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OPTICS (Fourth Edition)

光学（第四版）

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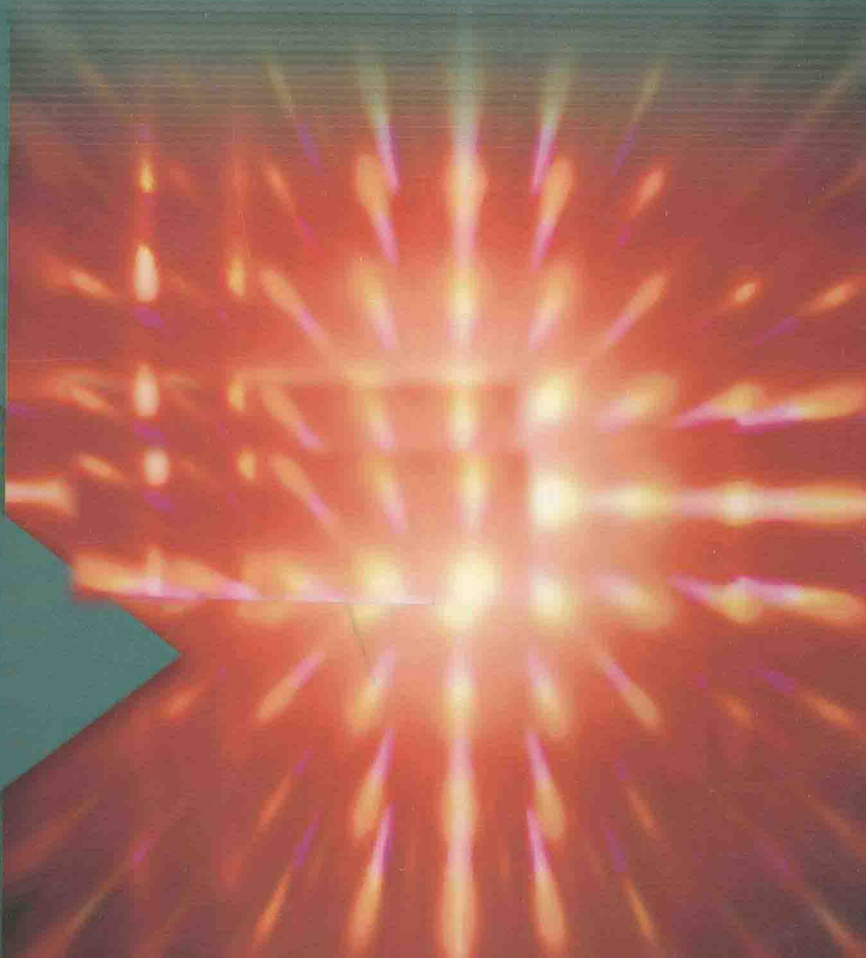

高等教育出版社
HIGHER EDUCATION PRESS

海外优秀理科类系列教材
改编版

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(Fourth Edition)

光　学

(第四版)

原著　Eugene Hecht
　　　Adelphi University
改编　张存林
　　　首都师范大学

高等教育出版社
Higher Education Press

图字：01－2004－5427 号
原书 ISBN：0－8053－8566－5

图书在版编目（CIP）数据

光学：第 4 版＝Optics：Fourth Edition：改编版/［美］赫克特（Hecht，E.）原著；张存林改编. —北京：高等教育出版社，2005.1（2013.4 重印）
ISBN 978－7－04－015576－1

Ⅰ.光… Ⅱ.①赫… ②张… Ⅲ.光学－高等学校－教材－英文 Ⅳ.O43

据核字（2004）第 112004 号

辑 张冰峰　封面设计 王凌波　责任绘图 朱 静
对 康晓燕　责任印制 田 甜

出版发行	高等教育出版社	咨询电话	400－810－0598
社　　址	北京市西城区德外大街 4 号	网　　址	http://www.hep.edu.cn
邮政编码	100120		http://www.hep.com.cn
印　　刷	北京铭成印刷有限公司	网上订购	http://www.landraco.com
开　　本	787×1092　1/16		http://www.landraco.com.cn
印　　张	52.5	版　　次	2005 年 3 月第 1 版
字　　数	1 300 000	印　　次	2013 年 4 月第 4 次印刷
购书热线	010－58581118	定　　价	88.80 元

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物 料 号　15576－00

内 容 简 介

本书是国外比较新的一本光学教材，被国外多所院校指定或推荐作为学生的主要参考书。书中基本覆盖了我国光学课程的主要教学内容，课程体系也和我国光学教学相接近。该书语言生动，讲解清楚，图片丰富，还介绍一些光学领域的最新成果和研究课题。经过国内有经验的教师根据国内教学要求有针对性地改编后，该书更加适合国内的教学实际，具有很强的教学适用性，是一本非常好的双语教学教材。

本书可供普通高等学校物理类专业作为双语教学教材使用，也可供其他专业和社会读者参考。

出版者的话

为适应当前我国高等学校各类创新人才培养的需要，大力推进教育部倡导的双语教学，配合教育部实施的“高等学校教学质量与教学改革工程”和“精品课程”建设的需要，国内一些出版社都陆续原版引进了不少海外优秀教材。海外优秀教材的立体化配套、多种教学资源的整合，以及为课程提供的整体教学解决方案，都有不少值得我们学习借鉴之处。但一个不容忽视的问题是，外文原版教材与我国现行的课程内容、教学体系、教学习惯等存在着巨大的差异性。譬如，重点课程的原版教材通常很厚，内容很多，容量是国内自编教材的好几倍。国外的情况是，老师未必会都讲，剩下大量的内容留给学生自学；而国内的情况不尽相同。受国内教学学时所限，完全照搬是不合时宜的。教材的国际化必须与本民族的文化教育传统相融合，在原有的基础上吸收国外优秀教材的长处，这使得我们需要对外文原版教材进行适当的改编。改编不是简单地使内容减少，而是结合国内教学特点，引进国外先进的教学模式及思想，在教学内容和方式上更中国化，使之更符合国内的课程设置及教学环境。

2004 年伊始，高等教育出版社有计划、大规模地开展了海外优秀理科系列教材的引进及改编工作。在引进改编海外优秀教材的过程中，我们坚持了两条原则：(1) 精选版本，打造精品系列；(2) 慎选改编者，保证品质。

首先，我们和 Pearson Education，John Wiley & Sons，McGraw-Hill 以及 Thomson Learning 等国外出版公司进行了广泛接触，经推荐并在国内专家的协助下，提交引进版权总数 200 余种，学科专业领域涉及数学、物理、化学化工、地理、环境等。收到样书后，我们聘请了国内高校一线教师、专家学者参与这些原版教材的评介工作，从中遴选出了一批优秀教材进行改编，并组织出版。这批教材普遍具有以下特点：(1) 基本上是近几年出版的，在国际上被广泛使用，在同类教材中具有相当的权威性；(2) 高版次，历经多年教学实践检验，内容翔实准确，反映时代要求；(3) 各种教学资源配套整齐，为师生提供了极大的便利；(4) 插图精美，丰富，图文并茂，与正文相辅相成；(5) 语言简练，流畅，可读性强，比较适合非英语国家的学生阅读。

其次，慎选改编者。原版教材确定后，随之碰到的问题是寻找合适的改编者。要改编一本教材，必须要从头到尾吃透它，有这样的精力自编一本教材都绰绰有余了。我们与国内众多高等院校的专家学者进行了广泛的接触和细致的协商，几经酝酿，最终确定下来改编者。大多数改编者都是有国外留学背景的中青年学者，他们既有相当高的学术水平，又热爱教学，长期工作在教学第一线。他们了解引进版教材的知识结构、表达方式和写作方法，最重要的是他们有时间，有精力，有热情，有的甚至付出了比写一本新教材更多的劳动。我们向他们表示最真诚的敬意。

在努力降低引进教材售价方面，高等教育出版社做了大量和细致的工作，这套引进改编的教材体现了一定的权威性、系统性、先进性和经济性等特点。

这套教材出版后，我们将结合各高校的双语教学计划，开展大规模的宣传和培训工作，及时地将本套丛书推荐给各高校使用。在使用过程中，我们衷心希望广大教师和学生提出宝贵的意见和建议。如有好的教材值得引进，也请与高等教育出版社高等理科分社联系。联系电话：010－58581384（数学）；010－58581354（物理）；010－58581380（化学化工）。E-mail：xuke@hep.com.cn。

高等教育出版社
2004年10月

Preface

To *Ca, b. w. l.*

As with previous revisions, this fourth edition has been guided by three distinct imperatives: to fine-tune *the* pedagogy, modernize the discourse, and update the content.

During the past several years, using the third edition in the classroom, a number of small but significant pedagogical refinements have evolved, and these have been incorporated throughout this revised text. The intent, as ever, is to be responsive to students' needs.

This edition continues the program of gradually modernizing the treatment. In this, there are several goals, vis-à-vis the student: to impart an appreciation of the central role of atomic scattering in almost every aspect of Optics; to provide an understanding, as early as possible, of the insightful perspective offered by Fourier Theory; and to make clear, from the outset, the underlying quantum-mechanical nature of light.

Technological advances have been made in a wide range of areas from lenses and lasers to telescopes and fiberoptics. This fourth edition treats (even if sometimes only in introductory fashion) many of the significant advances that today's students should be aware of.

At the request of users, I have added dozens of new problems throughout the text. Most of these were designed to develop needed analytic skills and are of the "easy-to-intermediate" variety. As in previous editions, the complete solutions to problems without asterisks can be found at the back of the book. It should be noted that the vast majority of the new problems are not provided with such solutions. This was done to increase the selection of potential homework questions.

Much effort was expended in redrawing well over a hundred pieces of existing art to make them clearer and the physics more readable. To further enhance the pedagogy, this edition also contains many new drawings and photographs.

Chapter 2 (*Electromagnetic Theory, Photons, and Light*) has been extensively reworked. Nowadays many students studying Optics come to it with little more than the brief exposure to electromagnetic theory afforded by the traditional introductory course in physics. With them in mind, Section 2.1, *Basic Laws of Electromagnetic Theory* (p. 12), has been expanded, making the material far more accessible to these students. In keeping with the commitment to discuss modern applications of Optics, a new section called *Optical Cooling* examines this important technique (p. 48).

The Propagation of Light(Chapter 3) now contains a discussion of the historical origins of the concept of *index of refraction*(p. 75). This helps to make Snell's Law easier to really understand. The chapter is further enhanced with a more thorough treatment of *Fermat and Mirages*(p. 99). A new section, 3. 11. 2, called *Photons and the Laws of Reflection and Refraction*(p. 140) completes the chapter.

The treatment of *Geometrical Optics*(Chapter 4) was refined here and there(e. g., p. 165, 169, 172, 184, and 236) to improve its clarity. The field of telecommunications is so important and so rapidly evolving that each edition of this book has had to treat several major technological advances. Accordingly, the discussion of fiberoptics was brought up to date with the consideration of such topics as erbium-doped fiber amplifiers(p. 209), wavelength division multiplexing, and optical switching via MOEMS(p. 214). Liquid mirrors are briefly considered on page 246. The chapter ends with a new section on *Gravitational Lensing*(p. 258).

The discussion of wavefront aberrations in Chapter 5(*More on Geometrical Optics*) has been enlarged(p. 283). There is a new piece concerning the upgraded Arecibo Observatory(p. 290) because it beautifully illustrates an important contemporary approach to dealing with spherical aberration.

Chapter 6(*The Superposition of Waves*) was reworked to make the material generally more accessible(e. g., p. 346). The phasor representation was used to illuminate the creation of both standing waves(p. 326) and partial standing waves(p. 327). Because of a very significant series of experiments published in the last several years, the discussion of *Group Velocity*(p. 338), Section 6. 2. 2, was enriched and new subsections on *Superluminal* and *Subluminal Light* were added.

In addition to a few new photos and the occasional clarifying remark, Chapter 7(*Interference*) now contains a section, 7. 8. 4, called *Radar Interferometry.*

Over the last two decades there's been some interesting work done on so-called nondiffracting beams. Accordingly, Chapter 8(*Diffraction*) contains a new section(8. 2. 7) entitled *The Zeroth-Order Bessel Beam*, that deals with the phenomenon.

In Chapter 9(*Polarization*), as elsewhere, the prose was tightened and the analysis clarified, here and there. A few new photographs and several fresh diagrams were included. The section(9. 7) on *Retarders* was extended, and the concepts of zero-ordered, multiple-ordered, and compound zero-ordered wave plates were introduced. A section on *Liquid Crystals*(9. 12) was added, and the operation of both the liquid crystal variable retarder and liquid crystal display(LCD) were explained.

Chapters 10(*Fourier Optics*), and 11(*Basics of Coherence Theory*) have undergone a line-by-line fine tuning, but little or no overhaul.

Chapter 12, *Modern Optics*: *Lasers and Other Topics*, has been revised with the addition of a subsection on *Gaussian Laserbeams* and some updating as required(e. g., it now includes material on the Omega laser).

This fourth edition continues the agenda of unifying the discourse, as much as possible, within the framework of a few grand ideas. Thus the concept of interference, which is one of the premier notions in Optics(and not surprisingly in Quantum Mechanics, as well), is used qualitatively to understand propagation phenomena long before it's studied formally in Chapter 7. Among other benefits, this approach of presenting advanced concepts in simplified form early in the exposition allows the student to develop a cohesive perspective.

Over the years, I have received comments, articles, and photographs, from hundreds of colleagues, and I most sincerely thank them all. I am especially grateful to Professors P. J. Dolan of Northeastern Illinois University, W. A. Mendoza of Jacksonville University, M. W. Coffey of the University of Colorado and H. Fearn of California State University for their contributions and suggestions. Prof. J. R. Peverley of The George Washington University kindly donated several very nice problems on Jones matrices and I thank him for helping to freshen up this edition. Anyone else wishing to contribute their favorite problems, please fell free to do so. Indeed, if you are interested in the discipline and wish to exchange ideas you can contact me by mail at Adelphi University, Physics Department, Garden City, N. Y. 11530 or at genehecht@ aol. com.

I'd like to thank the entire team at Addison Wesley, for all their help, without which this edition would never have seen the light of day, as it were. I am especially grateful to Adam Black whose enthusiasm for the project was sustaining, to Joan Marsh whose wise decisions made the whole thing manageable, and to Nancy Gee who handled the day-to-day operation with efficiency and good humor.

The book was produced by HRS Interactive, which did a brilliant job of getting it all together. Lorraine Burke watched over every aspect of the process with incredible patience and skill; Alan Wiener and Jennifer Burke cheerfully brought their production acumen to bear; Ed Burke designed a beautiful book and struggled mightily to maintain the highest standards; Hilda Espreo was the tireless compositor; and as ever, Pat Hannagan, with the able assistance of Chris Burke, produced incomparable art. All have my deepest respect and profound appreciation. Finally, I thank my dear friend, my wife, Carolyn Eisen Hecht for coping with one more edition of one more book.

Freeport, New York E. H.

Content

1

A Brief History

1.1 Prolegomenon

In chapters to come we will evolve a formal treatment of much of the science of Optics, with particular emphasis on aspects of contemporary interest. The subject embraces a vast body of knowledge accumulated over roughly three thousand years of the human scene. Before embarking on a study of the modern view of things optical, let's briefly trace the road that led us there, if for no other reason than to put it all in perspective.

1.2 In the Beginning

The origins of optical technology date back to remote antiquity. Exodus 38: 8 (ca. 1200B. C. E.) recounts how Bezaleel, while preparing the ark and tabernacle, recast "the looking-glasses of the women" into a brass laver (a ceremonial basin). Early mirrors were made of polished copper, bronze, and later on of speculum, a copper alloy rich in tin. Specimens have survived from ancient Egypt – a mirror in perfect condition was unearthed along with some tools from the workers' quarters near the pyramid of Sesostris II (ca. 1900B. C. E.) in the Nile valley. The Greek philosophers Pythagoras, Democritus, Empedocles, Plato, Aristotle, and others developed several theories of the nature of light. The rectilinear propagation of light (p. 77) was known, as was the *Law of Reflection* (p. 86) enunciated by Euclid (300B. C. E.) in his book *Catoptrics*. Hero of Alexandria attempted to explain both these phenomena by asserting that light traverses the shortest allowed path between two points. The burning glass (a positive lens used to start fires) was alluded to by Aristophanes in his comic play *The Clouds* (424B. C. E.). The apparent bending of objects partly immersed in water (p. 93) is mentioned in Plato's *Republic*. Refraction was studied by Cleomedes (50A. D.) and later by Claudius Ptolemy (130A. D.) of Alexandria, who tabulated fairly precise measurements of the angles of incidence and refraction for several media (p. 92). It is clear from the accounts of the historian Pliny (23 – 79A. D.) that the Romans also possessed burning glasses. Several glass and crystal spheres have been found among Roman ruins, and a planar convex lens was recovered in Pompeii. The Roman philosopher Seneca (3B. C. E. – 65A. D.) pointed out that a glass globe filled with water could be used for magnifying purposes. And it is certainly possible that some Roman artisans may have used magnifying glasses to facilitate very fine detailed work.

After the fall of the Western Roman Empire (475A. D.), which roughly marks the start of the Dark Ages, little or no scientific progress was made in Europe for a great while. The dominance of the Greco-Roman-Christian culture in the lands embracing the Mediterranean soon gave way by conquest to the rule of Allah. The center of scholarship shifted to the Arab world, and Optics was studied and extended, especially by Alhazen(ca. 1000 A.D.). He elaborated on the Law of Reflection, putting the angles of incidence and reflection in the same plane normal to the interface(p. 88); he studied spherical and parabolic mirrors and gave a detailed description of the human eye(p. 216).

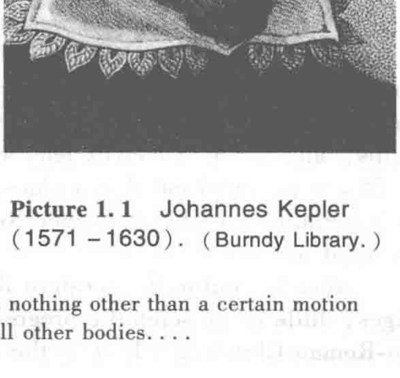
By the latter part of the thirteenth century, Europe was only beginning to rouse from its intellectual stupor. Alhazen's work was translated into Latin, and it had a great effect on the writings of Robert Grosseteste(1175 - 1253), Bishop of Lincoln, and on the Polish mathematician Vitello(or Witelo), both of whom were influential in rekindling the study of Optics. Their works were known to the Franciscan Roger Bacon(1215 - 1294), who is considered by many to be the first scientist in the modern sense. He seems to have initiated the idea of using lenses for correcting vision and even hinted at the possibility of combining lenses to form a telescope. Bacon also had some understanding of the way in which rays traverse a lens. After his death, Optics again languished. Even so, by the mid-1300s, European paintings were depicting monks wearing eyeglasses. And alchemists had come up with a liquid amalgam of tin and mercury that was rubbed onto the back of glass plates to make mirrors. Leonardo da Vinci(1452 - 1519) described the *camera obscura*(p. 237), later popularized by the work of Giovanni Battista Della Porta(1535 - 1615), who discussed multiple mirrors and combinations of positive and negative lenses in his *Magia naturalis*(1589).

This, for the most part, modest array of events constitutes what might be called the first period of Optics. It was undoubtedly a beginning - but on the whole a humble one. The whirlwind of accomplishment and excitement was to come later, in the seventeenth century.

1.3 From the Seventeenth Century

It is not clear who actually invented the refracting telescope, but records in the archives at The Hague show that on October 2, 1608, Hans Lippershey(1587 - 1619), a Dutch spectacle maker, applied for a patent on the device. Galileo Galilei(1564 - 1642), in Padua, heard about the invention and within several months had built his own instrument, grinding the lenses by hand. The compound microscope was invented at just about the same time, possibly by the Dutchman Zacharias Janssen(1588 - 1632). The microscope's concave eyepiece was replaced with a convex lens by Francisco Fontana (1580 - 1656) of Naples, and a similar change in the telescope was introduced by Johannes Kepler (1571 - 1630). In 1611, Kepler published his *Dioptrice.* He had discovered total internal reflection and arrived at the small angle approximation to the Law of Refraction, in which case the incident and transmission angles are proportional. He evolved a treatment of first-order Optics for thin-lens systems and in his book describes the detailed operation of both the Keplerian (positive eyepiece) and Galilean (negative eyepiece) telescopes. Willebrord Snell(1591 - 1626), professor at Leyden, empirically discovered the long-hidden *Law of Refraction* in 1621 - this was one of the great moments in Optics. By learning precisely how rays of light are redirected on traversing a boundary between two media, Snell in one swoop swung open the door to modern applied Optics. René Descartes (1596 - 1650) was the first to publish the now familiar formulation of the Law of Refraction in terms of sines. Descartes deduced the law using a model in which light was viewed as a pressure transmitted by an elastic medium; as he put it in his *La Dioptrique*(1637)

> recall the nature that I have attributed to light, when I said that it is nothing other than a certain motion or an action conceived in a very subtle matter, which fills the pores of all other bodies....



Picture 1.1 Johannes Kepler (1571 - 1630). (Burndy Library.)

The universe was a plenum. Pierre de Fermat(1601 - 1665), taking exception to Descartes's assumptions, rederived the Law of Reflection(p. 97) from his own *Principle of Least Time*(1657).

The phenomenon of diffraction, that is, the deviation from rectilinear propagation that occurs when light advances beyond an obstruction (p. 440), was first noted by Professor Francesco Maria Grimaldi(1618 - 1663) at the Jesuit College in Bologna. He had observed bands of light within the shadow of a rod illuminated by a small source. Robert Hooke(1635 - 1703), curator of experiments for the Royal Society, London, later also observed diffraction effects. He was the first to study the colored interference patterns(p. 390) generated by thin films(*Micrographia*, 1665). He proposed the idea that light was a rapid vibratory motion of the medium propagating at a very great speed. Moreover, "every pulse or vibration of the luminous body will generate a sphere" - this was the beginning of the wave theory. Within a year of Galileo's death, Isaac Newton (1642 - 1727) was born. The thrust of Newton's scientific effort was to build on direct observation and avoid speculative hypotheses. Thus he remained ambivalent for a long while about the actual nature of light. Was it corpuscular - a stream of particles, as some maintained? Or was light a wave in an all-pervading medium, the aether? At the age of 23, he began his now famous experiments on dispersion.

Picture 1.2 René Descartes by Frans Hals (1596 - 1650). (© Musées Nationaux.)

Picture 1.3 Sir Isaac Newton(1642 - 1727). (Burndy Library.)

> I procured me a triangular glass prism to try therewith the celebrated phenomena of colours.

Newton concluded that white light was composed of a mixture of a whole range of independent colors. He maintained that the corpuscles of light associated with the various colors excited the aether into characteristic vibrations. Even though his work simultaneously embraced both the wave and emission (corpuscular) theories, he did become more committed to the latter as he grew older. His main reason for rejecting the wave theory as it stood then was the daunting problem of explaining rectilinear propagation in terms of waves that spread out in all directions.

After some all-too-limited experiments, Newton gave up trying to remove chromatic aberration from refracting telescope lenses. Erroneously concluding that it could not be done, he turned to the design of reflectors. Sir Isaac's first reflecting telescope, completed in 1668, was only 6 inches long and 1 inch in diameter, but it magnified some 30 times.

At about the same time that Newton was emphasizing the emission theory in England, Christiaan Huygens(1629 - 1695), on the continent, was greatly extending the wave theory. Unlike Descartes, Hooke, and Newton, Huygens correctly concluded that light effectively slowed down on entering more dense media. He was able to derive the Laws of Reflection and Refraction and even explained the double refraction of calcite (p. 554), using his wave theory. And it was while working with calcite that he discovered the phenomenon of *polarization* (p. 538).

> As there are two different refractions, I conceived also that there are two different emanations of the waves of light. . . .

Thus light was either a stream of particles or a rapid undulation of aethereal matter. In any case, it was generally agreed that its speed was exceedingly large. Indeed, many believed that light propagated instantaneously, a notion that went back at least as far as Aristotle. The fact that it was finite was determined by the Dane Ole Christensen Römer (1644 - 1710). Jupiter's nearest moon, Io, has an orbit about that planet that is nearly in the plane of Jupiter's own orbit around the Sun. Römer made a careful study of the eclipses of Io as it moved through the shadow behind Jupiter. In 1676 he predicted that on November 9th Io would emerge from the dark some 10 minutes later than would have been expected on the basis of its yearly averaged motion. Precisely on schedule, Io performed as predicted, a phenomenon Römer correctly explained as arising from the finite speed of light. He was able to determine that light took about 22 minutes to traverse the diameter of the Earth's orbit around the Sun - a distance of about 186 million miles. Huygens and Newton, among others, were quite convinced of the validity of Römer's work. Independently estimating the Earth's orbital diameter, they assigned values to c equivalent to 2.3×10^8 m/s and 2.4×10^8 m/s, respectively. *

Picture 1.4 Christiaan Huygens (1629 - 1695). (Rijksmuseum voor de geschiedenis der natuurwetenschappen, courtesy AIP Emilio Segré Visual Archives.)

The great weight of Newton's opinion hung like a shroud over the wave theory during the eighteenth century, all but stifling its advocates. Despite this, the prominent mathematician Leonhard Euler (1707 - 1783) was a devotee of the wave theory, even if an unheeded one. Euler proposed that the undesirable color effects seen in a lens were absent in the eye (which is an erroneous assumption) because the different media present negated dispersion. He suggested that achromatic lenses (p. 303) might be constructed in a similar way. Enthused by this work, Samuel Klingenstjerna (1698 - 1765), a professor at Upsala, reperformed Newton's experiments on achromatism and determined them to be in error. Klingenstjerna was in communication with a London optician, John Dollond (1706 - 1761), who was observing similar results. Dollond finally, in 1758, combined two elements, one of crown and the other of flint glass, to form a single achromatic lens. Incidentally, Dollond's invention was actually preceded by the unpublished work of the amateur scientist Chester Moor Hall (1703 - 1771) in Essex.

1.4 The Nineteenth Century

The wave theory of light was reborn at the hands of Dr. Thomas Young (1773 - 1829), one of the truly great minds of the century. In 1801, 1802, and 1803, he read papers before the Royal Society extolling the wave theory and adding to it a new fundamental concept, the so-called *Principle of Interference* (p. 372):

> When two undulations, from different origins, coincide either perfectly or very nearly in direction, their joint effect is a combination of the motions belonging to each.

---

* A. Wróblewski, *Am. J. Phys.* **53**, 620 (1985).

He was able to explain the colored fringes of thin films and determined wavelengths of various colors using Newton's data. Even though Young, time and again, maintained that his conceptions had their very origins in the research of Newton, he was severely attacked. In a series of articles, probably written by Lord Brougham, in the *Edinburgh Review*, Young's papers were said to be "destitute of every species of merit."

Augustin Jean Fresnel(1788 - 1827), born in Broglie, Normandy, began his brilliant revival of the wave theory in France, unaware of the efforts of Young some 13 years earlier. Fresnel synthesized the concepts of Huygens's wave description and the interference principle(p. 440). The mode of propagation of a primary wave was viewed as a succession of spherical secondary wavelets, which overlapped and interfered to reform the advancing primary wave as it would appear an instant later. In Fresnel's words:

> The vibrations of a luminous wave in any one of its points may be considered as the sum of the elementary movements conveyed to it at the same moment, from the separate action of all the portions of the unobstructed wave considered in any one of its anterior positions.

These waves were presumed to be longitudinal, in analogy with sound waves in air. Fresnel was able to calculate the diffraction patterns arising from various obstacles and apertures(p. 441) and satisfactorily accounted for rectilinear propagation in homogeneous isotropic media, thus dispelling Newton's main objection to the undulatory theory. When finally apprised of Young's priority to the interference principle, a somewhat disappointed Fresnel nonetheless wrote to Young telling him that he was consoled by finding himself in such good company - the two great men became allies.

Picture 1.5 Augustin Jean Fresnel (1788 - 1827). (Cultural Service of the French Embassy.)

Huygens was aware of the phenomenon of polarization arising in calcite crystals, as was Newton. Indeed, the latter in his *Opticks* stated,

> Every Ray of Light has therefore two opposite Sides. . . .

It was not until 1808 that Étienne Louis Malus(1775 - 1812) discovered that this two-sidedness of light also arose upon reflection(p. 368); the phenomenon was not inherent to crystalline media. Fresnel and Dominique François Arago(1786 - 1853) then conducted a series of experiments to determine the effect of polarization on interference, but the results were utterly inexplicable within the framework of their longitudinal wave picture. This was a dark hour indeed. For several years Young, Arago, and Fresnel wrestled with the problem until finally Young suggested that the aethereal vibration might be *transverse* as is a wave on a string. The two-sidedness of light was then simply a manifestation of the two orthogonal vibrations of the aether, transverse to the ray direction. Fresnel went on to evolve a mechanistic description of aether oscillations, which led to his now famous formulas for the amplitudes of reflected and transmitted light(p. 106). By 1825 the emission(or corpuscular) theory had only a few tenacious advocates.

The first terrestrial determination of the speed of light was performed by Armand Hippolyte Louis Fizeau(1819 - 1896) in 1849. His apparatus, consisting of a rotating toothed wheel and a distant mirror(8633 m), was set up in the suburbs of Paris from Suresnes to Montmartre. A pulse of light leaving an opening in the wheel struck the mirror and returned. By adjusting the known rotational speed of the wheel, the returning pulse could be made either to pass through an opening and be seen or to be obstructed by a tooth. Fizeau arrived at a value of the speed of light equal to 315 300 km/s. His colleague Jean Bernard Léon Foucault(1819 - 1868) was also involved in research on the speed of light. In 1834 Charles Wheatstone (1802 - 1875) had designed a rotating-mirror arrangement in order to measure the duration of an electric spark. Using this scheme, Arago had proposed to measure the speed of light in dense media but was never able to carry out the experiment. Foucault took up the work, which was later to provide material for his doctoral thesis. On May 6, 1850, he reported to the Academy of Sciences that the speed of light in water was *less* than that in air. This result was in direct conflict with Newton's formulation of the emission theory and a hard blow to its few remaining devotees.

Picture 1.6 James Clerk Maxwell (1831 – 1879). (AIP Emilio Segré Visual Archives.)

While all of this was happening in Optics, quite independently, the study of electricity and magnetism was also bearing fruit. In 1845 the master experimentalist Michael Faraday (1791 – 1867) established an interrelationship between electromagnetism and light when he found that the polarization direction of a beam could be altered by a strong magnetic field applied to the medium. James Clerk Maxwell (1831 – 1879) brilliantly summarized and extended all the empirical knowledge on the subject in a single set of mathematical equations. Beginning with this remarkably succinct and beautifully symmetrical synthesis, he was able to show, purely theoretically, that the electromagnetic field could propagate as a transverse wave in the luminiferous aether (p. 21).

Solving for the speed of the wave, Maxwell arrived at an expression in terms of electric and magnetic properties of the medium ($c = 1/\sqrt{\epsilon_0\mu_0}$). Upon substituting known empirically determined values for these quantities, he obtained a numerical result equal to the measured speed of light! The conclusion was inescapable – *light was "an electromagnetic disturbance in the form of waves" propagated through the aether.* Maxwell died at the age of 48, eight years too soon to see the experimental confirmation of his insights and far too soon for physics. Heinrich Rudolf Hertz (1857 – 1894) verified the existence of long electromagnetic waves by generating and detecting them in an extensive series of experiments published in 1888.

The acceptance of the wave theory of light seemed to necessitate an equal acceptance of the existence of an all-pervading substratum, the luminiferous aether. If there were waves, it seemed obvious that there must be a supporting medium. Quite naturally, a great deal of scientific effort went into determining the physical nature of the aether, yet it would have to possess some rather strange properties. It had to be so tenuous as to allow an apparently unimpeded motion of celestial bodies. At the same time, it could support the exceedingly high-frequency ($\sim 10^{15}$ Hz) oscillations of light traveling at 186 000 miles per second. That implied remarkably strong restoring forces within the aethereal substance. The speed at which a wave advances through a medium is dependent on the characteristics of the disturbed substratum and not on any motion of the source. This is in contrast to the behavior of a stream of particles whose speed with respect to the source is the essential parameter.

Certain aspects of the nature of aether intrude when studying the optics of moving objects, and it was this area of research, evolving quietly on its own, that ultimately led to the next great turning point. In 1725 James Bradley (1693 – 1762), then Savilian Professor of Astronomy at Oxford, attempted to measure the distance to a star by observing its orientation at two different times of the year. The position of the Earth changed as it orbited around the Sun and thereby provided a large baseline for triangulation on the star. To his surprise, Bradley found that the "fixed" stars displayed an apparent systematic movement related to the direction of motion of the Earth in orbit and not dependent, as had been anticipated, on the Earth's position in space. This so-called *stellar aberration* is analogous to the well-known falling-raindrop situation. A raindrop, although traveling vertically with respect to an observer at rest on the Earth, will appear to change its incident angle when the observer is in motion.