# 1 A short survey of the history of optics

Until the beginning of the seventeenth century, our understanding of the nature and properties of light evolved rather slowly, although, in contrast to electrical phenomena, for example, optical phenomena are straightforward to observe.

Ever since ancient times we have known about the straight-line propagation of light, which is most obvious in the shadows cast from a light source. From this observation, the ancient Greeks already developed the concept of straight light rays. This idea, however, was intimately entangled with the theory of “seeing rays”, which were emitted from the eyes and palpated, with the help of light, visible objects like feelers.

Another well-known fact was the equality of the angles of incidence and reflection for light rays, and Hero of Alexandria was able to attribute this law to the more general principle of a shortest path for light. Common optical devices were the gnomon as well as plane and curved mirrors and lenses. At least since ancient Roman times, magnifying glasses were in use.

Concerning the nature of light, different concepts were put forward. The “atomists” following Democritus (about 460–371 BC) and his less well-known predecessor Leucippus (about 480–??? BC) believed that all objects consisted of atoms traveling through empty space. All changes could be attributed to the movements and rearrangements of atoms. In this view, light rays were considered to be a flux of light particles traveling in straight lines and freely through empty space and which could penetrate transparent bodies. The different types of colors were explained by different shapes or sizes of these atoms of light. Later the Roman Lucretius (about 96–55 BC) formulated a systematic summary of the atomistic viewpoint in his savant poem “De Rerum Natura”.

In clear contrast to these ideas was the opinion of Aristotle (384–322 BC), which he formulated in his treatments on the soul (“De Anima” II,7) and the senses (“De Sensu” III). For ontological reasons the concept of empty space as an existing non-being was unacceptable for Aristotle. For him, light was not a substance or body but a quality; to be more precise, the actuality of the quality of the transparent. The mere potentiality of the transparent is darkness. The transition from the potentially transparent to the actually transparent happens under the influence of fire or the shining bodies of Heaven. The primarily visible quality of objects is their color. Colors are qualities which, like light, become actual in bodies that are not completely transparent but only participate in the nature of transparency to a certain degree. Therefore, it seems natural that Aristotle calls light the “color of the transparent”.

As is commonly known, the mainstream thinking in Europe did not follow the atomistic view for many centuries. In particular, the simple and plausible color theory of Aristotle was of far-reaching influence and initiated, amongst others, the color theory developed by Goethe.

*Theoretical Optics.* Hartmann Römer

ISBN: 3-527-40429-5

Throughout the Middle Ages, the atomistic philosophy was only known from discussions among the Aristotelians and as an object of polemics for the Early Fathers. It was not until 1417, after Poggio Bracciolini (1380–1459) had recovered a hand-written document of Lucretius, that a first-hand presentation of the atomistic ideas was available.

During the long era following the end of the ancient world up to the beginning of the seventeenth century, the efforts for a better understanding of the nature of light saw but a few highlights.

In the moslem Near East one of the outstanding scientists was Ibn al Haitham (963–1039), in Europe known by the name Alhazen. He found that the assumption of Ptolemaeus (about 100–170) about the proportionality of the angles of incidence and reflection was an approximation that only holds for small angles. Furthermore, he succeeded in giving a precise description of the functioning of the human eye.

Roger Bacon (1215–1294) knew quite well about the properties of lenses and concave mirrors and is regarded as the inventor of the camera obscura. Even more important is the invention of spectacles around 1299 by Salvino degli Armati from Florence. At the end of this chapter, the reader will find a table of important names and dates related to the history of optics.

The breakthrough in the seventeenth century was initiated by the invention of new optical instruments. In 1600 the Dutch maker of spectacles, Zacharias Janssen from Middelburg, built the first microscope. This instrument was continuously improved during the seventeenth century and allowed a glimpse into a world that remained out of reach for the naked eye. The same holds for the telescope, which, according to most sources, was invented by the Dutch Hans Lippershey around 1608. News of this discovery spread fast throughout Europe and caused Galileo Galilei (1564–1642) in 1609 to construct his telescope. In 1611 Johannes Kepler (1571–1630) published the drawings of his telescope using a convex lens ocular.

Finally, in 1621, Willebrord Snell (1591–1626) found the correct law of refraction and thereby solved one of the fundamental problems in geometrical optics after more than 1500 years. Even Kepler had tried to attack this problem and failed. In its present form the law of refraction was published by René Descartes (1596–1650) who, in 1644, derived it from his bizarre theory of light, which we will discuss later. He also found the right explanation for the rainbow. In 1657, Pierre de Fermat (1601–1665) derived the law of refraction from the principle of least time, which assumed the propagation of light inside optically dense media to be slower than outside.

After the discovery of the law of refraction, mathematicians like Carl Friedrich Gauss (1777–1855), William Rowan Hamilton (1805–1865), and Ernst Abbe (1840–1905) took over and continuously improved the theory of geometrical optics. Hamilton based his theory on Fermat's principle, and it was only later that he applied his methods to the realm of analytical mechanics. During his lifetime it was in particular the discovery of conical refraction that made him famous.

The scientifically very fruitful seventeenth century saw also the discovery of many fundamental optical phenomena: In his book "Physicomathesis de Lumine, Coloribus et Iride", which appeared in 1665 after his death, the Jesuit clergyman Francesco Maria Grimaldi (1618–1663) described the phenomenon of refraction; double refraction was found in 1669 by Erasmus Bartholinus (1625–1698); and the phenomenon of polarization was discovered by Christiaan Huygens (1629–1695), who described the effect in his "Traité de la Lumière" in

1690. However, in contrast to the phenomenon of double refraction, he was not able to explain it. Finally, we should emphasize Olaus Rømer (1644–1710), who in 1676 determined the velocity of light from the delayed appearances of the eclipses of the moons of Jupiter during a period of increasing distance between Jupiter and the Earth.

Concerning the understanding of the natures of light and color, three different concepts competed during the seventeenth century. Still of great influence and part of the canonical teaching at universities was the philosophy of Aristotle, which coined, for example, the ideas of Kepler.

Others, like Robert Boyle (1627–1691), followed the ancient atomistic view and vehemently propagated a corpuscular theory of light. Boyle, for example, related the various colors to different velocities of the light particles.

A third group, the so-called "plenists", differed from the atomists in their objection to the existence of empty space. For them, light was in some obscure way related to flows, vortices, and waves; they assumed the global existence of a continuous, space-filling medium for the propagation of an action. These ideas laid the foundations for the wave theory of light, which later, in the nineteenth century, became the dominant view in science.

Because of its great influence on the philosophy of the seventeenth century, the plenistic theory of Descartes is of special importance. Any form of corporeal substance is a "res extensa", characterized by its principal property of extension and occupation of space. A physical vacuum would be a contradiction in itself.

Descartes distinguished three types of matter, which differentiated from the primordial homogeneous bulk substance: a very tiny, subtle matter that one may identify with an ether; a so-called spherical matter consisting of small impenetrable spheres; and finally the third type of bulk matter from which the large material bodies in our world are formed. All three forms of matter fill space completely, and any action between material substances can be traced back to a "mechanical origin", which for Descartes consisted only of collisions or direct contacts.

According to Descartes, light constitutes an action of pressure exerted onto the spherical matter by the subtle matter, which is in constant motion. Because the spheres are in direct contact and of infinite rigidity, light propagates with infinite velocity. Refraction can produce colored light, if the spheres of the second type of matter are set into rotation through a deflection of the propagation direction. From his model, Descartes was able to derive Snell's law of refraction. Descartes explained the planetary rotations about their own axes as well as around the Sun "mechanically" as vortex-like movements of the subtle matter, which in turn would carry along the third type of matter.

Descartes did not trust in the truth of sensations but was convinced that thinking and reason were the only sources of reliable knowledge. The general influence of his program to mathematize the natural sciences was great. However, especially in England, people like Francis Bacon and Isaac Newton objected to his way of gaining knowledge by pure speculations. His mechanical models were considered to be artificial, lacking justification based on experience, and without any power of explanation or prediction. On many occasions Newton emphasized his disapproval of "hypotheses", which to a large extent may be seen as his response to the Cartesian philosophy.

In his "Physicomathesis", Grimaldi comes much closer to a wave theory of light than Descartes. He not only describes the phenomena of diffraction on small objects, including color fringes and the brightening in the center of the shadow, but he also mentions the phenomenon of interference (although he did not use this word) behind two closely neighboring apertures, and the colors appearing in the reflection of light from surfaces with densely spaced grooves. He also observed deviations from straight-line propagation of light and called them “diffractions”. Grimaldi compares the propagation of light with the floating of a fine liquid, but he does not draw far-reaching conclusions from this picture. The long-winded, roundabout style of his writing strongly diminished the influence of his work. Often the distinction of flow, vortex formation, and real propagation of light waves is not obvious, but he makes the comparisons with spherically spreading water waves and the propagation of sound. He interprets the variety of colors as the undulations of a fluid, which are as versatile as the handwriting of different people.

It was Robert Hooke (1635–1703) who formulated a real wave theory of light. He considered light as the propagation of a longitudinal wave in an ether. In his “Micrographia” from 1665, he describes the appearance of color at thin films, and he seeks an explanation in the reflection of light at both sides, the front as well as the back side of the film. As he and his contemporaries were lacking the notion of interference, he was not able to complete this explanation. The appearance of color in the refraction of light is explained by wave fronts, which after refraction are no longer parallel to the direction of propagation. In general, colors were described as modifications of white light.

In his “Traité de la Lumière”, Christiaan Huygens developed the well-known principle now bearing his name, according to which at every point of space the passing light excites elementary waves (or wavelets). Using this picture he derived a simple and convincing explanation of Snell’s law of refraction, which to the present day is contained in almost every school textbook. The most brilliant triumph of this model was the quantitative description of double refraction in calcite by assuming spherically and ellipsoidally shaped wavelets.

Most surprisingly, Huygens model is not really a wave theory. His wavelets are rather to be compared with wave fronts or shock waves, from which the resulting wave fronts may be reconstructed as the envelope. They are not related to some kind of periodic motion.

In his Traité, he does not elaborate on the problem of colors, although his comments on Newton’s color theory indicate his preference for a color theory based on two or three primary colors.

We should now emphasize the contributions of Isaac Newton (1643–1724) who, for a long time, eclipsed all other natural philosophers not only because of his deciphering of the laws of motion and gravity but also for his contributions to the field of optics. Almost all lines of developments enter and sometimes even interfere in his works on optics, and nowhere else are the contradictory aspects of the wave and corpuscular theory of light more obvious than in his person.

With full justification, Newton is generally considered to be the representative for the corpuscular theory of light. In this aspect, he rather represented a minority of those scholars who were involved in the progress of optics at this time. Newton has often been blamed that under the pressure of his authority the breakthrough of the wave theory was delayed until the nineteenth century. However, a deeper look reveals that such an oversimplified judgment of Newton’s role is inappropriate.

Like his development of the infinitesimal calculus and theory of gravitation, one can trace back the works of Newton on optics to his earlier years, in particular to the eminently fruitful time between 1665 and 1667, which he spent in his birth town Woolsthorpe after the University of Cambridge had to be closed in the aftermath of the plague. Newton mainly published his results related to optics during the first four decades of his life.

As is well known, the starting point of his investigations of prismatic colors was the problem of chromatic aberrations in lens telescopes. He was convinced that it was impossible to correct the chromatic aberrations of lenses, which led him to the construction of a mirror telescope. This brought him the Membership of the Royal Society.

In 1672 his revolutionary article "New Theory about Light and Colors" appeared in the "Philosophical Transactions", the publication organ of the Royal Society. In this article Newton reports in a concise but lively style about his famous experiments on the decomposition of white light. His conclusion was that white light is composed of components of different colors and refractivities. These components cannot be further decomposed by a prism and cannot be modified by other means. However, it is possible to compose white light from these components. The colors of bodies can be explained by their varying reflection or absorption of the different colors contained in white light. His theory of an infinity of basic colors that cannot be viewed as a modification of the original white light was considered as revolutionary and led to fierce and controversial discussions.

Never again in his writings did Newton formulate his ideas as frankly and unprotected as he did in those thirteen pages. In his later publications, in particular in his main works, Newton preferred the unassailable but rigid form of a mathematical treatment with definitions, axioms, and propositions.

Three reasons may have been responsible for this caution: First, Newton tried to avoid scientific arguments, which he hated but with which he nevertheless saw himself confronted all the time. His relationship with Robert Hooke, for instance, consisted of a decade-long chain of wearing quarrels. Second, Newton had a general and constantly growing distrust in argumentation of the Cartesian type. Third, his position on the interpretation of physical phenomena often remained open because he himself could not make up his mind regarding a final opinion.

However, in a series of papers and lectures presented to the Royal Society around 1675/76, Newton cautiously commented on his view about the nature of light, emphasizing his aversion to hypotheses and clearly distinguishing facts from explanations.

The most important physical content of this works lies in the description of Newton's rings, as they are called today. These are concentric colored rings that become visible when a slightly curved convex lens is placed onto a plane glass plate. Only much later did it become clear that these rings result from the interference of light waves that are reflected at the boundaries of the thin layer of air between the two glasses. For the coming 130 years, the precision of Newton's observations was unparalleled; they later allowed the precise determination of the wavelengths of different colors. In this context Newton even surpassed Hooke whose special field was the color phenomena at thin layers.

From Newton's explanations it seems obvious that at that time he considered the existence of an ether, through which the waves could propagate, as very likely. "If I had to assume a hypothesis as true," he says, "it would be this one." The ether is a medium with a large density outside of material bodies but only a diluted density inside where it is displaced by other forms of substance. The ether not only mediates the electric and magnetic forces but also the excitations traveling in nerve fibers and – particularly surprising for Newton – the gravitation between material bodies. As we shall see in a moment, the ether also has an influence on the propagation of light. In order to fulfill all these different functions, the ether was thought to be a complicated mixture of several components.

Although the ether is able to vibrate, we should not, according to Newton's opinion, identify the nature of light with these ether undulations. The reason Newton mentions this is that for him the straight propagation of light is not compatible with a wave theory. Indeed, this was a fundamental problem at a time when a mathematical treatment of wave theory, the principle of interference, and, in particular, the method of Fourier analysis were not at hand. It was only 150 years later that Fresnel found a way out of this dilemma using his method of zone constructions.

Therefore, Newton saw himself forced to ascribe a corpuscular character to light. He explained the phenomena of refraction and total reflection by assuming that the light particles were dragged into spatial areas of diluted ether. According to his opinion, the velocity of light should be larger in transparent matter as compared to the ether between the bodies. In addition, violet light should consist of smaller particles because they are easier to deviate and therefore refracted more strongly. With these ideas, Newton opposed Fermat and Huygens.

When light particles traversed the interfaces between bodies or passed near such an interface, they would trigger undulations of the ether "like a stone thrown into water", and these denser and thinner parts of the ether, which propagate faster than light itself, had somehow to react back onto the motions of the light particles. Newton explicitly mentions the work of Grimaldi and explains the colored borders and fringes when light is refracted at edges or small objects as the interaction of light particles with excited ether waves.

This sophisticated theory of ether waves as a kind of "guiding waves" for light provided a qualitative and quantitative explanation for Newton's rings. Newton's only assumption was that the light particles, after hitting the interface, were either predominantly reflected or they passed through the interface, depending on whether they had hit a density peak or a density minimum of the excited ether waves. This also explained why light was sometimes reflected and sometimes diffracted at interfaces. The radius of Newton's rings allowed a precise determination of the wavelengths of the ether waves that were triggered by light particles of different colors.

Newton was well aware of the advantages inherent in the wave theory of light and he even proposed to relate the wavelengths of the ether undulations with the color of light. He knew, and he clearly states, that the color and dispersion phenomena of light as well as Newton's rings could be explained by both a wave theory and a corpuscular theory. As we have seen, it was the problem of understanding the straight-line propagation of light that led Newton to favor a corpuscular theory.

In 1704, almost 30 years later and one year after the death of Robert Hooke, Newton published his extensive work on the nature of light in his book "Opticks". The first Latin version followed in 1706, and the second English edition in 1717. Compared to his earlier writings, one finds characteristic changes in the form of representation as well as in his opinion.

For his "Opticks" he chooses the form of a mathematical treatment, like he did in the "Principia" from 1687. However, in contrast to the "Principia", he derives his results more by induction, starting from the phenomena and proceeding to their mathematical description. When Newton developed his theory of gravitation and experienced the sometimes nasty discussions about fundamental principles, his aversion to Cartesian-like explanations by hypotheses grew. In his famous "Scholium Generale" at the end of the "Principia", Newton refused to supplement a hypothetical interpretation for his action at a distance, which describes the gravitational forces. The second book of the “Principia” is mainly devoted to a disproof of Descartes’ vortex theory of the motion of planets. The ether itself appears as an, at best, unnecessary auxiliary hypothesis, which he rather considers to be disproved by the observed phenomena. Already the first sentence in “Opticks” reads: “It is not my intention to explain in this book the properties of light by hypotheses, but only to state them and to confirm them by calculation and experiment.”

For the interaction between light and matter, observed in the reflection, diffraction, and refraction of light, he prefers a description “free of hypotheses” in terms of an action at a distance between the particles of light and matter. A derivation of Snell’s laws of refraction, assuming an attractive force between light and matter, is already contained in the fourteenth section of part I of the “Principia”. Once more, the velocity of light must be larger inside a medium than for the vacuum.

“Opticks” consists of three parts: Book I contains an extended and systematic description of Newton’s theory of colors, including his quantitative explanation for the colors of the rainbow.

Book II is devoted to the colors appearing in thin layers and he tries to use this theory also for an explanation of the colors of material bodies. The excellent observational data were already contained in the treatments of 1675/76. The explanation of these phenomena by guiding waves in the ether is replaced by a formal description, neutral with respect to hypothetical interpretations: The theory of “fits”, as he called them, the tendencies for a light particle to be reflected or to pass through an interface, is developed in propositions XII–XX of the second book. For instance, in proposition XII one finds: “Each light ray, when passing through a diffracting surface, acquires a certain property or disposition which reappears in the further course of the ray in equal intervals and by which it easily passes through the next diffracting surface, and is slightly reflected between each recurrence of this property.” Whether a light ray is reflected or diffracted at an interface depends on the momentary disposition of easy reflectibility or easy transmissivity. In proposition XIII Newton speculates that light might acquire these changing dispositions already with its emission. From the radius of Newton’s rings one can determine the recurrence intervals of these dispositions in air and water. For an explanation of these dispositions, Newton considers a hypothesis neither as necessary nor as proven, however, in proposition XII he mentions the model of ether undulations “for the reader”, beginning with a characteristic remark: “Those who are not willing to accept a new discovery unless it is explained by some hypothesis may assume, for the time being, that . . . .” A description that is free of any hypotheses concerning the dispositions consists for Newton in undulations that are produced in material substances by forces at a distance between light and matter particles and then react onto the light.

In book III of “Opticks”, Newton describes his observations related to the refraction of light at small objects and edges. This is followed by an appendix where Newton poses some problems, which, in his opinion, are not yet sufficiently understood. He also includes general comments on the nature of light, its interaction with matter, and also on subjects of natural philosophy, which go far beyond the realm of optics. These famous “queries” allow a glimpse into Newton’s personal thoughts, interpretations, and doubts. From the way he poses the questions, it is usually not difficult to deduce the answers that Newton favored.

Newton's view about these subjects was everything else but settled, which manifests itself in the increasing number of queries added to each new edition, and by 1717 the edition of "Opticks" contained 130 queries. The first questions aim at an interpretation of the phenomena of reflection, refraction, and diffraction according to the ideas described above. Of special interest are the questions from 25 to 31, which were first included in the edition of 1706. The questions 25 and 26 describe double refraction of light in calcite. In this context Newton explains the phenomenon of polarization. For an explanation, Newton assigns a third quality to light, in addition to color and periodic dispositions, and which he calls the "sides" of a light ray.

The "sides" should be considered as a kind of orientation of a light ray that is perpendicular to the direction of propagation. A light ray hitting the surface of a calcite crystal may be diffracted in an ordinary or an extraordinary way, depending on the orientations of the sides relative to the crystal. A rotation by $90^\circ$ around the direction of propagation will exchange ordinary and extraordinary diffraction. Newton explains his ideas by pointing out that the force between two magnets also depends on their relative orientation. His theory of sides already contains many essential ingredients of today's theory of polarization. However, with respect to a quantitative description of the extraordinary diffraction at calcite, Huygens' theory of wavelets remained superior.

In questions 27 and 28 Newton makes a thorough effort to falsify the wave theory of light. He emphasizes the straight-line propagation of light signals and compares it with the sound of a cannon or a bell, which could be heard also behind a small hill. And he summarizes all arguments disfavoring the existence of an ether. In question 29 he establishes his corpuscular theory of light: differences in color correspond to differences in the size of light particles; refraction, reflection, dispositions, and sides are explained by an action at a distance between light and matter.

Newton's enigmatic character reveals itself in that the 1717 edition of the "Opticks" contains new questions 17 to 24, where his ether theory from 1675 and 1676 reappears, including an ether hypothesis for gravitation, while at the same time the other questions rejecting and disproving the ether hypothesis still remain.

People have sometimes tried to mark Newton as an early pioneer of quantum mechanics, arguing with his aversion against hypotheses, his emphasis on the importance of observation, and his way to use the wave theory and corpuscular theory of light side by side. These attempts should be considered as inappropriate and unhistorical. But anyhow, Newton's free and cautious use of hypotheses differs much from the dogmatism of his successors, who certainly retarded the development of optics during the eighteenth century.

Today, in quantum theory, the relationship between wave and corpuscular theory has found a subtle solution in terms of complementarity. However, it would be wrong to consider the controversies between the respective proponents of wave and corpuscular theory as superfluous.

First, even from today's perspective we would use the wave picture for a proper description of reflection, refraction, diffraction, and double refraction; second, the propagation mechanism of light quanta, which is determined by absorption and re-emission, differs in many ways from the propagation of light particles, which should be slower in vacuum than in a medium; and third, the equation for the quantum field, which, within the framework of quantum electrodynamics, describes both the electromagnetic waves and the photons, is a wave equation.

With respect to the fundamentals of optics, nothing essential happened during the eighteenth century. However, we should mention two practical achievements: first, the construction of achromatic lenses, which Newton considered to be impossible, first in 1733 by the amateur Chester Moor Hall (1704–1770) and again in 1757 by John Dolland (1706–1761); and second, the discovery of aberration by James Bradley (1692–1762) in 1725. Aberration refers to the apparent change in the position of a star due to the movement of the Earth, and it was considered to be a confirmation of the corpuscular theory of light, because it found a simple and straightforward explanation within this framework.

The nineteenth century saw the second period of a rapid evolution of optics, at the end of which the nature of light was understood to be a transverse electromagnetic wave phenomenon. In 1801, the ingenious Thomas Young (1773–1829), who also contributed considerably to the deciphering of the hieroglyphs by suggesting the identification of the "cartouches" or "royal rings" around the kings' names, formulated the principle of interference of waves and explained, as an immediate application, the diffraction of light. Building on the work of Newton and his at that time still unsurpassed accuracy of measurements, Young proposed a wave theoretic explanation of Newton's rings together with a determination of the wavelengths of light. In 1809 Etienne Louis Malus (1775–1812) discovered the polarization of light in the reflections at mirrors, which led to a small crisis for the wave theory of optics. His observations led to the compelling conclusion that light, if really of wave-like character, must be transverse, which seemed to contradict the prevailing opinion according to which the propagation of light in a matter-free space was only possible for a longitudinal wave. For this reason even Malus himself judged his discovery to be a confirmation of the corpuscular theory. It took another eight years until Thomas Young, in 1817, ventured to interpret light as a transverse wave.

Essential progress in wave theory is due to Augustin Jean Fresnel (1788–1827). His zone construction, published in 1818, solved the long-standing problem of explaining the straight-line propagation of light. Together with Dominique Jean François Arago (1786–1853), he showed in 1819 that two light rays with perpendicular polarization planes do not interfere. Starting from a theory of transverse waves, not only was Fresnel able to derive the formulas which today bear his name and which allow the exact determination of the intensities for the reflected and refracted parts of light, but also he completed the subject of crystal optics as a theory of propagating transverse waves in anisotropic crystals. Of similar importance is his work on the theory of diffraction, which was further pursued by Joseph Fraunhofer (1787–1826), whose formal concepts were finally completed by Gustav Robert Kirchhoff (1824–1887). These successes of wave theory remained unmatched by any corpuscular theory of light. One of the last and tenacious proponents of corpuscular light theory was Jean Baptiste Biot (1774–1862). He looked for a mechanistic explanation of Newton's fits in the form of prolonged and rapidly rotating light particles, which could penetrate through a surface if they hit the surface with their spiky heads, and which were reflected if they hit the surface with their flat sides. The final decision in favor of wave theory was the measurement of the velocity of light in water by Jean Bernard Léon Foucault (1819–1868), which in 1850 definitely proved that the speed of light inside a medium is slower than in the vacuum.

Based on the preliminary work of Michael Faraday (1791–1867), James Clerk Maxwell (1831–1879) derived his fundamental equations of electrodynamics, which imply the existence of transverse electromagnetic waves propagating with a fixed velocity, the velocity of light. The final experimental detection of these waves by Heinrich Rudolf Hertz (1857–1894) in 1888 made optics a branch of electrodynamics.

The theory of electrons developed by Hendrik Antoon Lorentz (1853–1928) allowed the explanation of optical properties of matter in terms of electromagnetic concepts. The derivation of Fresnel's equations from electrodynamics is also due to Lorentz. In addition, we owe him essential contributions to the solution of the ether problem.

The final *coup de grâce* for the notion of an ether in its traditional form came in 1905, when Albert Einstein (1879–1955) formulated his theory of special relativity. The famous experiment by Albert Abraham Michelson (1852–1931) and Edward Williams Morley (1838–1923) did not reveal any measurable motion of the Earth with respect to the ether, as one would have expected according to the ether hypothesis.

Just when the final victory of the wave theory of light seemed complete, Max Planck (1858–1947) explained, in 1900, the spectral energy distribution of a black body using his quantum hypothesis. In 1905 Albert Einstein (1879–1955) took up the concept of energy quantization and applied it to the hitherto unexplained photoelectric effect. In his interpretation, Einstein went far beyond the ideas of Planck in that he described light as consisting of single energy quanta, so-called photons, thus assigning particle-like properties to light. The development of quantum theory at the beginning of the twentieth century finally led to a deeper understanding of the nature and the properties of light.

The discovery of the laser, the advance of the computer, the rapid development of holography and diffractive optics, the development of new materials, in particular materials with special nonlinear properties, as well as the sophistication and expansion of theoretical methods has led to a new revolution of optics during the past few decades. At present, optics can be considered as a particularly strong and growing branch of physics.

**Table 1.1:** Important people and events for the evolution of optics.

| | | |
|---|---|---|
| Euclid (about 300 BC) | | "Katoptrik" (first scientific epos), general ideas about optics |
| Ibn al Haitham (AD 963–1039) | | |
| R. Bacon (1214–1294) | | discovery of the camera obscura |
| S. degli Armati | 1299 | discovery of spectacles |
| Z. Janssen | 1600 | the first microscope |
| H. Lippershey (1587–1619) | 1608 | construction of the first telescope |
| G. Galilei (1564–1642) | 1609 | telescope |
| J. Kepler (1571–1630) | 1611 | telescope |

**Table 1.1:** continued

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|---|---|---|
| W. Snell (1591–1626) | 1621 | formulation of the law of refraction |
| R. Descartes (1596–1650) | 1637 | "La Dioptrique", theory of the rainbow, law of refraction |
| P. de Fermat (1609–1665) | 1657 | derivation of the law of refraction, principle of temporally shortest path of light |
| F. Grimaldi (1618–1663) | 1665 | "Physicomathesis de Lumine, Coloribus et Iride", discovery of diffraction |
| E. Bartholinus (1625–1698) | 1670 | discovery of double refraction |
| C. Huygens (1629–1695) | 1678/90 | "Traité de la Lumière", wavelets, explanation of double refraction, discovery of polarization |
| R. Hooke (1635–1703) | 1665 | "Micrographia", wave theory, colors of thin layers |
| I. Newton (1643–1727) | 1668 | construction of the mirror telescope, |
| | 1672 | "New Theory about Light and Colours", |
| | 1675/76 | lectures about Newton's rings, |
| | 1704 | "Opticks" (Latin 1706, 2nd English edn. 1717), mirror telescope, theory of colors, component theory of white light, colors of the rainbow, Newton's rings, polarization, diffraction, corpuscular theory |
| O. Rømer (1644–1710) | 1676 | measurement of the speed of light |
| J. Bradley (1692–1762) | 1725/28 | stellar aberration of the light of fixed stars and its explanation |
| C. M. Hall (1704–1770) | 1733 | construction of achromatic lenses |
| J. Dolland (1706–1761) | 1757 | construction of achromatic lenses |
| F. W. Herschel (1738–1822) | 1800 | discovery of infrared radiation |

**Table 1.1:** continued

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|---|---|---|
| J. W. Ritter (1776–1810) | 1801 | discovery of ultraviolet radiation |
| W. H. Wollaston (1766–1828) | 1801 | discovery of ultraviolet radiation |
| E. L. Malus (1775–1812) | 1809 | polarization by reflection |
| D. Brewster (1781–1858) | 1815 | Brewster's angle |
| T. Young (1773–1829) | 1801<br>1817 | development of interferometry,<br>interpretation of light as a transverse wave |
| C. F. Gauss (1777–1855) | | geometrical optics |
| J. Fraunhofer (1787–1826) | 1814/15<br>1821/23 | Fraunhofer lines,<br>development of diffraction theory |
| J. A. Fresnel (1788–1827) | 1818<br>1819<br>1821/22 | Fresnel's zone construction,<br>Fresnel's equations,<br>development of diffraction theory |
| D. J. F. Arago (1786–1853) | | polarization, color phenomena, interference |
| W. R. Hamilton (1805–1865) | | geometrical optics, conical refraction |
| G. R. Kirchhoff (1824–1889) | 1859<br>1883 | spectral analysis, together with R. W. Bunsen,<br>diffraction theory |
| R. W. Bunsen (1811–1899) | 1859 | spectral analysis, together with G. R. Kirchhoff |
| H. Fizeau (1819–1896) | 1849 | terrestrial measurement of velocity of light |
| J. B. L. Foucault (1819–1868) | 1850 | measurement of velocity of light in media |
| H. von Helmholtz (1821–1894) | | theory of aberrations of optical instruments |

**Table 1.1:** continued

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|---|---|---|
| E. Abbe (1840–1905) | | theory of resolution of optical instruments |
| J. C. Maxwell (1831–1879) | 1862 | Maxwell's equations, fundamentals of electromagnetic light theory |
| L. G. Gouy (1854–1926) | | phase change at caustics |
| A. Sommerfeld (1868–1951) | | rigorous solution of diffraction problems |
| H. Hertz (1857–1894) | 1888 | detection of electromagnetic waves |
| W. C. Röntgen (1845–1923) | 1895 | X-rays |
| H. A. Lorentz (1853–1928) | | electron theory of optical properties of matter |
| M. Planck (1858–1947) | 1900 | light quanta |
| A. Einstein (1879–1955) | 1905 | theory of photon effect, special relativity |
| A. A. Michelson (1852–1931) | 1880 | interferometer, Michelson–Morley experiment |
| D. Gabor (1900–1979) | 1948 | holography |
| T. H. Maiman (1927– ) | 1960 | laser |
| C. H. Townes (1915– ) | 1964 | Nobel prize for the development of lasers |
| A. M. Prochorow (1922– ) | | |
| N. G. Basow (1916– ) | | |