The Miracle of Light

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An Exploration of the Discovery of Light's Physical Properties

Thank you and good afternoon. I am deeply honored to have this opportunity to speak to you today. I first became aware of the Quest club soon after moving to Fort Wayne from Ann Arbor, Michigan when, in the fall of 1994, I purchased a copy of the collection of papers published under the title ***The Quest for Fort Wayne***. I am grateful to Chancellor Michael Wartell for frequently inviting me to meetings as a guest and then putting forward my name for membership in this organization. While there exists a certain level of trepidation accompanying my first Quest paper, it is reassuring to see so many friends and colleagues in attendance today.

DEFINING MIRICALES AND LIGHT

The greatest challenge I encountered in preparing this paper stemmed, quite naturally, from the wording of the topic - ***The Miracle of Light***. As I considered the topic, my thoughts ranged from the celebration of the miracle of lights that begins in nine days with the start of Hanukkah to the tireless efforts of Edison to perfect the incandescent bulb. Clearly I needed to focus my thinking and limit the scope of my research to concepts that could be covered with some degree of success in the time allowed by this format.

In 1988 Lockwood presented a paper on lasers. I believe that was the only consideration of the physics of light by the Quest Club; and it happens to be the only paper with the word **miracle** in the title. Since two decades have passed, it seems reasonable to start this paper with a basic understanding of **miracles** and **light**.

In formal terms, a miracle is thought of as a disruption or suspension of the laws of nature by some supernatural force or agent. Yet nothing could be more natural than light. It certainly is a fundamental way in which we experience the natural world and has been the topic of scientific study for millennia. Einstein recognized the incompatibility that exists between the miraculous and the scientific when he said “you can live as if nothing is a miracle” or “you can live as if everything is a miracle”. If an intellect as great as his could not reconcile this incompatibility then there is little hope for me to do so.

I will, however, attempt to provide an understanding of the basic characteristics of light and a history of the evolution of thought regarding the physics of light. Since I am much more comfortable in the realm of the rational than I am in the realm of the miraculous, I will ask you to help me parse those aspects of light that seem to disrupt the laws of nature from those that define them.

Light, as we experience it in the visible spectrum, is a form of electromagnetic radiation with wavelengths ranging from about 400 to 700 nanometers; a small portion of the much broader electromagnetic spectrum that includes AM radio with wavelengths of hundreds of meters, to radar and microwaves, the infra-red, visible light, ultra violet, x-rays, and finally gamma rays with wavelengths of one tenth of an angstrom, or one hundredth of a nanometer. All light exhibits three fundamental properties: intensity, wavelength, and polarization. Intensity is a measure of the energy flux passing through an area; wavelength describes the spacing between equivalent points on the wave form; and polarization is a description of the orientation of the oscillations of the wave in the direction of propagation. Polarizing filters such as those found in sunglasses and cameras block light waves traveling with an orientation perpendicular to the filter, thus reducing glare and increasing optical contrast.

ANCIENT CONCEPTS OF LIGHT

The Greek pre-Socratic philosopher Empedocles established the classical cosmological theory of the four elements: fire, air, water, and earth. This model was in turn expanded by Aristotle to include a fifth element, the quintaessentia, more commonly known as the aether through which light waves were thought to travel in much the same way that sound waves move through air. From this conception comes our common use of the term quintessential, meaning the most perfect embodiment of something, its pure and concentrated essence. Hamlet, in his conversation with Rosencrantz and Guildenstern describes human life as the "quintessence of dust" when he questioned the relationship of the self-aware to the natural world. Light, as a symbol of both life and intelligence, is a powerful metaphor for what the troubled prince was considering.

The primitive notion that light originated in the eye, traveled through the aether, and was reflected back to the eye was formally challenged by the geometric experimentation of Euclid in his study of the properties of light in the treatise ***Optica***. Yet the concept of an aether through which light traveled remained a foundation of scientific thought supported by the work of Newton, Huygens, and Maxwell until 1887 when Albert Michelson and Edward Morley of Case Western Reserve famously failed in their attempt to measure the existence of an aether wind in what must be counted as Cleveland's most significant contribution to the collective knowledge of mankind.

Einstein's special theory of relativity published in 1905 removed the need for an absolute frame of reference, established a fixed value for the speed of light of three hundred million meters per second, and in turn relegated the notion of an aether to the domain of the mythological.

THE DUEL NATURE OF LIGHT

If we now know there is no aether through which light travels, what else do we know about light's properties and how was that knowledge obtained? The evolution of our theoretical understanding of light has been an essential part of the development of the two great achievements of twentieth-century physics, relativity theory and quantum theory.

The period of classical physics extending from the renaissance to the end of the 19th century and was characterized by two competing theories concerning the nature of light. The corpuscular theory held that light was composed of rapidly moving particles (corpuscles), while the wave theory of light held that waves of light energy moved through a medium – the aether. The corpuscular theory was advanced by Isaac Newton.

His experiments were summarized in the book ***Opticks*** published in 1704. The corpuscular concept was most strongly supported by the observation that light casts shadows with sharp edges. Conversely, sound and water waves were known to bend around obstacles and occupy those areas that would otherwise be in shadow. Newton was aware of the concept of diffraction, first described by the Jesuit priest Francesco Maria Grimaldi in the mid 1600's. However, Newton concluded that the effect was so small that it could not be equivalent to the large-scale bending observed for other waveforms. The diffraction of light, of course, is responsible for numerous commonly observed phenomena such as the holographic images found on the faces of credit cards. Newton attributed the diffraction effect to an attraction between the obstacle and the light particles as they pass, resulting in acceleration of the particles, a concept he termed inflexion. He proposed an analogous explanation for the refraction of light, which is now know to in fact be caused by the slowing of light as it enters different material such as glass, water, or crystal. His misconception was driven by an incomplete understanding of the relationship between the wavelength of the light and the scale of the obstacle with which the light is interacting.

The opposing theory was championed by Newton's great contemporary and scientific rival, the Dutchman Christiaan Huygens, who in 1690 published his ***Treatise on Light***. A key observation that supported Huygens' wave theory was the observation that two beams of light can pass through each other without being deflected, a property that was also commonly observed for water and sound waves. It only stood to reason that if light were corpuscular in nature, some of the particles traveling along intersecting paths must collide and be deflected. Huygens conceptualized light as a pressure wave moving through the aether and in that he was incorrect. Irrespective of the nagging experimental evidence in support of a wave model for light, the overwhelming authority of Newton held sway throughout the eighteenth century until, as always happens in science, accumulated factual evidence overwhelmed reliance upon the heroic reputation of previous workers.

Thomas Young and Augustin Fresnel in the early nineteenth century used experimentation and theoretical analysis to understand the processes of light interference. Interference had been previous observed in other wave systems, demonstrating that two intersecting wave fronts can cancel each other, resulting in regions of zero wave amplitude. Corpuscular, or particle-based, systems never behave in this way.

Young's famous double slit experiment required the experimental light to have the characteristic of coherence. That is, the light must be of a single wave length, or color, and consist of smooth wave fronts. Common light sources such as flames and incandescent lamps produce incoherent light consisting of a full spectrum of wavelengths with complexly jumbled wave fronts. Using color filters to produce light of a single wave length he allowed that light to first pass through a pinhole to produce smooth wave fronts that then went on to pass through the double slits. The constructive and destructive interference of the intersecting wave fronts produces alternating bands of light and dark on a screen behind the slits. Augustin Fresnel, one of the greatest applied optical physicists of the nineteenth century and perhaps best known for his work on the lenses used in lighthouses, turned his attention to the question of the wave-like properties of light. In 1821, Fresnel demonstrated that light was a transverse wave, not a pressure-like longitudinal wave as theorized by Huygens. The final compelling evidence that light is made of waves not corpuscles came in 1850 when Jean Bernard Leon Foucault (made famous by his huge pendulum) directly measured the speed of light in air and water. By demonstrating that the refraction of light was due to the slowing of the wave fronts in water relative to their speed in air, he was able to directly refute Newton’s concept of accelerating corpuscles.

THE QUANTUM NATURE OF LIGHT AND THE BIRTH OF A NEW PHYSICS

The next major step in understanding the nature of light came when physicists began to explore the relationship between light and solids. When a solid is heated, it emits electromagnetic energy across a continuous spectrum, including visible light. Everyone is familiar with a bar of glowing iron in a forge, the heating coil of an electric stove, and the bright orange wires of an electric space heater. Importantly, the power of the light emitted varies continuously as a function of the wavelength in such a way as to describe a skewed frequency distribution. At higher temperatures, the peak of this curve shifts to shorter wavelengths and the total power – the area under the curve – increases. Physicists have termed this phenomenon “black body” radiation due to the theoretical simplicity of considering a solid black object. In 1894 the German physicist Max Planck turned his attention to the problem of black body radiation. He had been commissioned by electric companies to create maximum light from light bulbs with minimum energy. The problem had been stated by first by Gustav Kirchhoff in 1859as: “how does the intensity of the electromagnetic radiation emitted by a black body depend on the frequency of the radiation and the temperature of the body?”

Attempts to use classical physics to explain the characteristics of black body radiation failed because they predicted ever increasing power at shorter wavelengths. Observations clearly indicated a decrease at short wavelengths. The use of classical mechanical explanations for light was a failure and there existed no obvious theoretical replacement.

The answer was to be found in the interactions between light and gas. Pure elemental gasses like hydrogen were found to emit light not across a broad spectrum, but rather as discrete lines of energy at specific wavelengths. Likewise, when white light was passed through a gas, the gas was found to absorb light at the same wavelengths. The emission and absorption spectra observed for each gas was unique. Danish physicist Neils Bohr used the line spectrum of hydrogen to explain its atomic structure in 1913.

Bohr found that absorption and emission of light by a gas occurs when electrons move from one energy state (or orbit as it is termed) to another and that those transitions in energy state only occur as discrete changes in the angular momentum of the electron. The steps in energy level are known as quanta of radiation. When the energy state of an atom drops, the quantized energy that is released takes the form of a bundle of light energy known as a photon. Photons are elementary particles that have no mass but act as the force carriers of electromagnetic radiation.

Building on Bohr's work, the American physicist Arthur Compton in 1922 demonstrated the dual nature of light through his discovery that a photon's momentum ia proportional to its wavelength. Forty-five years after Michelson and Morley's experiment ended the conception of an aether, Compton firmly reestablished the fact that light had duel properties. He found that light behaves as a wave as it passes through space or through a transparent material, but when the light interacts with electrons at the subatomic scale, it does so as if it were a particle. Further experimentation in 1927 by Louis de Broglie demonstrated that not only did light have a dual nature but that any moving particle also has an associated wave. That is to say, solids have some characteristics that are best described by waves just as electromagnetic waves have some characteristics that are best described as particles. De Broglie's work brought together the physics of light and matter into the new domain of wave mechanics.

The work of these many giants of physics has been richly rewarded by the Nobel Prize selection committee. First in 1907, Albert Michelson for his work attempting to measure the aether; 1918, Max Plank for the discovery of energy quanta; 1921, Albert Einstein for the discovery of the law of the photoelectric effect; 1922 Niels Bohr, for his understanding of the structure of atoms and of the energy emanating from them; 1927, Arthur Compton for the effect named after him; and 1929, Louis de Broglie for the discovery of the wave nature of electrons. Reading this list makes one wonder for what accomplishments prizes in the other years were awarded?

THE IMPACT OF LIGHT ON MODERN LIFE

Having completed a tour of the history of the development of the observational and theoretical understanding of light's properties and having established how the study of light lead to the creation of modern physics, it is now appropriate to consider how light is central to some of the major technological innovations that are part of modern life. First, let us return to Lockwood's topic, lasers.

A laser is a device that emits a high energy beam of electromagnetic radiation over a very narrow band of wavelengths. The word laser is an acronym for the term "Light Amplification by Stimulated Emission of Radiation". The amplification occurs as light is reflected within a cavity between two mirrors through a material known as the gain medium. The gain medium produces an amplification of the light's intensity through stimulated emissions as caused by electronic transitions from higher energy states to lower energy states. That is, many, many photons are emitted. The gain medium can be composed of various crystals or glasses that have been doped with rare earth elements, gasses such as helium neon or argon, or various semi-conductors such as gallium-arsenide. The two mirrors that bound the amplification cavity are not identical. Rather one is highly reflective while the other allows some of the light energy to escape in a tight beam.

The physics of laser light has its origins in Einstein's 1917 paper "On the Quantum Theory of Radiation" wherein he predicted the stimulated emission of electromagnetic radiation. In the early 1950's Charles Townes of Columbia University and two researchers in the Soviet Union, Nikolay Basov and Aleksandr Prokhorov, developed the first microwave amplifiers, known as masers – the forerunners of the modern laser – and the three shared the 1964 Nobel Prize in physics for the construction of oscillators and amplifiers based on the maser-laser principle. In 1957 Townes and Arthur Schawlow developed and patented the first "optical maser" while working for Bell Laboratories. At the same time, Columbia graduate student Gordon Gould was working on similar technologies and in 1959 published a paper that first used the term laser. The result was a thirty year legal battle over who had the rights to the laser intellectual property. Eventually settled in 1987, Gould was granted patents for several aspects of the laser technology.

Without question, lasers are an essential technology of modern civilization. Used in printers, CD and DVD players, barcode scanners, and laser pointers they have become as ubiquitous and are as easily overlooked as microprocessors in our daily life.

More recently, one of the most heavily marketed applications of light technology must be Verizon's FiOS fiber optic service for voice, video, and data. Who did not received innumerable solicitations via telephone, mail, and even door-to-door salesmen during Verizon's recent battle with Comcast for market share in the Fort Wayne region? A fiber optic cable system relies upon the internal reflection of light within a long thin strand of optically pure glass – known as the core. The glass fiber core is surrounded by a material that causes the light to reflect, the cladding. Because of these internal reflections, the light signal can follow the cable around complex bends over great distances with little drop in signal fidelity. While there are many advantages that fiber optic cables have over copper electric wires, signal quality does degrade with distance due to impurities in the glass core and imperfect reflectivity of the cladding.

One of the most exciting emerging technologies based on laser light is the concept of optical computing. While still in the development stage, optical computing presents several important advantages over traditional electronic computing technology, including greater performance, less heat generation, and the elimination of electromagnetic signal interference. There are two approaches to developing optical computing technology. The first involves the replication of conventional computing technology using the physics of optical systems. In this approach, electronic components are replaced by optical systems. This technique will allow for the creation of electronic/optical hybrid computers. Conversely, a more radical approach involves a complete redesign of computing technology that takes advantage of the differences between the physics of photons and the physics of electrons. While no optical computing devices are currently available commercially, a number of successful prototypes have been built in the laboratory.

Without question, the physics of light will be utilized by new technologies in ways we have not yet imagined and while we might be far away from the photon torpedoes of science fiction, the theoretical advances of 19th and 20th century physics research paved the way for modern laser and optical technologies.

A LUMINATED STRAND WEAVING THE MYSTICAL TO THE RATIONAL

The experimental and theoretical exploration of light's properties has provided the foundation for the development of modern physics. As knowledge and understanding has grown with each new discovery of light's complex properties we have been required to expand our ability to reconcile the geometric simplicity of its macroscopic character with the seemingly supernatural complexity of its properties at the subatomic scale. The history of the physics of light traces a path through some of the greatest achievements of the human mind. Is light miraculous? Perhaps not in the formal, theological, sense. It certainly does, however, possess the ability to confound our day-to-day conceptions of reality and challenge us to continue to expand the boundaries of knowledge. If, as Hamlet suggested, it is our ability to think, to question, and to search for truth that defines us, then light provides not only a metaphorical description of our essence – it has also illuminated our path to greater knowledge.

Perhaps the Swiss psychologist Carl Jung captured this theme in the most evocative way when he said

"As far as we can discern, the sole purpose of human existence is to kindle a light in the darkness of mere being."

Again, thank you for this opportunity, and I wish you all a miraculous and enlightening holiday season.

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