines, and whose paths are governed by the laws of reflection and refraction at interfaces between different media. These laws were discovered empirically as far back as 984 AD and have been used in the design of optical components and instruments from then until the present day. They can be summarised as follows:

When a ray of light hits the boundary between two transparent materials, it is divided into a reflected and a refracted ray.

The law of reflection says that the reflected ray lies in the plane of incidence, and the angle of reflection equals the angle of incidence.

The law of refraction says that the refracted ray lies in the plane of incidence, and the sine of the angle of refraction divided by the sine of the angle of incidence is a constant:

$$\frac{\sin \theta_1}{\sin \theta_2} = n,$$

where n is a constant for any two materials and a given colour of light. If the first material is air or vacuum, n is the refractive index of the second material.

The laws of reflection and refraction can be derived from Fermat's principle which states that *the path taken between two points by a ray of light is the path that can be traversed in the least time.*

Approximations

Geometric optics is often simplified by making the paraxial approximation, or “small angle approximation”. The mathematical behaviour then becomes linear, allowing optical components and systems to be described by simple matrices. This leads to the techniques of Gaussian optics and *paraxial ray tracing*, which are used to find basic properties of optical systems, such as approximate image and object positions and magnifications.

Reflections

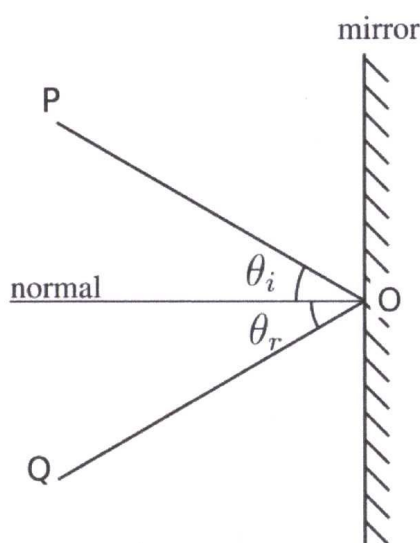


Diagram of specular reflection

Reflections can be divided into two types: specular reflection and diffuse reflection. Specular reflection describes the gloss of surfaces such as mirrors, which reflect light in a simple, predictable way. This allows for production of reflected images that can be associated with an actual (real) or extrapolated (virtual) location in space. Diffuse reflection describes non-glossy materials, such as paper or rock. The reflections from these surfaces can only be described statistically, with the exact distribution of the reflected light depending on the microscopic structure of the material. Many diffuse reflectors are described or can be approximated by Lambert's cosine law, which describes surfaces that have equal luminance when viewed from any angle. Glossy surfaces can give both specular and diffuse reflection.

In specular reflection, the direction of the reflected ray is determined by the angle the incident ray

makes with the surface normal, a line perpendicular to the surface at the point where the ray hits. The incident and reflected rays and the normal lie in a single plane, and the angle between the reflected ray and the surface normal is the same as that between the incident ray and the normal. This is known as the Law of Reflection.

For flat mirrors, the law of reflection implies that images of objects are upright and the same distance behind the mirror as the objects are in front of the mirror. The image size is the same as the object size. The law also implies that mirror images are parity inverted, which we perceive as a left-right inversion. Images formed from reflection in two (or any even number of) mirrors are not parity inverted. Corner reflectors retroreflect light, producing reflected rays that travel back in the direction from which the incident rays came.

Mirrors with curved surfaces can be modelled by ray-tracing and using the law of reflection at each point on the surface. For mirrors with parabolic surfaces, parallel rays incident on the mirror produce reflected rays that converge at a common focus. Other curved surfaces may also focus light, but with aberrations due to the diverging shape causing the focus to be smeared out in space. In particular, spherical mirrors exhibit spherical aberration. Curved mirrors can form images with magnification greater than or less than one, and the magnification can be negative, indicating that the image is inverted. An upright image formed by reflection in a mirror is always virtual, while an inverted image is real and can be projected onto a screen.

Refraction occurs when light travels through an area of space that has a changing index of refraction; this principle allows for lenses and the focusing of light. The simplest case of refraction occurs when there is an interface between a uniform medium with index of refraction n_1 and another medium with index of refraction n_2 . In such situations, Snell's Law describes the resulting deflection of the light ray:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

where θ_1 and θ_2 are the angles between the normal (to the interface) and the incident and refracted waves, respectively.

The index of refraction of a medium is related to the speed, v , of light in that medium by

$$n = c / v,$$

where c is the speed of light in vacuum.

Snell's Law can be used to predict the deflection of light rays as they pass through linear media as long as the indexes of refraction and the geometry of the media are known. For example, the propagation of light through a prism results in the light ray being deflected depending on the shape and orientation of the prism. In most materials, the index of refraction varies with the frequency of the light. Taking this into account, Snell's Law can be used to predict how a prism will disperse light into a spectrum. The discovery of this phenomenon when passing light through a prism is famously attributed to Isaac Newton.

Some media have an index of refraction which varies gradually with position and, thus, light rays in the medium are curved. This effect is responsible for mirages seen on hot days: a change in index of refraction air with height causes light rays to bend, creating the appearance of specular