OPTICS

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OPTICS

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Preface

In recent times, the study of optics has moved into the forefront of scientific and technological thought with a whirlwind of activity, a remarkable series of accomplishments, and an almost dazzling promise of things to come. The old and venerable science, built on the magnificent structure of electromagnetic theory, has never lost its general appeal and applicability. Even so, we are in the midst of an exciting theoretical and technical metamorphosis. Optics is moving in new directions, exemplified by such diversity in form and concept as the photon, spatial filtering, fiber optics, thin films, and, of course, the laser with its myriad theoretical implications and practical potentialities.

The classic treatises of Drude, Sommerfeld, Wood, Rossi, Sears, Ditchburn, Born and Wolf, Jenkins and White, Strong, Towne, and many others, are of lasting value and continued interest. Yet there is a compelling need for a new undergraduate text which will speak in the contemporary jargon of picoseconds, megahertz and nanometers, of Q-switching, coherence length, frequency stability and bandwidth; a text which will embrace the pedagogically valuable classical methods along with the major new developments, techniques, and emphasis.

We have begun our treatment with a brief outline of the historical development of the subject. The modern theory of the nature of light unfolds as the culmination of over two thousand years of activity. Yet it should be appreciated within the perspective of this established pattern of change: We cannot quite see the next rung on the ladder, but we are surely not at the top.

For most optical phenomena, the distinctly quantum mechanical characteristics of light are obscured and its wave nature is the most prevalent manifestation. Accordingly, Chapter 2 deals with the mathematical description of wave motion. The wave equation is developed from very simple considerations which require no knowledge of differential equations. Chapter 3 evolves the electromagnetic theory of light from its most elementary beginnings. At that point, the foundation is set, and the rest of the structure of classical optics (including geometrical optics) is formulated predominantly in terms of wave interactions.

One of the themes which we have woven into the fabric of this book is that optics is physics, and is fundamental to physics. The interrelationships between atomic processes and the associated optical phenomena are explored wherever possible. Rather than isolating optics, we have tried to underscore the remarkable continuity that exists amongst the various fields of physics.

We include numerous descriptions of simple experiments which can be performed away from the laboratory. In many cases, the resulting optical effects are illustrated photographically in order to emphasize the point that elaborate or expensive equipment is not always needed. There is much to be seen with a few microscope slides, and we would encourage the "seeing."

The book is meant to serve as the text for what is often the one and only optics course offered to undergraduates. Its appeal should, therefore, be rather broadly based. To that end, much of the book has been prepared so that it can be used after only a thorough introductory course in both general physics and calculus. More difficult topics are placed at the ends of the chapters in which they appear. Thus, the chapter on diffraction begins with Fraunhofer diffraction via the simple Huygens-Fresnel theory, proceeds to the more involved Fresnel diffraction, and concludes with a discussion of the Kirchhoff treatment and boundary diffraction waves. The advanced student will be adequately stimulated and challenged by some of the more sophisticated techniques, such as the Fourier transform approach to diffraction and image theory, matrix methods in the discussion of polarization, paraxial ray tracing and multilayer films, just to mention a few.

The book provides a fairly extensive selection of material germane to modern optics, from which an instructor can formulate a course reflecting his own emphasis and the needs of his students. For example, an elementary course need not specifically include Chapters 11, 12, and 13, that is, *Fourier Optics*, *Coherence*, and *Quantum Optics*. Even so, pertinent aspects of this material are treated throughout the preceding portion of the text. Moreover, certain sections are adequately self-explanatory and can be offered as reading assignments.

We have given a good deal of attention to being consistently clear, avoiding the temptation to be overly succinct with difficult or subtle points. Ideas which might profit from further elaboration are either footnoted or included in the problem section, along with guiding comments where necessary. The *complete* solutions to roughly two-thirds of all problems appear in the back of the book. (A problem number followed by an *asterisk* indicates the absence of such a solution.)

The student is encouraged to refer to the literature and many "readable" articles are cited, including those which are chosen for their elaborate bibliographies. Books which are of interest are referred to via author and title—publishers, publication dates, and so on, are given in a complete reference listing at the end of the text.

The authors are fortunate to have profited from the assistance rendered by their friends and colleagues, Professor H. Ahner, Professor D. Albert, and Professor M. Garrell. We also thank Dr. A. Delisa, Dr. J. De Velis, Dr. S. Jacobs, and Dr. M. Scully for helpful discussions and commentary. We are particularly indebted to Dr. Howard A. Robinson, the translation editor of the *Soviet Journal of Optical Technology*, who carefully read the entire text and made many valuable and insightful suggestions. Our thanks for assistance in the preparation of the manuscript are extended to H. Merkl Villez, M. La Rosa, R. Auerbach, S. Auerbach, and especially to Carolyn Eisen Hecht, whose cooperation and patience sustained the effort.

Finally, we thank our many students who used the early typescript, tried out the experiments, did the problems, took some of the photographs, and served as the medium in which the book grew.

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A Brief History 1

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.

The complete story has myriad subplots and characters, heroes, quasi-heroes and an occasional villain or two. Yet from our vantage in time, we can sift out of the tangle of millennia perhaps four main themes—the optics of reflection and refraction, and the wave and quantum theories of light.

1.2 IN THE BEGINNING

The origins of optical technology date back to remote antiquity. *Exodus* 38:8 (ca. 1200 B.C.) 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 by the pyramid of Sesostris II (ca. 1900 B.C.) in the Nile valley. The Greek philosophers, Pythagoras, Democritus, Empedocles, Plato, Aristotle and others evolved several theories of the nature of light (that of the last named being quite similar to the ether theory of the nineteenth century). The rectilinear propagation of light was known, as was the law of reflection enunciated by Euclid (300 B.C.) 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) was alluded to by Aristophanes in his comic play *The Clouds* (424 B.C.). The apparent bending of objects partly immersed in water is mentioned in Plato's *Republic.* Refraction was studied by Cleomedes (50 A.D.) and later by Claudius Ptolemy (130 A.D.) of Alexandria who tabulated fairly precise measurements of the angles of incidence and refraction for several media. It is clear from the accounts of the historian Pliny (23–79 A.D.) that the Romans also possessed burning-glasses. Several glass and crystal spheres, which were probably used to start fires, have been found amongst Roman ruins, and a planar convex lens was recovered in Pompeii. The Roman philosopher Seneca (3 B.C.–65 A.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 (475 A.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. Alexandria fell to the Moslems in 642 A.D. and by the end of the seventh century, the lands of Islam extended from Persia across the southern coast of the Mediterranean to Spain. The center of scholarship shifted to the Arab world where the scientific and philosophic treasures of the past were translated and preserved. Rather than lying intact, but dormant, optics was even extended at the hands of one 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; he studied spherical and parabolic mirrors and gave a detailed description of the human eye.

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 (1215–94) 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-thirteen hundreds, 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* later popularized by the work of Giovanni Battista Della Porta (1535–1615). Porta 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 dull one. It was more a time for learning how to play the game than actually scoring points. 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, probably 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). Turning his telescope skyward, Galileo, on January 7, 1610, discovered the moons of Jupiter. Within the same year he saw Saturn's rings and further concluded that the sun rotated, this after observing moving spots on its surface. But many doubted their eyes and others would not look. In a letter to Kepler, Galileo wrote

> Why are you not here? What shouts of laughter we should have at this glorious folly! And to hear the professor of philosophy at Pisa labouring before the Grand Duke with logical arguments, as if with magical incantations to charm the new planets out of the sky.

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 goes on to evolve a treatment of first-order optics for thin-lens systems and 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, and he should perhaps be given equal credit for its discovery. 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)

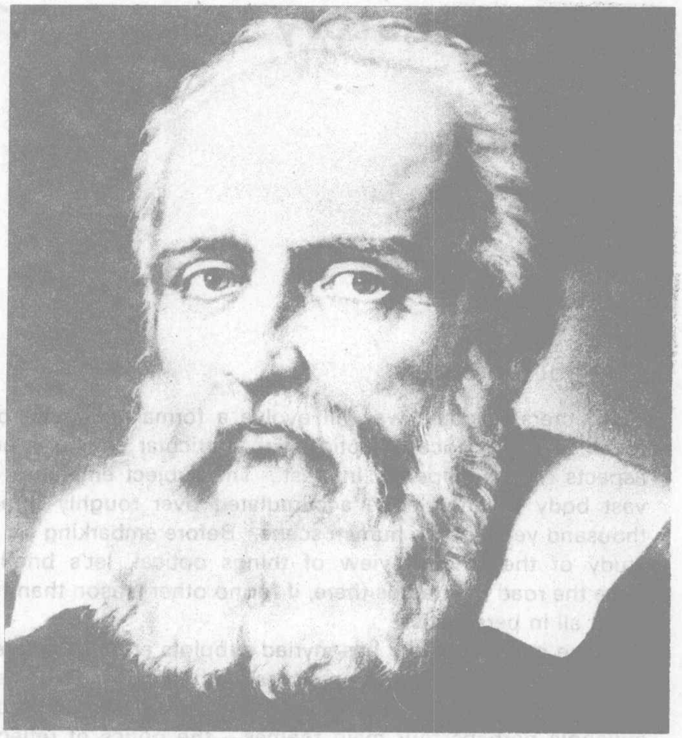

Fig. 1.1 Galileo Galilei (1564–1642)

> . . . 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.

the universe was a plenum. Pierre de Fermat (1601–65), taking exception to Descartes' assumptions, rederived the law of reflection from his own *principle of least time* (1657).

Fig. 1.2 René Descartes (1596–1650)

Departing from Hero's shortest-path statement, Fermat maintained that light propagates from one point to another along a route taking the least time, even if it has to vary from the shortest actual path to do it.

The phenomenon of diffraction, i.e. the deviation from rectilinear propagation which occurs when light advances beyond an obstruction, was first noted by Professor Francesco Maria Grimaldi (1618–63) 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 generated by thin films (*Micrographia* 1665) and correctly concluded that they were due to an interaction between the light reflected from the front and back surfaces. 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. In the year Galileo died Isaac Newton (1642–1727) was born. The thrust of Newton's scientific effort is clear from his own description of his work in optics as *experimental philosophy*. It was his intent 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 ether? At the

Fig. 1.3 Pierre de Fermat (1608–1665)

Fig. 1.4 Sir Isaac Newton (1642–1727)

age of twenty-three, he began his now famous experiments on dispersion.

> 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 ether into characteristic vibrations. Furthermore, the sensation of red corresponded to the longest vibration of the ether and violet to the shortest. Even though his work shows a curious propensity for simultaneously embracing both the wave and emission (corpuscular) theories, he does become more committed to the latter as he grows older. Perhaps his main reason for rejecting the wave theory as it stood then was the blatant problem of explaining rectilinear propagation in terms of waves which 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 six inches long and one inch in diameter but it magnified some 30 times.

At about the same time that Newton was emphasizing the emission theory in England, Christian Huygens (1629–95), 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, using his wave theory. And it was while working with calcite that he discovered the phenomenon of *polarization*.

> 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 ethereal matter. In any case, it was generally agreed that its speed of propagation was exceedingly large. The fact that it was indeed finite was determined in 1676 by the Dane Olaf Römer (1644–1710). Jupiter's nearest moon has an orbit about that planet which is nearly in the plane of Jupiter's own orbit around the sun. Römer found that the interval, T, between successive eclipses of the satellite as it passed into the shadow of Jupiter increased when the Earth–Jupiter distance was increasing, and vice versa. He correctly deduced that if the planets' separation increases by a distance d during one revolution of the Jovian moon, T will exceed the actual period T_0 by an amount d/c where c is the speed of light, i.e. $T - T_0 = d/c$. The corresponding value of c was found to be about 48,000 leagues per second or roughly 214,000 km/s.

Fig. 1.5 Christian Huygens (1629–1695)

The great weight of Newton's opinion hung as a shroud over the wave theory during the eighteenth century, all but stifling its advocates. There were too many content with dogma and too few nonconformist enough to follow their own experimental philosophy, as surely Newton would have had them do. Despite this, the prominent mathematician Leonhard Euler (1707–83) was a devotee of the wave

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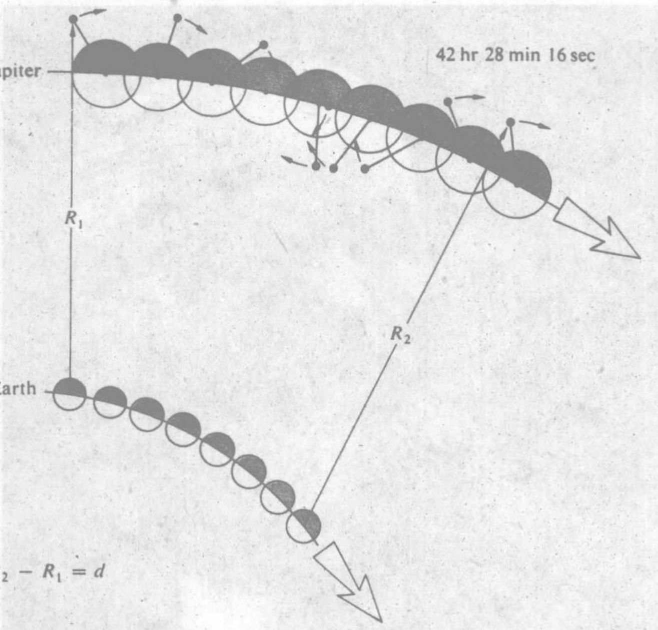

Fig. 1.6 Römer's measurement of *c*.

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 might be constructed in a similar way. Enthused by this work, Samuel Klingenstjerna (1698–1765), 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 (1706–61), 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. This was an accomplishment of very great practical importance. Incidentally, Dollond's invention was actually preceded by the unpublished work of the amateur scientist Chester Moor Hall (1703–71) of Moor Hall 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. On November 12, 1801, July 1, 1802 and November 24, 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.*

> 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.

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 researches 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"—and that's going pretty far. Under the pall of Newton's presumed infallibility the pedants of England were not prepared for the wisdom of Young, who in turn became disheartened.

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 thirteen years earlier. Fresnel synthesized the concepts of Huygens' wave description and the interference principle. The mode of propagation of a primary wave was viewed as a succession of stimulated 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. Dominique François Jean Arago (1786–1853) was an early convert to Fresnel's wave theory and they became fast friends and sometime collaborators. Under criticism from such renowned men and proponents of the emission hypothesis as Pierre Simon de Laplace (1749–1827) and Jean-Baptiste Biot (1774–1862), Fresnel's theory took on a mathematical emphasis. He was able to calculate the diffraction patterns arising from various obstacles and apertures 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, somewhat disappointedly Fresnel nonetheless wrote to Young telling him that he was consoled by finding himself in such good company—the two great men became allies.

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

> Every Ray of Light has therefore two opposite Sides.

He further developed this concept of lateral asymmetry even though avoiding any interpretation in terms of the hypothetical nature of light. Yet it was not until 1808 that Étienne Louis Malus (1775–1812) discovered that this two-sidedness of light became apparent upon reflection as well; it was not inherent to crystalline media. Fresnel and Arago 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 ethereal 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 ether, transverse to the ray direction. Fresnel went on to evolve a mechanistic description of ether oscillations which led to his now famous formulas for the amplitude of reflected and transmitted light. 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 (1819–96) 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 (1819–68) was also involved in research on the speed of light. In 1834 Charles Wheatstone (1802–75) had designed a rotating-mirror arrangement in order to measure the duration of an electric spark. Using this scheme, Arago 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, of course in direct conflict with Newton's formulation of the emission theory and it was a hard blow to its very few remaining devotees.

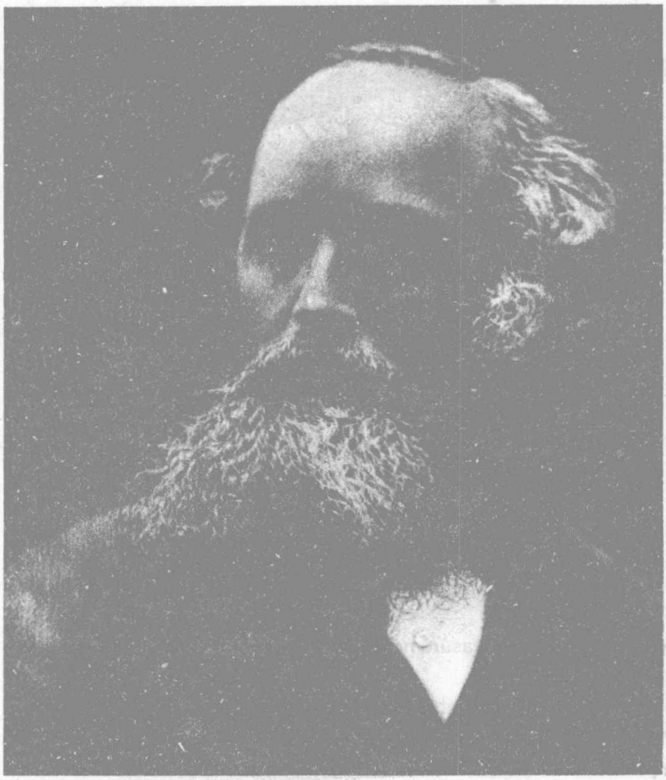

Fig. 1.7 James Clerk Maxwell (1831–1879)

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 (1831–79) brilliantly summarized and even extended all the then known empirical knowledge on the subject in a single set of mathematical equations. Beginning with this remarkably succinct and beautifully symmetric synthesis, he was able to show, purely theoretically, that the electromagnetic field could propagate as a transverse wave in the luminiferous ether. Solving for the speed of the wave, he 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 ether.* Maxwell died at the age of forty-eight, eight years too soon to see the experimental confirmation of his insights and far too soon for physics. Heinrich Rudolf Hertz (1857–94) verified the existence of long-wavelength 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 ether. 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 ether, 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/s. That implied remarkably strong restoring forces within the ethereal substance. The speed at which a wave advances through a medium is dependent upon the characteristics of the disturbed substratum and not upon 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 ether intrude when studying the optics of moving objects and it was this area of research, evolving quite quietly on its own, which 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, he 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. Thus a corpuscular model of light could explain stellar aberration rather handily. Alternatively, the wave theory also offers a satisfactory explanation provided that it is assumed that *the ether remains totally undisturbed as the earth plows through it.* Incidentally, Bradley, convinced of the correctness of his analysis, used the observed aberration data to arrive at an improved value of *c*, thus confirming Römer's theory of the finite speed of light.

In response to speculation as to whether the earth's motion through the ether might result in an observable difference between light from terrestrial and extraterrestrial sources, Arago set out to examine the problem experimentally. He found that there were no observable differences. Light behaved just as if the earth were at rest with respect to the ether. To explain these results, Fresnel suggested in effect that light was partially dragged along as it traversed a transparent medium in motion. An experiment by Fizeau in which light beams passed down moving columns of water and an experiment in 1871 by Sir George Biddell Airy (1801–92) using a water-filled telescope to examine stellar aberration both seemed to confirm Fresnel's drag hypothesis. Assuming an ether at *absolute rest*, Hendrik Antoon Lorentz (1853–1928) derived a theory which encompassed Fresnel's ideas.

In 1879 in a letter to D. P. Todd of the U.S. Nautical Almanac Office, Maxwell suggested a scheme for measuring the speed at which the solar system moved with respect to the luminiferous ether. The American, Albert Abraham Michelson (1852–1931), then a naval instructor, took up the idea. Michelson, at the tender age of 26, had already established a favorable reputation by performing an extremely precise determination of the speed of light. A few years later, he began an experiment to measure the effect of the earth's motion through the ether. Since the speed of light in ether is constant and the earth, in turn, presumably moves relative to the ether (orbital speed of 67,000 miles/h), the speed of light measured with respect to the earth should be affected by the planet's motion. Michelson's work was begun in Berlin but because of traffic vibrations, it was moved to Potsdam and in 1881, he published his findings. There was no detectable motion of the earth with respect to the ether—the ether was not stationary. But the decisiveness of this surprising result was blunted somewhat when Lorentz pointed out an oversight in the calculation. Several years later Michelson, then professor of physics at Case School of Applied Science in Cleveland, Ohio, joined with Edward Williams Morley (1838–1923), a well-known professor of chemistry at Western Reserve, to redo the experiment with considerably greater precision. Amazingly enough, their results, published in 1887, once again were negative;

> It appears from all that precedes reasonably certain that if there be any relative motion between the earth and the luminiferous aether, it must be small; quite small enough entirely to refute Fresnel's explanation of aberration.

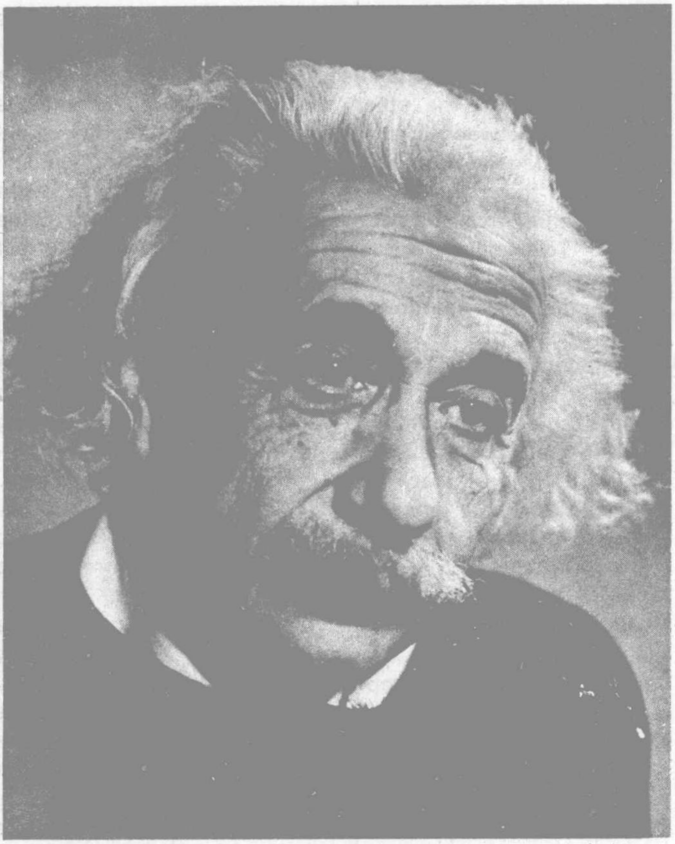

Fig. 1.8 Albert Einstein (1879–1955) [Photo by Fred Stein.]

Thus, while an explanation of stellar aberration within the context of the wave theory required the existence of a relative motion between earth and ether, the Michelson–Morley experiment refuted that possibility. Moreover, the findings of Fizeau and Airy necessitated the inclusion of a partial drag of light due to motion of the medium.

1.5 TWENTIETH-CENTURY OPTICS

Jules Henri Poincaré (1854–1912) was perhaps the first to grasp the significance of the experimental inability to observe any effects of motion relative to the ether. In 1899 he began to make his views known and in 1900 he said

> Our aether, does it really exist? I do not believe that more precise observations could ever reveal anything more than *relative* displacements.

In 1905 Albert Einstein (1879–1955) introduced his *special theory of relativity* in which he too, quite independently, rejected the ether hypothesis.

> The introduction of a "luminiferous ether" will prove to be superfluous inasmuch as the view here to be developed will not require an "absolutely stationary space."

He further postulated that

> light is always propagated in empty space with a definite velocity *c* which is independent of the state of motion of the emitting body.

The experiments of Fizeau, Airy and Michelson–Morley were then explained quite naturally within the framework of Einstein's relativistic kinematics.* Deprived of the ether, physicists simply had to get used to the idea that electromagnetic waves could propagate through free space—there was no alternative. Light was now envisaged as a self-sustaining wave with the conceptual emphasis passing from ether to field. The electromagnetic wave became an entity in itself.

On October 19, 1900, Max Karl Ernst Ludwig Planck (1858–1947) read a paper before the German Physical Society in which he introduced the beginnings of what was to become yet another great revolution in scientific thought—*quantum mechanics*, a theory embracing submicroscopic phenomena. In 1905, building on these ideas, Einstein proposed a new form of corpuscular theory in which he asserted that light consisted of globs or "particles" of energy. Each such quantum of radiant energy or photon,† as it came to be called, had an energy proportional to its frequency ν, i.e. $\mathscr{E} = h\nu$ where h is known as Planck's constant. By the end of the nineteen-twenties, through the efforts of such men as Bohr, Born, Heisenberg, Schrödinger, De Broglie, Pauli, Dirac and several others, quantum mechanics had become a well-verified structure. It gradually became evident that the concepts of particle and wave, which in the macroscopic world seem so obviously mutually exclusive, must be merged in the submicroscopic domain. The mental image of an atomic particle (e.g. electrons, neutrons, etc.) as a minute localized lump of matter would no longer suffice. Indeed, it was found that these "particles" could generate interference and diffraction patterns in precisely the same way as would light. Thus photons,

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* See, for example, *Special Relativity* by French, Chapter 5.

† The word *photon* was coined by G. N. Lewis, *Nature*, December 18, 1926.

Fig. 1.9 These photos, which were made using electronic amplification techniques, are a compelling illustration of the granularity displayed by light in its interaction with matter. Under exceedingly faint illumination the pattern (each spot corresponding to one photon) seems almost random, but as the light level increases the quantal character of the process gradually becomes obscured. (See *Advances in Biological and Medical Physics* V, 1957, 211–242.) Courtesy Radio Corporation of America.

protons, electrons, neutrons, etc., the whole lot, have both particle and wave manifestations. Relativity liberated light from the ether and showed the kinship between mass and energy (via $\mathscr{E} = mc^2$). What seemed to be two almost antithetic quantities now became interchangeable. Quantum mechanics went on to establish that a particle* of momentum p, had an associated wavelength λ such that $p = h/\lambda$ (whether it had rest mass or not). The neutrino, a neutral particle having zero rest mass, was postulated for theoretical reasons in 1930 by Wolfgang Pauli (1900–58) and verified experimentally later on in the fifties. The easy images of submicroscopic specks of matter became untenable and the wave–particle dichotomy dissolved into a duality.

Quantum mechanics also treats the manner in which light is absorbed and emitted by atoms. Suppose we cause a gas to glow by heating it or passing an electrical discharge through it. The light emitted is characteristic of the very structure of the atoms constituting the gas. Spectroscopy, which is the branch of optics dealing with spectrum analysis,

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* Perhaps it might help if we just called them all *wavicles*. By the way, how do you envision in your mind's eye the meeting of an electron and a positron and their subsequent annihilation with the creation of two photons?

developed from the researches of Newton. William Hyde Wollaston (1766–1828) made the earliest observations of the dark lines in the solar spectrum (1802). Because of the slit-shaped aperture generally used in spectroscopes, the output consisted of narrow colored bands of light, the so-called *spectral lines*. Joseph Fraunhofer (1787–1826) independently greatly extended the subject. After accidentally discovering the double line of sodium, he went on to study sunlight and made the first wavelength determinations using diffraction gratings. Gustav Robert Kirchhoff (1824–87) and Robert Wilhelm Bunsen (1811–99) working conjointly at Heidelberg, established that each kind of atom had its own signature in a characteristic array of spectral lines. And in 1913 Niels Henrik David Bohr (1885–1962) set forth a precursory quantum theory of the hydrogen atom which was nonetheless able to predict the wavelengths of its emission spectrum. The light emitted by an atom is now understood to arise from its outermost electrons. An atom which somehow absorbs energy (e.g. via collisions) changes from its usual configuration, known as the ground state, to what's called an excited state. After some finite time, it relaxes back to the ground state, the electrons return to their original configuration with respect to the nucleus, giving up the excess energy often in the form of light. The process is the domain of modern quantum theory which describes the minutest details with incredible precision and beauty.

The flourishing of applied optics in what has transpired of the second half of the twentieth century represents a renaissance in itself. In the nineteen fifties several workers began to inculcate optics with the mathematical techniques and insights of communications theory. Just as the idea of momentum provides another dimension in which to visualize aspects of mechanics, the concept of spatial frequency offers a rich new way of appreciating a broad range of optical phenomena. Bound together by the mathematical formalism of Fourier analysis, the outgrowths of this contemporary emphasis have been far-reaching. Of particular interest is the theory of image formation and evaluation, the transfer functions and the idea of spatial filtering.

The advent of the high-speed digital computer brought with it a vast improvement in the design of complex optical systems. Aspherical lens elements took on renewed practical significance and the diffraction-limited system with an appreciable field of view became a reality. The technique of ion bombardment polishing, where one atom at a time is chipped away, was introduced to meet the need for extreme precision in the preparation of optical elements. The use of single and multilayer thin-film coatings (reflecting, anti-reflecting, etc.) became commonplace. Fiber optics evolved into a practical tool and thin-film light guides were being studied. A great deal of attention was paid to the infrared end of the spectrum (surveillance systems, missile guidance, etc.) and this in turn stimulated the development of IR materials. Plastics began to find serious applications in optics (lens elements, replica gratings, fibers, aspherics, etc.). A new class of partially vitrified glass-ceramics with exceedingly low thermal expansion was developed. A resurgence in the construction of astronomical observatories (both terrestrial and extraterrestrial) running across the whole spectrum was well under way by the end of the sixties.

The first laser was built in 1960 and within a decade laser beams spanned the range from infrared to ultraviolet. The availability of high-power coherent sources led to the discovery of a number of new optical effects (harmonic generation, frequency mixing, etc.) and thence to a panorama of marvelous new devices. The technology needed to produce a practicable optical communications system was fast evolving. The sophisticated use of crystals in devices such as second-harmonic generators, electro-optic and acousto-optic modulators and the like spurred a great deal of contemporary research in crystal optics. The wavefront reconstruction technique known as holography, which produces magnificent three-dimensional images, found numerous other applications (nondestructive testing, data storage, etc.).

The military orientation of much of the developmental work of the sixties began to give way in the seventies to the urgency of improving the quality of life. Optical systems are finding increasing uses in health technology, environmental protection and earth resources monitoring.

The vitality of optics in the seventies is in marked contrast to the comparatively dreary state of optical technology even three or four decades ago. The melding of optics and electronics into what is being called *electro-optics* is indicative of the new emphasis.

Profound insights are slow in coming. What few we have took over three thousand years to glean even though the pace is ever quickening. It is marvelous indeed to watch the answer subtly change while the question immutably remains—*what is light?*[*]

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[*] For more reading on the history of optics, see F. Cajori, *A History of Physics* and V. Ronchi, *The Nature of Light*. Excerpts from a number of original papers can conveniently be found in W. F. Magie, *A Source Book in Physics*, and in M. H. Shamos, *Great Experiments in Physics*.

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