A *Very* Brief History of Light

M. Suhail Zubairy

M.S. Zubairy (✉)
Institute for Quantum Science and Engineering (IQSE) and Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843-4242, USA
e-mail: zubairy@tamu.edu

1.1   Introduction

While tracing the history of ideas that shaped our understanding of nature and the properties of light, it is quite remarkable to see how one can almost neatly divide the geographical regions where human thoughts progressed during a certain time period followed by a decay and setting of the dark ages. We can divide the history of light into four distinct eras. The first era, with its center initially in Athens and then Alexandria, belonged to the Greeks. This era extended from about 800 BC till around 200 AD. It seems that hardly anything of significance in our understanding of light was contributed between 200 AD till around 750 AD when Muslims burst onto the scene. The second era belongs to the Islamic civilization, with its centers in Baghdad and Cordoba. It had its golden age till around middle to late thirteenth century when Mongol invasion destroyed the eastern center in Baghdad in 1258 and the decay set in the Western Center of Cordoba. The third era started in Europe around the fourteenth century when medieval Europe that had slipped into a dark age after the fall of Roman Empire started to emerge out of it. The crusades (1095–1272) and the conquest of Islamic Spain made the Muslim scholarship and the Greek traditions accessible to the Europeans, helping to initiate the glorious era of scientific revolution in the West. The last era started with the dawn of twentieth century that opened not only with new and revolutionary theories of Physics but also with a revolution in communication technology. This has helped to make science, and optics, a global preoccupation.

1.2   Greeks and Antiquity

The Greek civilization flourished in the eastern Mediterranean area, extending from Athens in Greece to Anatolia, Syria, and Egypt from Archaic period in about eighth century BC till about 200 AD. This civilization produced the highest level of intellect in many branches of human thought such as mathematics, philosophy, ethics, and astronomy. Through the galaxy of thinkers, such as Archimedes, Socrates, Plato, Aristotle, Euclid, Ptolemy, and Galen, they left a lasting imprint on the human civilization. Their most lasting legacy is not the theories that these giants of history presented as most of them have either been overturned or replaced during the evolution of human thought. Their lasting legacy to the mankind lies in placing the rational thinking at the apex of creation that has reverberated through millennia, long after the Greek civilization disappeared.

Light in Antiquity   The earliest studies concerning light had to do with understanding vision. For example, the ancient Egyptians believed that light was the activity of their god Ra seeing. When Ra's eye (the Sun) was open, it was day. When it was closed, night fell. The earliest studies on the nature of light and vision can be attributed to the Greek and Hellenistic traditions. The Greek period, extending from the Archaic period till around 320 BC and centered in Athens, produced many earliest ideas about vision through the works of Democritus, Epicurus, Plato, and Aristotle. After the death of Alexander, the center shifted to Alexandria where Ptolemy I, a general in the Alexander's army, established a new dynasty that lasted till the Roman conquest of Egypt in the first century BC. In this Hellenistic period, the glorious traditions of Greek scholarship in the field of light and vision continued through the works of Euclid, Hero of Alexandria, Ptolemy, and Galen.

The theory of vision attempts to explain how objects, near and far, their shape, size, and color, are perceived by us. The earliest systematic studies of vision are

attributed to atomists who reduced every sensation, including vision, to the impact of atoms from the observed object on the organ of observation. There were different schools of thought among atomists. For example, Democritus (460 BC–370 BC) believed that the visual image did not arise directly in the eye, but the air between the object and the eye is contracted and stamped by the object seen and the observing eye. The pressed air contains the details of the object and this information is transferred to the eye. Epicurus (341 BC–270 BC), on the other hand, proposed that atoms flow continuously from the body of the object into the eye. However the body does not shrink because other particles replace and fill in the empty space.

An alternate theory of vision due to Plato (428 BC–328 BC) and his followers advocated that light consisted of rays emitted by the eyes. The striking of the rays on the object allows the viewer to perceive things such as the color, shape, and size of the object. Our vision was initiated by our eyes reaching out to "touch" or feel something at a distance. This is the essence of extramission theory of light that would be influential for almost a 1000 years until Alhazen would conclusively prove it to be wrong.

Hellenistic Era, Euclid, Hero of Alexandria, and Ptolemy   Euclid (b. 300 BC) is the father of Geometry. His book *Elements* laid down the foundation of axiomatic approach to geometry and is one of the most influential books ever written. Little original references are available about Euclid and what we know about him was written centuries after he lived by Proclus (c. 450 AD) and Pappus of Alexandria (c. 320 AD). His work in optics follows the same methodology as *Elements* and gives a geometrical treatment of the subject. Euclid believed in extramission and his theory of vision is founded in the following postulates:
1. Rectilinear rays proceeding from the eye diverge indefinitely;
2. The figure contained by the set of visual rays is a cone of which the vertex is at the eye and the base at the surface of the object seen;
3. Those things are seen upon which visual rays fall and those things are not seen upon which visual rays do not fall;
4. Things seen under a larger angle appear larger, those under a smaller angle appear smaller, and those under equal angles appear equal;
5. Things seen by higher visual rays appear higher, and things seen by lower visual rays appear lower;
6. Similarly, things seen by rays further to the right appear further to the right, and things seen by the rays further to the left appear further to the left;
7. Things seen under more angles are seen more clearly.

Euclid did not define the physical nature of these visual rays. However, using the principles of geometry, he discussed the effects of perspective and the rounding of things seen at a distance.

Euclid had restricted his analysis to vision. Hero of Alexandria (10–70), who also believed in the extramission theory of Euclid, extended the principles of geometrical optics to consider the problems of catoptrics, particularly, reflection from smooth surfaces. Hero derived the law of reflection by invoking the principle of least distance. According to him, light from a point A to another point B follows a path that is shortest. On this basis, he showed that when light reflects from a surface, angle of incidence is equal to the angle of reflection. Specifically, the image appears to be as far behind the mirror as the object is in front of the mirror. Hero's principle of least distance would be replaced by the principle of least time by Pierre Fermat more than 1500 years later to derive the law of refraction.

The most influential and perhaps last important figure in optics of the Greek–Egyptian era was Claudius Ptolemy (90–168). He is most well known for

championing the geocentric model for the movement of planets, a view that would survive for almost 1400 years until it was replaced by a heliocentric model through the work of Nicholas Copernicus in 1543. His book on the subject *Almagest* was very influential in shaping the thinking on astronomy and, along with *Elements* by Euclid, was the longest read book in the history of science. Ptolemy wrote *Optics* in which he discussed the theory of vision, reflection, refraction, and optical illusions. Like Euclid and Hero, Ptolemy championed the extramission theory of vision. He considered visual rays as propagating from the eye to the object seen. However, instead of considering visual rays as discrete lines as postulated by Euclid, he considered them forming a continuous cone. Ptolemy carried out careful experiments on refraction and concluded that, for light propagating from one medium to another, the ratio of the angle of incidence to the angle of refraction was constant and depended on the properties of the two media. He thus derived the small angle approximation of the law of refraction. The formulation of theory based on experimental results, frequently supported by the construction of special apparatus, is the most striking feature of Ptolemy's *Optics*.

1.3 Islamic Period

Islam has its roots in Mekkah, a city that was on the cross road of trade route from Syria to Yemen in the sixth and seventh century. The founder of the religion, Prophet Muhammad (PBUH), was born there in 570 and claimed to have received his first revelations from God in 610. Under severe opposition from his kinsmen to the new religion, he migrated to the northern city of Madinah in 622. This marked the beginning of the Islamic era. When Muhammad (PBUH) died in 632, Islam had spread throughout the Arabian Peninsula. He was followed by four caliphs, Abu Bakar, Umar, Usman, and Ali, in the leadership of the Islamic community. Under Umar, the conquests of Persia, Syria, and Egypt expanded the Islamic writ to a major part of the Middle East. These caliphs were followed by the Ummayad dynasty (660–750) when North Africa, Spain, Western China (Xinjiang), and Western India (modern Pakistan) came under the Muslim rule. The capital of Ummayads was Damascus. In 750, the Ummayads were replaced by Abbasids (descendants of an uncle of the Prophet named Abbas). They continued to rule till 1258 when Mongols attacked and conquered their capital Baghdad. The Ummayad's rule in the Iberian Peninsula continued till 1492 (the year when Columbus landed in the new world). The tenth and eleventh century Egypt was ruled by Fatimids, a dynasty founded by the descendants of Fatima, daughter of Prophet Muhammad (PBUH).

Contrary to some modern claims and perceptions, Islam was an enlightened religion in its beginning, deeply rooted in the search of knowledge. The Islamic holy book, Qur'an, that was believed by Muslims to be the direct word of God as revealed to Prophet Muhammad (PBUH) exhorted human beings to contemplate and seek knowledge through words such as "And say, Lord increase my knowledge" (Qur'an 20:114) and "He (God) has subjected to you, as from Him, all that is in the heavens and on earth: behold in that are Signs indeed for those who reflect" (Qur'an 45:13). Similarly the sayings, such as "the ink of a scholar is more holy than the blood of a martyr" and "The most learned of men is the one who gathers knowledge from others on his own; the most worthy of men is the most knowing and the meanest is the most ignorant", attributed to Prophet Muhammad (PBUH) emphasize the importance of the pursuit of knowledge. These and other similar injunctions in the Qur'an and the Prophetic traditions helped to develop an attitude in the Muslim community that supported the quest of knowledge and promoted an environment where open discussion was encouraged. Science was not seen to be contrary to the faith. Rather it was considered to be a religious duty

to seek knowledge and understanding. As the Islamic Empire increased in size so did the thirst for more knowledge in all fields.

Armed with this attitude, Muslims built a civilization in the Eighth century that would last for several centuries and contributed to almost all aspects of human knowledge. It is unprecedented in the annals of history that an empire would bring with it a great civilization as well. The Muslims built a body of knowledge by first learning and then expanding on the older traditions, particularly Greek. Their own contributions would, in turn, provide a foundation for the emergence of the modern Western civilization.

Bayt-al-Hikmah (House of Wisdom)   Traditionally the beginning of the Islamic Golden Age of science is attributed to the Abbasid caliph Harun al-Rashid (763–809) who ruled an empire stretching from modern Pakistan to North Africa to the shores of Atlantic Ocean from 786 till 809. However the age may have started earlier, even in the Ummayad period, when the foundations of Islamic Jurisprudence were being laid down through discussion and reason. This tradition crossed into the secular body of knowledge, leading first to assimilating what old sages from Greek, Indian, and other civilizations had contributed and then building their own contributions in fields ranging from philosophy and medicine to mathematics and physical sciences.

Harun al-Rashid and his court is fantasized in the book *One Thousand and One Nights*. He laid the foundation of *Bayt-al-Hikma* (House of Wisdom) in the newly built capital city of Baghdad. However it was formally completed in 830 in the era of his equally brilliant son, al-Mamun (786–833) who ruled from 813 till 833. Originally the House of Wisdom was a scientific academy and a public library where books from all parts of the empire were brought and translated in Arabic. These included old texts from India, Greece, and Persia in the fields of philosophy, mathematics, astronomy, medicine, and optics. By 850, House of Wisdom had the largest repository of manuscripts of its time. Gradually this center turned into a center of research and many famous names of Islamic Golden era were associated with it. These included, among others, Jabir bin Hayyan (721–815) who is regarded as father of chemistry, Al-Khwarizmi (780–850) who is credited with inventing algebra, Al-Kindi (800–873) who is regarded as the first Muslim philosopher, Hunayn ibn-Ishaq (809–873) whose contributions in medicine were influential till the modern era, and Alhazen (865–1040) who is regarded as the father of optics.

Al-Mamun himself took great interest in the progress of the House of Wisdom and is reputed to have intellectual discussions with the scholars that had started coming from distant lands. Al-Mamun supported organized research in areas such as developing detailed maps of the world, measurement of the circumference of the Earth, and the confirmation of data from Ptolemy's *Almagest*. This is the first known example of the state sponsored research. Gradually other institutions of higher learning, such as Al-Azhar University (970) in Cairo and Al-Nizamiyya (1095) in Baghdad, developed in and outside Baghdad.

Al-Kindi and Optics   Abu Yusef Yaqoub ibn Ishaq Al-Kindi (800–873) was the first great philosopher of the Islamic era. He synthesized, adopted, and promoted Greek philosophy in the Islamic world. He worked with a group of translators at the House of Wisdom who rendered works of Aristotle, Plato, Euclid, and other Greek mathematicians and scientists into Arabic. Al-Kindi's main authority in philosophical matters was Aristotle. His philosophical treatises include *On First Philosophy*, in which he argues that the world is not eternal and that God is a simple *One*. Al-Kindī tried to demonstrate that philosophy is compatible with Islamic traditions and had a great

influence on later Muslim philosophers Abdullah ibn-Sina (known in the West as Avicenna) and Ibn-Rushd (known in the West as Averroes).

Al-Kindi was also the first to undertake serious studies in optics and the theory of vision. His work on optics, *De Aspectibus* in Latin translation, exerted a strong impact on Islamic and Western optics throughout the middle ages. In optics, Al-Kindi followed the traditions of Euclid, and carried on by Ptolemy and others in which geometrical constructions were used to explain phenomena such as vision, reflection, refraction, shadows, and burning mirrors. Whereas Euclid considered the straightness of a visual ray as an axiom, Al-Kindi proved it experimentally by considering the shadows projected by different opaque objects. He treated the geometry of visual cone, rejecting the discreteness of Euclid's rays and replacing them with a cone of continuous beam of radiation similar to Ptolemy.

Al-Kindi's work was followed in tenth century by Al-Razi and Al-Farbi who started objecting to the extramission theory of light. A series of strong arguments against the notion of visual fire were put forward around 1000 by the great ibn-Sina. He argued that the visual fire cannot reach remote objects as it will have to fill an enormous space each time we opened our eyes. He also argued that Euclid's discrete rays may leave large areas of a distant object unobservable.

Ibn-Sahl and Snell's Law 600 Years Before Snell   Snell's law of refraction is an important law relating to the propagation of light between two media with different refractive indices. Refractive index of a medium is inversely proportional to the speed of light in that medium. The law of refraction thus forms the basis of understanding the bending of light rays from various kinds of lenses. The credit of the discovery of the law of refraction is given to Willebrord Snellius (1580–1626) who derived it using trigonometric methods in 1621. However recent studies indicate that this law was discovered more than 600 hundred years earlier during the Islamic Golden Age of Baghdad by a scientist named Abu Sad Al Alla Ibn Sahl (940–1000). Ibn Sahl excelled in optics and wrote a treatise *On Burning Mirrors and Lenses* in 984 in which he discussed the focusing properties of the parabolic and elliptical burning mirrors. He also presented an analysis of how hyperbolic glass lenses bend and focus light. As a lemma in his derivation of the focusing property of light by a plano-convex hyperbolic lens, he presented a geometric argument based on the sine law of refraction. This appears to be a major achievement and shows how far Muslims had advanced in pure and applied mathematics as well as optics by the end of tenth century. A question, however, remains about how such a major discovery could remain ignored for so many centuries. A plausible explanation is that Ibn Sahl did not state the law of refraction explicitly. Instead it was hidden as a sort of lemma and his emphasis was on the focusing property of lenses.

Alhazen, Father of Modern Optics   Abu Ali al-Hasan ibn al- Hasan ibn al-Haytham (965–1040), known in the west as Alhazen, is a central figure in science. He is often described as the greatest physicist between Archimedes and Newton. He was the first person to follow the scientific method, the systematic observation of physical phenomena and their relation to theory, thus earning the title First Scientist from many. His most important contribution in optics is his book *Kitab-al Manzir* (Book of Optics) which was completed around 1027. This book, comprising seven volumes, was the first comprehensive treatment of optics and covered subjects such as the nature of light, the physiological treatment of eye, and the bending and focusing

properties of lenses and mirrors. This book was most influential in the transition from the Greek ideas about light and vision to the modern day optics. Alhazen's Book of Optics was translated in Latin at the end of twelfth century under the title *De Aspectibus* and would remain the most influential book in optics till Newton's *Opticks* published in 1704.

Alhazen proved the long held theory of Euclid, Hero, and Ptolemy that light originated from the eye to be wrong and showed that light originated from the light sources. He did this by carrying out a simple experiment in a dark room where light was sent through a hole by two lanterns held at different heights outside the room. He could then see two spots on the wall corresponding to the light rays that originated from each lantern passing through the hole onto the wall. When he covered one lantern, the bright spot corresponding to that lantern disappeared. He thus concluded that light does not emanate from the human eye, but is emitted by objects such as lanterns and travels from these objects in straight lines. Based on these experiments, he invented the first pinhole camera (that Kepler would use and call *camera obscura* in the seventeenth century) and explained why the image in a pinhole camera was upside down.

Alhazen's theory of vision was not limited to the description of light rays originating from the objects and entering the eye. He also understood that an explanation of vision must also take into account the anatomical and psychological factors. He proved that the perception of an image occurs not in the eyes but in the brain and that the location of an image is largely determined by psychological factors.

Alhazen did not invent the telescope but he explained how a lens worked as a magnifier. He contended that magnification was due to the bending, or refraction, of light rays at the glass-to-air boundary and not, as was thought, to something in the glass. He correctly deduced that the curvature of the glass, or lens, produced the magnification. He concluded that the magnification takes place at the surface of the lens, and not within it.

His work on catoptrics in Book V of the Book of Optics dealt with problems of reflection from spherical and parabolic mirrors. It also contains a discussion of what is now known as Alhazen's problem. The problem was first formulated by Ptolemy in 150 AD. Draw lines from two points in the plane of a circle such that they meet at a point on the circumference, making equal angles with the normal at that point. The problem was to locate this point. This problem is equivalent to the Billiard table problem: On a circular table there are two balls; at what point along the circumference must one be aimed at in order for it to strike the other after rebounding off the edge. Alhazen's interest in this problem stemmed from the following formulation of the problem: When light is sent from a source towards a spherical mirror, find the point on the mirror where the light will be reflected to the eye of an observer. The problem is insoluble using a compass and a ruler because the solution requires solution of an equation of fourth degree. Alhazen solved this problem geometrically by the aid of a hyperbola intersecting a circle. This problem remained unsolved using algebraic methods for almost a thousand years until it was finally solved in 1997 by the Oxford mathematician Peter M. Neumann.

1.4   Scientific Revolution

The publication in 1543 of Nicholaus Copernicus's *De Revolutionibus Orbium Coelestium* (On the Revolutions of the Heavenly Spheres) marks the beginning of the scientific revolution. He proposed a heliocentric model of the solar system, a system in which Sun was held at rest and all the planets including Earth circled

around it, replacing the long held Ptolemaic geocentric model in which earth was at rest. Without the benefit of the knowledge of the law of gravitation, it was hard to believe how earth could be moving around the sun still maintaining the stability of all objects including the humans on its surface. The hostility to a model that took away the centrality of earth in a solar system was so great (particularly in the Church) that Copernicus could not publish his heliocentric theory till the end of his life. According to a legend, Copernicus received the copy of his book *De Revolutionibus* on the very last day of his life, thus dying without knowing that his work heralded a new era of human history. There were, however, birth pangs of this new world of science, most famous being Galileo's heresy conviction in 1633 for his support of Copernicus.

Kepler   The most important figure to follow Copernicus was the German astronomer, Johannes Kepler (1571–1630), whose laws on planetary motion would prove pivotal for Newton's law of gravitation. Kepler is a key figure in the history of light and vision as well. His interest in the subject appears to have originated in his observation of a solar eclipse on July 10, 1600 by means of *camera obscura*. Several years ago, Tycho Brahe (1546–1601), the greatest naked-eye astronomer of the time, had observed that the angular diameter of the moon appeared to be larger during a solar eclipse when observed through the pin-hole camera than when observed directly. Kepler understood that this anomaly could not be explained without a full understanding of the optical instruments, in this case, the *camera obscura*. He noted that the finite diameter of the pinhole should be responsible for this anomaly. He discovered the solution by an experimental technique where he stretched a thread through an aperture from a simulated luminous source to the surface on which the image was formed. He traced out the image cast by each point on the luminous body seeing, in the process, the geometry of radiation in three-dimensional terms. In this way, Kepler was able to formulate a satisfactory theory of radiation through apertures based on the rectilinear propagation of light rays.

Kepler did not stop at explaining Tycho Brahe's problem of seemingly variable lunar diameter. In 1601, he noted that eye itself possesses an aperture and should be treated in the same way as the aperture in a pinhole camera. Kepler published his theory of vision in 1604.

Descartes   Until Kepler, the main motivation of studying the nature of light came from a desire to understand vision. René Descartes (1590–1650) appears to be the first person to concern himself with the intrinsic nature of light and the laws of optics. Descartes was a French philosopher and mathematician who had a great impact on western philosophy. He is heralded as the Father of Modern Philosophy. His mathematical contributions included a connection between geometry and algebra that allowed for the solving of geometrical problems using algebraic equations. Descartes promoted the accounting of physical phenomena by way of mechanical explanations.

Descartes main contribution to optics is his book *Dioptrics* that was published in 1637. It deals with many topics relating to the nature of light and the laws of optics. He compares light to a stick that allows a blind person to discern his environment through touch.

Descartes used a tennis ball analogy to derive the laws of reflection and refraction of light. The credit of the discovery of the law of refraction is given to Willebrord Snellius (1580–1626) who derived it using trigonometric methods in

1621. However Snell did not publish his work in his lifetime. Descartes published the law of refraction 16 years after Snell's death, as Descarte's law of refraction.

Fermat and Principle of Least Time   Together with Descartes, Pierre de Fermat (1601–1675) was one of the two greatest French mathematicians of the first half of the seventeenth century. A lawyer by profession, Fermat made a number of important contributions in analytical geometry, probability, and number theory. He is most well known for the Fermat's Last Theorem (no three positive integers a, b, c can satisfy the relation $a^n + b^n = c^n$ for any integer n that is larger than 2) that he conjectured in 1621 but could not be proved till 1994.

Fermat's major contribution in optics relates to his derivation of Snell's law using the principle of least time. Just as Hero of Alexandria had derived the law of reflection on the basis of the principle of least distance 1400 years ago, Fermat argued that light rays going from a point located in a region where it propagates with a particular speed to a point in another region where it propagates with a different speed, it would follow a path that takes the shortest time. This yielded the correct Snell's law.

Newton   Sir Isaac Newton (1642–1727) is definitely the defining figure in the history of science. His *Principia* laid down the foundation of classical mechanics. His law of gravitation is a bright example of the nature of scientific law–law that applies equally well for all objects, big and small. His contributions in mathematics, particularly his co-discovery of calculus with Wilhelm Leibniz, provided tools that would be so vital for almost all the subsequent major discoveries in physics and other branches of science. They played key role in shaping the physics of the coming centuries.

It is, however, interesting to note that the most important experimental contributions to physics made by Newton are all in the field of optics. He was the first to show that the color is the property of light and not of the medium. Through ingenious experiments he could show that the light generated by sun consisted of all the colors. For example, when sun light passes through a prism, it is dispersed in a rainbow of colors. The red color bends the least and the violet color bends the most. This ability of glass prisms to generate multiple colors was known since antiquity but it was not attributed to light. Instead color was considered as a characteristic of the material. What Newton showed was that when a particular color passed through the prism, no such dispersion took place. In a relatively complicated setup, when these colors were combined together and passed through the prism again, Newton recovered white light, proving that white light consisted of all the colors.

The other major contribution of Newton towards optics is his design of reflecting telescope. All the telescopes through his time were unwieldy refracting telescopes that suffered from chromatic aberrations. The earliest refracting telescope, built in 1608, is credited to Hans Lippershey who got the patent for the design. These refracting telescopes consisted of a convex objective lens and a concave eyepiece. Galileo used this design in 1609. In 1611, Kepler described how a telescope could be made with a convex objective lens and a convex eyepiece lens. Newton designed a reflecting telescope where incoming light is reflected by a concave mirror onto a plane mirror that reflected the light to the observer. This design was simple and less susceptible to chromatic aberrations. All the major telescopes that exist today are improved versions of Newton's reflecting telescope.

Newton was also concerned with the nature of light and advocated corpuscular theory of light. According to him, light is made up of extremely small corpuscles, whereas ordinary matter was made of grosser corpuscles. He speculated that

through a kind of alchemical transmutation they change into one another. According to him, "Are not gross Bodies and Light convertible into one another,.. . .. And may not Bodies receive much of their Activity from the Particles of Light which enter their Composition?" It is surprising that Newton advocated corpuscular theory of light when there was evidence that supported the wave behavior. For example, Francesco Grimaldi (1618–1663) made the first observation of the phenomenon that he called diffraction of light. He showed through experimentation that when light passed through a hole, it did not follow a rectilinear path as would be expected if it consisted of particles but took on the shape of a cone. Newton explained that the phenomenon of diffraction was only a special case of refraction that was caused somehow by the ethereal atmosphere near the surface of the bodies. Newton could explain the phenomenon of reflection with his theory. However he could explain refraction by incorrectly assuming that light accelerated upon entering a denser medium because the gravitational pull was stronger.

Huygens, Wave Nature of Light   When Newton was expounding a corpuscular nature of light, his contemporary, Christian Huygens (1629–1695) suggested a wave picture of light. Huygens published his results in his *Traite de la lumie*re (Treatise on light) in 1690. Crucial to his wave theory was the result recently obtained by Olaus Romer (1679) that the speed of light is finite. He considered light waves propagating through the *ether* just as sound waves propagate through air. He explained the high but finite speed of light by the elastic collisions of a succession of spheres that made the *ether*. The light waves, according to Huygens, were thus longitudinal waves as opposed to the later studies by Fresnel and Maxwell that showed light to consist of transverse waves.

Huygens formulated a principle (that now bears his name) which describes wave propagation as the interference of secondary wavelets arising from point sources on the existing wavefront. In propagation each ether particle collides with all the surrounding particles so that ". . . around each particle there is made a wave of which that particle is the center."

Young and Double-Slit Experiment   Till the beginning of nineteenth century, Newton's status was so great particularly in the British Isles that few dared to challenge his corpuscular theory of light. It was, however, Thomas Young (1773–1829) who, in 1802, conclusively demonstrated the wave nature of light through his double-slit experiment. He described his experiment in these words in *The Course of Lectures on Natural Philosophy and the Mechanical Arts* (1807): ". . .. when a beam of homogeneous light falls on a screen in which there are two very small holes or slits, which may be considered as centres of divergence, from whence the light is diffracted in every direction. In this case, when the two newly formed beams are received on a surface placed so as to intercept them, their light is divided by dark stripes into portions nearly equal, but becoming wider as the surface is more remote from the apertures, so as to subtend very nearly equal angles from the apertures at all distances, and wider also in the same proportion as the apertures are closer to each other. The middle of the two portions is always light, and the bright stripes on each side are at such distances, that the light coming to them from one of the apertures, must have passed through a longer space than that which comes from the other, by an interval which is equal to the breadth of one, two, three, or more of the supposed undulations, while the intervening dark spaces correspond to a difference of half a supposed

undulation, of one and a half, of two and a half, or more." With this he firmly established the wave nature of light.

By repeating his experiment, Young could relate color to wavelength and was able to calculate approximately the wavelengths of the seven colors recognized by Newton that composed white light. According to him "…. it appears that the breadth of the undulations constituting the extreme red light must be supposed to be, in air, about one 36 thousandth of an inch, and those of the extreme violet about one 60 thousandth."

The Young's double-slit experiment was not only decisive in debunking Newton's corpuscular theory of light, but it also continued to play a crucial role in our understanding of the nature of light and matter even in the twentieth century. For example, in 2002, *Physics World* published the results of a survey on the all-time Ten Most Beautiful Experiments in Physics. Young's double-slit experiment made not one but two appearances on this prestigious list—at number 1 was the double-slit experiment applied to the interference of electrons and, at number 5 was the original experiment by Young.

Young's double-slit experiment was, however, regarded highly controversial and counterintuitive in his own time. How can a screen uniformly illuminated by a single aperture develop dark fringes with the introduction of a second aperture? And how could the addition of *more* light result in *less* illumination? Young's theory would eventually find broad acceptance, particularly through the works of Fresnel in France.

Fresnel, Theory of Diffraction, and Polarization of Light   Augustin Jean Fresnel (1788–1827), a contemporary of Young, championed the wave nature of light based on his work on diffraction. Fresnel began by undertaking experiments with diffraction. He noted that when light passed through a diffractor, one could see a series of dark and bright bands behind the diffractor. However when he blocked one edge of the diffractor, the bright bands within the shadow vanished and the bright bands remained only on the unblocked side of the diffractor. From this, he concluded that the bright bands in the shadow were produced by light coming from both edges and the bright bands, when one edge was blocked, resulted from the reflection of light from one edge of the diffractor. He was able to develop a mathematical theory for these observations based on a wave theory of light and could predict the position of bright and dark lines based on where the vibrations were in phase and out of phase. He published his first paper on wave theory of diffraction in 1815.

An episode indicates the stunning success of the wave nature of light as formulated by Fresnel. In 1819, Fresnel presented his work on wave theory of diffraction in a competition by the French Academy of Sciences. The committee of judges, headed by Francois Arago, included Jean-Baptiste Biot, Pierre-Simon Laplace, and Simeon-Denis Poisson. They were all prominent advocates of Newton's corpuscular theory and were not well disposed to the wave theory of light. Poisson was, however, impressed by Fresnel's submission and extended his calculations to come up with an interesting consequence: "Let parallel light impinge on an opaque disk, the surrounding being perfectly transparent. The disk casts a shadow - of course - but the very center of the shadow will be bright. Succinctly, there is no darkness anywhere along the central perpendicular behind an opaque disk (except immediately behind the disk)". According to the corpuscular theory, there could be no bright spot behind the disk. As Chair of the Committee, Arago asked Fresnel to verify Poisson's prediction and amazingly Fresnel found the bright spot as predicted. This discovery was an impressive vindication of the wave theory and Fresnel won the competition. This spot is now known as "Poisson spot."

Despite the triumph of the wave theory of light, the properties of the polarized light still provided a strong argument in favor of the corpuscular theory, since no explanation from a wave theory had ever been made. Following the success of the wave theory in explaining the interference and diffraction phenomena, Fresnel and Arago embarked upon explaining the properties of the polarized light based on Fresnel's theory. In 1817, Fresnel became the first person to obtain what was later called circularly polarized light. The only hypothesis that could explain the experimental results was that light is a transverse wave. In 1821, Fresnel published a paper in which he claimed that light is a transverse wave. Young had independently reached the same conclusion. The assertion that light is a transverse wave was not readily accepted by many, including Arago. Again Fresnel was vindicated when he could explain the double refraction from the transverse wave hypothesis. This helped to seal the status of light as a transverse wave.

Maxwell and Electromagnetic Waves It was left to James Clerk Maxwell (1831–1879) to complete the classical picture of light as consisting of electric and magnetic waves. This was a truly remarkable outcome of his efforts to unify the two known forces of nature: electric force and magnetic force. It was known through the work of Michael Faraday that a time rate of change of magnetic field yielded electric force. The insight due to Maxwell was that if electricity and magnetism were the two sides of the same coin then a change of electric field should similarly result in a magnetic field. This motivated him to add a term in the Ampere's law that corresponded to a time rate of change of the electric field. This addition immediately yielded a wave equation for an electromagnetic wave propagating at the same velocity as known for light, 3×10^8 m/s. The picture of light that emerged was thus that of undulations of mutually perpendicular electric and magnetic fields propagating. The direction of propagation was perpendicular to both the electric and magnetic fields. Maxwell's results were published in 1865. Thus the light waves were shown to be transverse waves in line with Young and Fresnel as opposed to the picture adopted by Huygens where light was seen as a longitudinal wave propagating through the medium *ether*. This description of light as an electromagnetic wave was experimentally demonstrated by Heinrich Hertz (1857–1894) in 1888.

1.5 Light in Twentieth Century

According to a quote, attributed to Lord Kelvin in an address to the British Association for the Advancement of Science in 1900, "There is nothing new to be discovered in physics now. All that remains is more and more precise measurement." The classical theories of mechanics, electromagnetics, thermodynamic, and, of course, light were firmly in place and it was a justified feeling to believe that the basic laws of nature were fully understood.

There were, however, two "clouds" on the horizon of physics at the dawn of the twentieth century. Interestingly enough, both of these involved light. The first cloud, the Rayleigh–Jeans ultraviolet (UV) catastrophe and the nature of black-body radiation, led to the advent of quantum mechanics, which of course was a radical change in physical thought up to that point. The second cloud, namely the null result of the Michelson–Morley experiment, led to special relativity, which is the epitome of classical mechanics, and the logical capstone of classical physics. These theories, quantum mechanics and the theory of relativity, were major departures from the classical theory as first formally introduced by Newton.

They would shape the physics of the twentieth century. They also dramatically revised our understanding of the nature of light.

Black-Body Radiation, Kirchhoff and Planck   The concept of a black body was introduced by Gustav Kirchhoff (1824–1887) in 1860. Kirchhoff knew from looking at the spectral lines from the sun that there was heat energy in empty space, and postulated equilibrium radiation. However the knowledge of what it consisted of was still primitive. By 1860, Maxwell's equations had not yet been postulated, and the electromagnetic nature of both heat and light rays had not yet been established. Nor had the existence of atoms in the walls of a cavity, nor that an oscillator radiates and absorbs electromagnetic energy, or that such energy carries momentum. Thus it is rather amazing that Kirchhoff should have established on the basis of relatively simple arguments that within a cavity at equilibrium, this radiation should be independent of the substance of the walls of the cavity, and that at a fixed temperature a good emitter of radiation should be a good absorber. A perfect absorber should then radiate an energy equivalent to everything that falls upon it within the cavity at equilibrium, independently at each frequency. He called the radiation emitted by such a perfect absorber the black-body radiation, and postulated that there should be a universal function $u(\nu,\mathrm{T})$ that describes the radiation density in equilibrium with the walls, that on average gets both absorbed and reemitted, at any particular frequency ν and temperature T. The challenge was to find the explicit form of the function $u(\nu,T)$. This search would eventually lead to the birth of quantum mechanics in early twentieth century.

In 1888 Hertz showed the reality of Maxwell waves. In 1893 Wien applied the laws of thermodynamics and electromagnetism to the problem of black-body radiation and succeeded in reducing Kirchhoff's universal function to a function of one variable. That is as far as one can go in classical physics. Wien tackled the problem of including the frequency in the black-body law by considering an adiabatic motion of a wall of the cavity. This induced a Doppler shift on the radiation, while at the same time the wall did work on the radiation.

The Rayleigh–Jeans formula gave results in agreement with the experimental observations at low frequencies; however, it failed miserably at high frequencies. The radiancy, according to Rayleigh and Jeans, is inversely proportional to the fourth power of the frequency, which indicates that at high frequencies the radiancy will approach infinity, thus leading to unphysical results in the ultraviolet region of the spectrum. By 1900, this failure, known as the Rayleigh–Jeans ultraviolet catastrophe, had caused people to question the basic concepts of classical physics and thermodynamics.

It was, however, Max Planck (1858–1947) who would eventually present the radiation formula that matched the experimentally observed black-body radiation spectra for the entire range of frequency spectrum. Planck presented his results that would eventually revolutionize our understanding of the laws of nature, literally at the close of the nineteenth century, on December 15, 1900, at a meeting of the German Physical Society.

When Planck addressed the problem of black-body radiation, he realized that since the results were independent of the nature of the material in the cavity, one could use a simple model for the cavity. So he chose to consider a damped harmonic oscillator as a model for the material in the walls. Planck's derivation consisted of three steps. In the electromagnetic step, he calculated the equilibrium energy of these harmonic oscillators of frequency ν driven by the periodic electric field of frequency ω. In the thermodynamic step, he calculated the entropy of the linear oscillators that gave the correct value for the function $u(\nu,\mathrm{T})$. In the third

and crucial statistical step, he calculated the entropy of the linear oscillators and showed that the expression for entropy in the thermodynamic step could only be recovered if he assumed the total energy of the oscillators was made up of finite energy elements, and each element had an energy ε that is equal to $n\hbar\nu$. Here n is an integer and $\hbar$ is a constant that eventually carried Planck's name and is called Planck's constant. This last step was a departure from a classical description and Planck would later describe it as "an act of desperation" to get the correct expression for the Kirchhoff function that agreed with experiments. It is important to realize that the Planck relation $\epsilon = n\hbar\nu$, for integer values of n, is a significant departure from classical thought in two ways. First, it postulates that energy is proportional to frequency, not amplitude, as would be expected for a classical oscillator. Second, for a given frequency ν, the energy is quantized, i.e., it comes in units of $\hbar\nu$.

Planck's derivation for the black-body spectrum was based on the quantization of the material of the cavity and not the radiation itself. However it would have far reaching consequences for the ultimate description of the nature of light through the work of Albert Einstein and others.

Einstein and the Notion of Photon   The revival of the particle theory of light, and the beginning of the modern concept of the photon, is due to Albert Einstein (1879–1955). Einstein is a giant in the history of science. He is the founding figure of both quantum mechanics and the theory of relativity. His impact on our understanding of the nature of light is immense.

In his 1905 paper on the photoelectric effect, the emission of electrons from a metallic surface irradiated by UV rays, Einstein was forced to postulate that light comes in discrete bundles, or quanta of energy, borrowing Planck's hypothesis: $\epsilon = n\hbar\nu$. This re-introduced the particulate nature of light into physical discourse, not as localization in space in the manner of Newton's corpuscles, but as discreteness in energy. This gave the Planck hypothesis a new and bold meaning.

There were three issues associated with the photoelectric effect: When light of frequency ν falls on a photoemissive surface, energy of the ejected electron T_e obeys $\hbar\nu = \Phi + T_e$; rate of emission is proportional to the intensity of incident light; and there is no time delay between the time in which the field begins falling on the photoactive surface and the instance of photoelectron emission. The first two of these phenomena can, in contrast to what we read in most textbooks, be explained fully by simply quantizing the atoms associated with the photodetector. However, the third point, namely the lack of a delay is a bit more subtle. It may be reasonably argued that quantum mechanics teaches us that the rate of ejection is finite even for small times, i.e., times involving a few optical cycles of the radiation field. Nevertheless, one may argue that the concept of the photon is really explicit here in the sense that conservation of energy is at stake. That is, if we have only a short period of time τ elapsing between the instants that the radiation field E begins to interact with the photoemitting atoms and the emission of the photoelectron, the amount of energy which has fallen on the surface would be given by $\epsilon_0 E^2 A\tau$, where A is the cross-section of the incident beam. For sufficiently short times, the energy which has fallen on the photodetector may not exceed $\hbar\nu$. This clearly shows that we are not able to conserve energy if we take a semiclassical point of view. However, the photon concept in which the ejection of the photoelectron implies that a photon is annihilated gets around this problem completely. This is one of the triumphs of the quantum field theory. In any case, it is a tribute to Einstein's deep understanding of physics that he was able to introduce the photon concept from such limited, and in some ways, misleading information.

This was a difficult situation. On the one hand, were the interference and diffraction experiments that required a wave nature of light for their explanation

and, on the other, was the photoelectric effect that could be understood by invoking a particle type picture. A complete resolution and the formal theory that would rigorously explain all these phenomena would have to wait almost a quarter century—till the birth of quantum mechanics in the summer of 1925.

Before discussing these developments, we briefly discuss the other "cloud" at the end of the nineteenth century—the null result of the Michelson–Morley experiment—and the birth of the theory of relativity.

Michelson–Morley Experiment and the Birth of the Theory of Relativity   Towards the end of nineteenth century, the concept of ether was firmly ingrained within the physics community. For example, Maxwell stated in an article entitled *Ether* for the *Encyclopedia Britannica* (1878): "There can be no doubt that the interplanetary and intersteller spaces are not empty but are occupied by a material substance or body, which is certainly the largest, and probably the most uniform, body of which we have any knowledge." He himself attempted unsuccessfully to measure the influence of ether's drag on the motion of the earth. It was, however, Albert Michelson (1852–1931) and Edward Morley (1838–1923), who carried out an experiment in 1887 to decisively establish the existence of Ether. They sent white light, through a half-silvered mirror into an interferometer, now called Michelson interferometer. The light beam was split into two beams, one of them traveling straight to a mirror in one arm and the other propagating at right angles to another mirror, with both beams recombining at the beam splitter after traveling equal distances They thus produced a pattern of constructive and destructive interference whose transverse displacement would depend on the relative time the light took to traverse the paths in the two arms. If the earth moves through the ether medium, the beam traveling along ether would take a longer time than the beam traveling in the perpendicular direction. Michelson and Morley expected a fringe shift equal to 0.4 fringes. What they measured was the maximum displacement of 0.02 and an average shift much less than 0.01. They thus concluded that the hypothesis concerning the existence of Ether medium is false. This null result—the most famous null result in the history of physics—was initially a major disappointment.

A resolution of the null result of the Michelson–Morley experiment came in 1889 by an Irish physicist, George FitzGerald. He postulated that the results of Michelson–Morley experiment could be explained using the hypothesis of the contraction of moving bodies in the direction of motion, the amount of contraction being just the right amount to give the same time difference as to explain the null result. According to him: "I would suggest that almost the only hypothesis that can reconcile. . . is that the length of the material bodies changes, according as they are moving through the ether or across it, by an amount depending on the square of the ratio of their velocities to that of light." In 1892, unaware of FitzGerald's hypothesis, Lorentz came to the same conclusion. Today we call it FitzGerald–Lorentz contraction. This was, however, an ad-hoc solution to the null result of the Michelson–Morley experiment with no basis in theory. This set up Lorentz (1853–1928) on the road to the derivation of Lorentz transformation and Einstein to his theory of relativity.

In 1905, Einstein formulated the theory of special relativity, based on the two postulates: The principle of relativity, i.e., the laws of physics do not change, even for objects moving in inertial (constant speed) frames of reference and the principle of the speed of light, i.e., the speed of light c is the same for all observers, regardless of their motion relative to the light source. Based on these postulates, Einstein could derive the Lorentz transformation and the length contraction. This represented a major departure from the Newton's notion of absolute space and

time. A most celebrated consequence of the theory of relativity was the equivalence of energy E and mass m via the relation $E = mc^2$. The notion of stationary ether that had been the ever existing background in all the theories since antiquity played no role in the theory of relativity.

Einstein also went on to develop a general theory of relativity that would provide a geometric theory of gravitation. This theory is based on the equivalence principle under which the states of accelerated motion and being at rest in a gravitational field are physically identical. In 1915, Einstein published a paper in which he described gravity as a geometric property of space and time. In particular, the curvature of spacetime changes in the vicinity of a massive object. The predictions of this theory were at variance with Newton's theory of gravitation and motivated one of the most dramatic experiments in the history of Physics—an experiment that would pit the two giants of science, Isaac Newton and Albert Einstein, and their conflicting theories of gravitation against each other. The experiment was the bending of light by a massive object.

Bending of Light, Newton, Einstein, and Eddington   We recall that Newton championed a corpuscular nature for light. Newton had also noted, while formulating his theory of gravitation, that any material particle moving at a finite speed would experience a force while passing in the vicinity of a massive object. This pull by gravity should bend the trajectory of the particle and the bending angle should be independent of the mass of the particle. Thus if light is composed of small particles, they should also experience such deflection. Newton himself did not calculate this deflection as, in his time, the finite speed of light was not well established. However he postulated this deflection and, towards the end of his treatise *Opticks* (1704), he noted "Do not Bodies act upon Light at a distance, and by their action bend its Rays, and is not this action strongest at the least distance?". The finite speed of light was well established by early nineteenth century and a German astronomer, Johann Georg von Soldner (1804), presented calculations based on Newton's corpuscular theory that light weighs and bends like high speed projectiles in a gravitational field. He produced a value of 0.87 arc sec bending angle for light grazing the Sun.

In 1911, more than hundred years later, Einstein calculated the bending of light by combining the equivalence principle with special theory of relativity to predict a deflection of light from the sun by the angle of 0.87 arc second. This is the same value that Newtonian theory predicted. He obtained this result before he formulated the general theory of relativity and the associated curved space time. When he included the effects of general theory of relativity, the predicted value for the bending of light doubled to 1.83 arc second. This result was published on November 18, 1915. Thus the predictions of Newton and Einstein were at odds with each other and an experimental activity followed soon to decide who was right. The bending of light by a massive object also became the first test of the esoteric Einstein's general theory of relativity.

After the First World War was over, Sir Arthur Eddington (1882–1944) organized an expedition to the island of Principe near Africa to watch the solar eclipse on May 29, 1919 and to measure the observed curving of light from distant stars by the gravitational pull of the sun. While the expedition was being planned, Eddington wrote: "The present eclipse expeditions may for the first time demonstrate the weight of light (i.e. Newton's value) and they may also confirm the added effect of Einstein's weird theory of non-Euclidean space, or they may lead to a result of yet more far reaching consequences of no deflection". When the results were announced, they agreed with Einstein's predicted value. Einstein became an overnight international celebrity and an iconic figure.

Birth of Quantum Mechanics   The first quarter of twentieth century was per-haps the most remarkable period in the history of Physics. Through the discoveries of the quantum theory of Planck, Einstein, and Niels Bohr and the Einstein's theories of special and general relativity, the outlook on con-ventional or classical Physics had completely transformed. Newtonian Phys-ics was unable to explain effects that happened at sub-atomic level or at high speeds, speeds comparable to the speed of light. The capstone of these developments was the birth of quantum mechanics that took place in the summer and winter of 1925 through the works of Werner Heisenberg, Max Born, Pascual Jordan, and Paul Dirac, on one hand, and Erwin Schrodinger, on the other. This new theory, that replaced Newton's and Maxwell's theories, would have revolutionary consequences in our story on the nature of light. An important underlying feature of the new theory was the notion of complementarity, namely two observables are *complementary* if precise knowledge of one of them implies that all possible outcomes of measuring the other one are equally probable. This injected the notion of wave-particle duality in the discourse on the nature of both light and matter.

Dirac, Quantum Theory of Light   With the advent of quantum mechanics, the dual nature of light was apparent. There were phenomena such as interfer-ence and diffraction that could be explained based on the wave nature of light. Then there were phenomena such as excitation of an atom by absorbing a photon that required a particle nature of light. It was Paul Adrien Dirac (1902–1982) who, in a seminal paper published in 1927, synthesized the wave and particle natures of light in a single theory. According to the Maxwell's theory, the light consisted of electromagnetic waves of different frequencies. The oscillating waves could be looked upon as a sort of simple harmonic oscillators. Central to Dirac's quantum theory of radiation was the notion that each mode of the electromagnetic field could be identified as a quantized simple harmonic oscillator. Both satisfy the same commutation relation $[\hat{q}, \hat{p}] = i\hbar$, although q and p represent different things in the two cases. In the case of harmonic oscillator, they represent the position and momentum of the oscillating particle, while in the case of electromagnetic case, they represent the electric (E) and magnetic (B) fields of the light in a given wavevector and polari-zation mode k. Thus, the quantum electromagnetic field consists of an *infinite* product of such generalized harmonic oscillators, one for each mode of the field. A Heisenberg-type uncertainty relation applies to the Maxwell fields: $\Delta E \Delta B \geq \hbar/2 \times$ constant, i.e., the electric and the magnetic fields associated with light cannot be measured arbitrarily precisely. Such field fluctuations are an intrinsic feature of the quantized theory. The uncertainty relation can also be formulated in terms of the in-phase and in-quadrature components of the electric field. To introduce the notion of a photon, it is convenient to recast the above quantization of the field in terms of the annihilation ($\hat{a}$) and creation ($\hat{a}^\dagger$) operators of a harmonic oscillator. These correspond to the positive and negative frequency parts of the electric field operator, respectively.

By analogy to the theory of the harmonic oscillator, the application of $\hat{a}$ produces a state with one *less* quantum of energy, and the application of $\hat{a}^\dagger$ produces a state with one *more* quantum of energy. This naturally leads to discrete energies for the oscillator in each mode: $n_k = 0, 1, 2, \ldots$. In the absence of any medium, the modes $E_k(\mathbf{r})$ are just the plane-wave solutions to the Maxwell equations. Alternately, we can define a localized "pulse" basis for the photon by summing over many wave vectors and frequencies, just as for classical waves. Thus, quantum electrodynamics permits both wave and particle perspectives on

light. The wave perspective is exemplified by the picture of a stochastic electro-magnetic field. The particle perspective follows from the language of annihilation and creation operators which are subject to the appropriate commutation relation. Combining these perspectives, one can adopt a rigorous definition of the photon as follows: A photon corresponds to a single excitation of a particular mode k of the electromagnetic field in a suitably defined cavity, such that the annihilation and the creation operators for the field mode satisfy a Boson commutation relation. The wave-particle picture of light embedded in the Dirac's theory of light had novel and important consequences. The most important was the reshaping of our concept of vacuum.

Quantum Vacuum   Before the advent of quantum field theory, the vacuum was perceived as *nothing*—a place where no light existed, nothing moved, and there was no energy present. The quantum mechanical picture of vacuum turned out to be dramatically different. According to Dirac's theory of light, the quantum harmonic oscillator associated with each electromagnetic wave of frequency ν has an energy equal to $\hbar\nu/2$ in vacuum. There are infinite number of mode in the universe, each associated with a frequency ν. Thus the total energy in the universe can be calculated by adding this vacuum energy for each mode and the result is an infinite amount of energy. In addition, as noted above, there are quantum mechanical fluctuations as a result of Heisenberg's uncertainty relation that cannot be neglected, even in vacuum. This forbids a classical description of absolutely zero electric and magnetic fields in vacuum. Instead we have fluctuations—randomly nonzero fields at any time. We thus have a revolutionary new way of thinking about light that field quantization introduced into the scientific discourse, namely that the electromagnetic field, when quantized, has the ability to exist in a state of pure nothingness—the so-called vacuum state—and yet have observable consequences in the material world.

Spontaneous Emission   An important consequence of the fluctuations in the vacuum field is the phenomenon of spontaneous emission by an atom. A photon is created in response to these fluctuations. Thus, even in the absence of an applied field, an atom in the excited state can decay to the ground state and spontaneously emit a photon. Since the direction and time of emission are random, this process represents a fundamental source of quantum noise, and a limitation to any coherent process (such as lasing). The excited atomic level acquires a finite bandwidth which is the inverse of the emission lifetime. We can use quantum theory to calculate the spatio-temporal profile of the emitted photon as detected by a photodetector.

Lamb Shift   Perhaps the greatest triumph of field quantization is the explanation of the Lamb shift between, for example, the $2s_{1/2}$ and $2p_{1/2}$ levels in a hydrogenic atom. Relativistic quantum mechanics predicts that these levels should be at the same energy. Willis Lamb (1913–2008), however, experimentally observed in 1947 a frequency splitting of about 1 GHz in contradiction to the theoretical prediction. We can understand the shift intuitively by picturing the electron forced to fluctuate about its first-quantized position in the atom due to random kicks from the surrounding, fluctuating vacuum field. Its average displacement $< \Delta\mathbf{r} >$ is zero, but the squared displacement $< (\Delta\mathbf{r})^2 >$ is slightly nonzero, with the result that the electron "senses" a slightly different Coulomb pull from the positively charged nucleus than it normally would. The effect is more prominent nearer the nucleus where the Coulomb potential falls off

more steeply, thus the *s* orbital is affected more than the *p* orbital. This is manifested as the Lamb shift between the levels.

Casimir Force   In 1947, Hendrick Casimir (1909–2000) predicted that if two conducting plates separated by a distance *a* are placed in vacuum, and no external force is acting on them, they would attract each other with a force equal to $\hbar c \pi^2 / 240 a^4$. This Casimir force was experimentally observed in 1958. Casimir explained this force arising purely as a consequence of the quantized modes of the radiation in vacuum. When the two conducting plates are inserted in the vacuum, the space is divided into three regions, the two infinite regions outside the plates and another region inside the two plates. The regions outside the plates have continuum of frequencies, i.e., all possible frequencies, resulting in an infinite amount of energy when we add the contributions of all the modes. The region inside the plates, however, allows only discrete number of modes satisfied by the resonance condition $a = \pi n c / \nu_n$, where ν_n is the frequency of the *n*th mode. These are also infinite number of modes, one for each value of *n*. The total amount of the vacuum field energy between the plates is also infinite. Thus we have an infinite amount of energy outside the plates and an infinite amount of energy between the plates. The truly dramatic result is that when we subtract these two infinities, the outcome is finite. As the system tends to evolve to a state with minimum energy there is a resulting force and this force is attractive. This is a highly counterintuitive result. Julian Schwinger called it "One of the least intuitive consequences of quantum electrodynamics" and according to Bryce DeWitt: "What startled me, in addition to the crazy idea that a pair of electrically neutral conductors should attract one another, was the way in which Casimir said the force could be computed, namely, by examining the effect on the zero-point energy of the electromagnetic vacuum caused by the mere presence of the plates. I had always been taught that the zero-point energy of a quantized field was unphysical."

Laser: A Coherent Light Source   All the studies on light from the antiquity until the middle of nineteenth century were based on incoherent light sources such as the sun, candle light, sodium lamp, or light bulb. In 1950s a new coherent source of light was invented, first in the microwave region and then in the optical region. This new kind of light source, laser, is one of the greatest inventions of the second part of the twentieth century. It has helped to revolutionize many branches of science and technology ranging from bio-technology and precision measurements to communication and remote sensing. The physical process behind conventional light sources is spontaneous emission and they operate in thermal equilibrium. Initially majority of atoms and molecules are in their ground state. When energy is supplied to the atoms or molecules, some of them go to the excited states and then radiate via spontaneous emission. As discussed above, the spontaneous emission process is due to the ubiquitous vacuum fluctuations and each atom radiates independently of each other. The resulting light is a white light sent in all directions and is incoherent. On the other hand, the dominant emission process in a laser is stimulated emission. By a clever design, the radiated photons by the atoms or molecules are able to stimulate other atoms to radiate with the same frequency and same direction. The resulting radiation is coherent, monochromatic, and highly directional.

In 1954, Gordon, Zeiger, and Charles Townes (1915–2015) showed that coherent electromagnetic radiation can be generated in the radio frequency range by the so-called maser (microwave amplification by stimulated emission of

radiation). The first maser action was observed in ammonia. The maser principle was extended by Arthur Schawlow (1921–1999) and Townes, and also by Basov and Prokhorov, to the optical domain, thus obtaining a LASER (light amplification by stimulated emission of radiation). A laser consists of a set of atoms interacting with an electromagnetic field inside a cavity. The cavity supports only a specific set of modes corresponding to a discrete sequence of frequencies. The active atoms, i.e., the ones that are pumped to the upper level of the laser transition, are in resonance with one of these frequencies of the cavity. A resonant electromagnetic field gives rise to stimulated emission, and the atoms transfer their excitation energy to the radiation field. The emitted radiation is still at resonance. If the upper level is sufficiently populated, this radiation gives rise to further transitions in other atoms. In this way all the excitation energy of the atoms is transferred to a single mode of the radiation field.

The first pulsed laser operation was demonstrated by Theodore Maiman (1927–2007) in ruby in 1960. The first continuous wave (cw) laser, a He–Ne gas laser, was built by Ali Javan later in the same year. Since then, a large variety of systems have been demonstrated to exhibit lasing action; generating coherent light over a frequency domain ranging from infrared to ultraviolet. These include dye lasers, chemical lasers, and semiconductor lasers.

The Birth of Quantum Optics   The advent of laser required a careful description of the various sources of light. The question was: What is the fundamental difference between the conventional light sources, such as the sun, and the newly discovered laser light? An answer to this question led to a new field of study in Physics: Quantum Optics. Roy Glauber, in a series of seminal papers in 1963, at first controversial, differentiated between laser (coherent) light and normal (blackbody) light in terms of the photon statistics. This work had far reaching consequences as it showed that there could be all kinds of light sources that have to be distinguished by their quantum states and the corresponding statistical properties. These sources could range from a photon number state, in which light quanta could behave like particles, to a coherent state, which is as close to a classical Maxwellian description of light as electromagnetic wave as the quantum mechanics allows.

Quantum Interference and Delayed Choice Quantum Eraser   Before closing this brief story of light, we observe that the paradigm of quantum interference, the interference of probability amplitudes associated with different paths taken by a photon, defines our present understanding on the nature of light. In some ways, this is a culmination of the centuries-old debate on the nature of light reviewed through this article. The modern quantum perspective on this debate is that light is neither wave nor particle, but an elusive, intermediate entity that obeys the superposition principle. The quintessential experiment that demonstrates wave-particle duality is the Young's two-slit interference experiment. When a single photon goes through the slits, it registers as a point-like event on the screen (measured say by a CCD array). An accumulation of such events over repeated trials builds up a probabilistic fringe pattern that is characteristic of wave interference. However, if we arrange to measure which slit the photon goes through, the interference always disappears.

This picture is, however, not so simple. The counterintuitive aspect of complementarity is epitomized in the problem of quantum eraser, as was shown by Marlan Scully in 1982. The inability to discern which-path information, or the indistinguishability of interfering pathways, in the double-slit experiment is the key to preserving the wave properties of the photon and the appearance of fringes

on the screen. What if, rather than subject the photon to a classical measurement, we can have it interact *quantum mechanically* with a localized marker particle (such as an atom) and leave behind a record of its path? The interference pattern then survives or not depends on the marker states, which carry the tell-tale information about which path the photon took to the detector. The coherence is destroyed as soon as we have the which-path information. One then wonders whether it might not be possible to retrieve the coherence, and the fringes, by destroying the which-path information contained in the marker—long after the photon is detected on the screen. This is the essence of the quantum eraser idea. An experimental demonstration of quantum eraser elicits a response of incredulity as the following quote by Brian Greene in his beautiful book *The Fabric of the Cosmos* indicates: "These experiments are a magnificent affront to our conventional notions of space and time. . . . . For a few days after I learned of these experiments, I remember feeling elated. I felt I'd been given a glimpse into a veiled side of reality."

1.6   Epilogue

We have come a long way from the earliest studies on light, trying to understand vision as light emanating from our eyes, to the description of light as rays, then as particles, and then waves, and finally exhibiting both particle and wave natures. We can only speculate how our present understanding of light will be perceived decades or centuries from now. Will our picture of light quanta as both waves and particles survive or will something more intuitive replace this incomprehensible picture? It is an irony that the greatest strides taken in the scientific understanding have come in our time, yet we feel least certain of our understanding of what light is, what photon is. In spite of the great success of the mathematical theory to describe light and its amazing agreement with experiment, the question "What is Light?" can ignite a heated discussion. To quote Albert Einstein (1954), "All the fifty years of conscious brooding have brought me no closer to the answer to the question: What are light quanta? Of course today every rascal thinks he knows the answer, but he is deluding himself."

Bibliography

Lindberg DC (1976) Theories of vision: from Al-Kindi to Kepler. University of Chicago Press, Chicago

Pais A (1982) Subtle is the lord: the science and the life of Albert Einstein. Oxford University Press, New York

1

Scully MO, Suhail Zubairy M (1997) Quantum optics. Cambridge University Press, Cambridge

Aharonov Y, Suhail Zubairy M (2005) Time and the quantum: erasing the past and impacting the future. Science 307:875

Muthukrishnan A, Scully MO, Suhail Zubairy M (2003) The concept of the photon-revisited? Opt Photonics News 14(10):18–27

Greenberger DM, Erez N, Scully MO, Svidzinsky AA, Suhail Zubairy M (2007) Planck, photon statistics, and Bose-Einstein condensate. In: Wolf E (ed) Progress in optics, vol 50. Elsevier, Amsterdam, p 275

Lyons J (2009) The house of wisdom: how the Arabs transformed western civilization. Bloomsbury Press, New York

Darrigol O (2012) A history of light: from Greek antiquity to the nineteenth century. Oxford University Press, Oxford

Mark Smith A (2015) From sight to light: the passage from ancient to modern optics. University of Chicago Press, Chicago

Weinberg S (2015) To explain the world: the discovery of modern science. HarperCollins, New York